THE UTILIZATION OF GROUNDWATERS BY PUMPING FOR IRRIGATION.

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INTRODUCTION.

The purpose of the following paper is to present in brief compass a survey of modern irrigation pumping and a retrospect of the progress of the past ten years. The paper treats briefly of groundwater supplies, their occurrence, regimen, and recharge; of the methods of developing groundwater supplies by means of wells; of pumping machinery; and of the economics of this type of irrigation. It is a discussion of what is, and not of what ought to be; and a mention of new things rather than a description of the old.

Pumping for irrigation in a crude form is of great antiquity. In Egypt, India and China odd pumps, such as endless chain buckets and scoop wheels, were employed; and the Kairez or long tunnels of central Asia, many of which are still in use, were remarkable examples of groundwater development suited to earlier times. But probably at no time in the past has there been any utilization of groundwaters at all comparable in extent or in effectiveness with that of today in the great Southwest, from Arkansas to California. And, with the advancement in knowledge, in methods, and in machinery, pump irrigation has come to occupy a distinct and important field of engineering activity.

The magnitude of pump irrigation was revealed by the census of 1910.[1 *] The statistics relating to irrigation show a total of 307,496 acres (124,400 hectares) irrigated by pumping

* [1] is reference to bibliography number.

from wells in 1909 in the United States west of the 100th meridian. Ninety percent of this acreage was in California, and the remaining ten percent was situated mostly in Arizona, New Mexico, Texas and Washington. Also, the census furnishes data on the irrigation wells in use in 1910. The total number of pumped wells was 14,558, of which 10,724 were in California. The total capacity of the pumped wells was 5,426,139 gallons (20,540 cu. m.) per minute, of which amount 76 percent was in California, while Arizona, New Mexico and Texas were of next importance in the order named. The census of 1900 did not include any data on wells or irrigation pumping.

Pumping from wells for the irrigation of rice, in Louisiana, Arkansas and Texas, is of increasing importance, having been developed entirely since 1900. The number of pumped wells in the rice district in 1910 was 848, with a combined capacity of 802,653 gallons (3038 cu. m.) per minute. Texas was credited with 55.5 percent of the total well capacity, Arkansas with 33.5 percent and Louisiana with 11 percent.

Since 1910 there has been a rapid increase in irrigation pumping. Representatives of the office of Irrigation Investigations, U. S. Department of Agriculture, have made a canvass to ascertain the number of new pumping plants installed in California during the years 1911-1914 inclusive. Their estimate is 15,262, which is 164 percent of the number in use in 1910. Allowing for a moderate number of replacements, it is certain that the number of plants has more than doubled in four years. In Arizona, the percentage of increase is much higher. It is believed that there are four times as many pumping plants in operation now as in 1910. The preparation and cropping of land has lagged somewhat behind the water development, however, and the acreage irrigated at the present time in Arizona is probably not over one-half of the acreage to which the pumping plants are ready to supply water.

Elsewhere in irrigated countries, it is presumable that much progress is being made along similar lines. It is hoped that this paper will be amplified by discussions that will record the recent progress in those countries and, also, the present practice in other regions than Arizona and California, to which this paper chiefly applies.

From the nature of pump irrigation it is of necessity divided into small projects. Many times, indeed, the projects seem quite insignificant, perhaps a pump capacity of 300 gallons (1.14 cu. m.) per minute and 40 acres (16.2 hectares) of ground. It is only when the hundreds of projects are considered in the aggregate that their importance is truly appreciated. But, it must

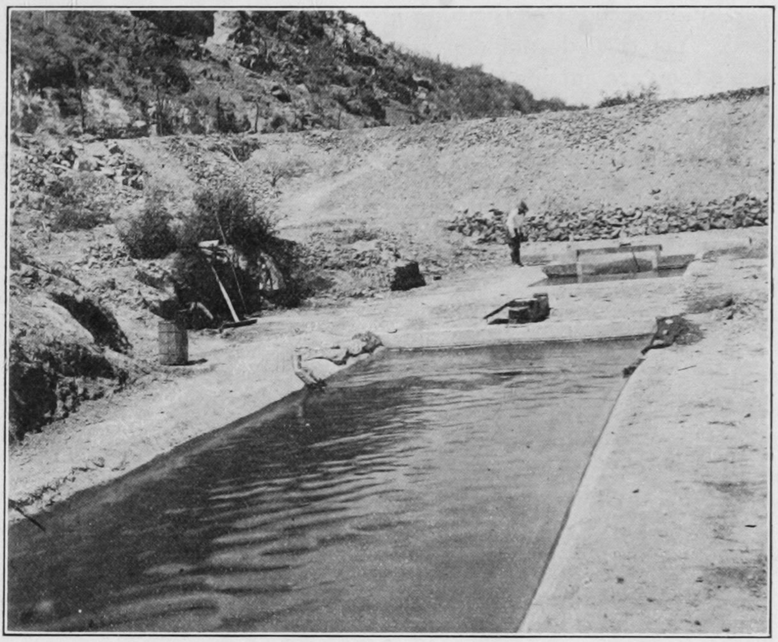

Fig. 1. Intake to New Siphon of Tucson Farms Co. Ditch.

A Venturi irrigation meter is being checked against a temporary weir. This ditch carries the combined flow from 20 wells.

be remembered that unless the small individual project is scientifically designed and intelligently operated, failure or a low degree of success will result. Pump irrigation stands or falls with the farmer's individual pumping plant.

Occasionally large groups of pumping plants are designed as a single unit by one engineer. Such are the Portales Valley project in New Mexico,[2] the Tucson Farms Co. project at Tucson, Arizona, and the Sacaton pumping project of the U. S. Indian

Service.[3] The first named included 69 pumping plants at the outset, the Tucson project has 78 pumping plants, while the Sacaton string of ten wells has a capacity of serving 10,000 acres (4047 hectares) of land in one unit.

There are many large irrigation pumping projects in central California, Oregon and Washington, which derive their water supply from flowing rivers. These projects are noteworthy on account of the high character of pumping machinery used. Yet they do not depend upon groundwater supplies and hence they are outside the province of this paper.

In general the individual plants are operated independently of each other. For various reasons, cooperative pumping is disliked and evaded, but, as will appear later on, there are obvious advantages in cooperation, even for small plants.

GROUNDWATER SUPPLIES.

In times past, groundwaters have been very much of a mystery to most people, and even now in many localities one hears the most astounding theories concerning their magnitude, motions, origin, and the methods of locating good supplies. Today, however, there is available to the engineer a comprehensive and valuable mass of data on the groundwaters of this country. For these data we are indebted, in large measure, to the able scientists of the U. S. Geological Survey, whose researches have been extended into every State. The results of their studies have been embodied, for the most part, in the familiar red-covered "Water Supply and Irrigation Papers". It is of interest to note that the first paper in that series, published in 1896, was one entitled "Pumping Water for Irrigation". Since 1903, there has been a Groundwater Division of the Geological Survey, under the direction, at first, of N. H. Darton, later of W. C. Mendenhall, and since 1912, of O. E. Meinzer, to all of whom great credit is due for the valuable results accomplished. A most useful work which is greatly needed now is a volume bringing together for the general student all the important principles relating to groundwaters and correlating the salient facts that are now to be found in the many scores of detached reports.

Perhaps the most notable quantitative study of groundwaters so far published is that of Chas. H. Lee, Assoc. Mem. Am. Soc. C. E., in Owens Valley, California.[4] The success attained in Lee's investigations emphasizes strongly the possibility of basing important future groundwater development upon a foundation as rational and as reliable as that commonly enjoyed by surface water projects.

Groundwater occurs widely distributed thru all classes of material from sand to granite. Altho various rocks, especially sandstone and limestone, are drawn upon largely for water supplies in other regions, they are of little importance in the Southwest where pump irrigation is practiced. The great structural valleys of the Western States and the coastal plains of both California[5] and Texas are filled to great depths with loose unconsolidated materials, colluvial and alluvial, which serve as groundwater reservoirs. Practically all of the water pumped for irrigation is derived from such sources of supply. Cross-sections of typical valleys, as revealed by logs of wells, show alternating strata of gravels, sands, and clays, with coarse unsorted outwash on the flanks and much calcareous cementation in the deeper gravels. The water-table conforms in some measure to the surface topography, but normally it has much flatter gradients.

In Arizona valleys, the Recent gravels are in most cases coarse, loose, and clean. The underlying Pleistocene formations,[6] deposited under more arid conditions than those of today, are less sorted and porous; alternating with the alluvial or lacustrine clays, are beds of gravel and outwash, oftentimes tightly cemented with a lime matrix; former persistent land surfaces are marked now by layers of travertine, known locally as caliche; and deep wells show an increasing induration, so that the valley fill merges by insensible gradations into solid rock. Consequent upon these conditions are two important results: First, the underdrainage of valleys is restricted and the water-table is maintained within economic reach of the surface; and second, the first water-bearing gravels are the best ones, so that deep drilling is seldom justifiable or necessary. In southern California, too, it is most expedient, oftentimes, to locate wells in the Recent gravels close to the river courses and to force the water thru long pipe-lines to the land to be irrigated.

It is now recognized that, with some exceptions, the rock basins of the structural valleys of the Southwest are practically water-tight, and that, therefore, each valley fill is an entity in its relation to groundwater. The contained groundwater can be compared with the water held in a surface reservoir, but with this distinction, that as the draft on the groundwater reservoir increases, the pumping lift increases, and finally pumping operations arrive at economic limitations. As in the storage of surface waters, groundwater supplies must be renewed, and they are by no means inexhaustible. In localities where pump irrigation is highly developed already, the great problem is the management of the groundwater supplies so as to secure maximum use of the groundwater reservoirs without serious permanent lowering of the water plane.

The valley fill receives increments to its water supply from various sources, chief of which, in the Southwestern States, is percolation from the streams which issue from the mountains. Seepage from irrigation canals and the downward percolation from irrigated lands are of next importance,—an unflattering commentary on our present systems of irrigation. Direct precipitation on valley lands has little influence on the supply, and, likewise, the overflow areas of valley bottomlands, for while they absorb considerable water, yet a surprisingly small amount of it reaches the saturated groundwater zone. Those five items constitute the water income of a groundwater reservoir; the outgo consists of the water pumped or flowing from wells, and the natural water losses. The latter consist of drainage into rivers, underflow thru the deposits overlying the outlet gap of the rock basin, springs, evaporation from the soil and transpiration from vegetation. The heaviest losses, evaporation and transpiration, are restricted to shallow-water areas. The water can be lifted from 7 to 10 feet (2.1 to 3 m.) by capillarity in fine soils, but, usually, transpiration from the stems and leaves of vegetation accounts for the major part of the groundwater loss. In Owens Valley the loss was found to be mostly thru salt grass, while under different climatic conditions it takes place thru sage brush or other shrubs or thru trees.

The possible safe yield of a groundwater reservoir available for pumping includes all that portion of the natural losses which can be prevented by lowering the water-table. Pumping at a few points is inadequate; wells must be located systematically at suitable intervals on the shallow-water area or on the flanking slopes where they will intercept the groundwater movement. Estimates of safe yield are based, usually, on investigations of rainfall, stream-flow, and seepage losses from streams. The method of estimating safe yield by measuring the natural water losses is likely to be used more as our knowledge of plant transpiration increases. Lee measured both income and outgo in Owens Valley and found an equality between them. Sometimes it is desirable to base estimates on rainfall records, areas, and the logs and yields of wells, but such estimates must be regarded as of a reconnaissance nature.

In the more arid valleys, the entire discharge of mountain streams is absorbed into the delta cones built up at the canyon mouths or into the gravels along the upper stream courses. But, where, normally, a portion of the river discharge escapes to the sea, or at least beyond the irrigated area, it is possible to increase the groundwater supply by artificially spreading out the floods over gravelly areas into which the flood-waters are absorbed. Water-spreading, as it is called, has become an established feature of river control in southern California.[7] It was first attempted on the Santa Ana River, at San Bernardino, about 1900, and was continued on a small scale by private companies until 1909. In that year a public organization, involving all the irrigation interests of the Santa Ana River, was effected, spreading ground has been acquired, and the magnitude of spreading operations gradually extended. Water-spreading is practiced also on the San Jacinto and San Gabriel rivers, and on many smaller streams. The method used on the Santa Ana River is to build concrete head-gates at favorable points, to divert the water into canals or old channels and conduct it to broad sand and gravel areas, to divide the stream into laterals and subdivide each lateral into smaller ditches, and, finally, to discharge the water broadcast over the spreading ground. Varied methods are used on other rivers to meet local conditions. On the San Jacinto River, where the surface is a uniform slope of sand with a grade about one-fourth as steep as that on the Santa Ana River, the basin method is used. Areas of several acres each are enclosed with levees.

The water is diverted from the river into the highest basins and overflows successively into the lower ones. Water-spreading is of the highest value and can be made to equalize the water supply between wet and dry years. There are many places in Arizona, and no doubt in other states and other countries, where spreading is needed and is practicable.

The amount of groundwater that can be developed at one place is extremely variable. The geologic criteria for good wells are: clean coarse gravels, and ample continuous supply of water. The former factor is dependent on the character of rocks in the mountains of the watershed.[8] Granitic rocks invariably produce coarse sands and gravels, while soft, close-textured rhyolites produce thick beds of clay. The contrast is seen frequently on the opposite sides of a valley. Examples of heavy yields from wells are quite common. The battery of ten wells of the Tempe Canal Co., at Tempe, Arizona, yields 27 second-feet (0.765 cu. m. per sec.) with 14 feet (4.3 m.) draw-down. These wells are spaced at 50-foot (15.2 m.) intervals and are 200 feet (61 m.) in depth. The average yield of eighteen 16-inch (40.6 cm.) wells near Mesa, Arizona, drilled by the U. S. Reclamation Service, is 0.32 second-foot per foot (0.03 cu. m. per sec. per meter) of draw-down. The Azusa Irrigating Co., in the San Gabriel Valley, California, has a 26-inch (66 cm.) well, 400 feet (122 m.) deep, which is said to deliver 9 second-feet (0.255 cu. m. per sec.). The lift at this well is 160 feet (49 m.). The Covina Irrigating Co., has a 26-inch (66 cm.) well, of the same depth, which delivers 7.2 second-feet (0.204 cu. m. per sec.).

The quality of irrigating water is a matter of critical interest to engineers, and not a few wells have been abandoned because the salty character of the water unfits it for irrigation. A costly well near Sentinel, Arizona, was found to contain 575 parts of sodium chloride per 100,000. It was pumped continuously for several weeks at the rate of about 1100 gallons (4164 litres) a minute in the hope of exhausting the brine and obtaining better water, but there was no material improvement. In some localities the first water-bearing stratum yields very alkaline water and the deeper strata yield good water; in other places these conditions are just reversed. Specifications for some recent wells have required separate samples of the water from each stratum for the purpose of analysis. Black alkaline waters can be improved by treatment with gypsum. In the Rillito and Whitewater valleys of southern Arizona the well waters contain sodium bicarbonate, and in both valleys there are beds of crude gypsum close at hand. Water treatment plants for irrigation water supplies are an attractive possibility.

WELL DRILLING.

Irrigation wells are of the following types:

1. Wells dug to full depth
2. Wells drilled or bored from the surface
3. Wells dug to water-level, and drilled or bored below the water-level.

The first type is decreasing in use. It is best adapted to valleys where the water-plane is shallow and the first water-bearing stratum is the best one, conditions that are found frequently on the bottomlands of Southwestern rivers. Well digging is a simple operation above the water-plane, but is neither simple nor easy below the water-plane, especially in caving ground. The difficulty lies in the control of the curbing. Timbering, similar to that done in mine shafts, has been used. But the best results have been obtained with caisson curbs built of reinforced concrete. These curbs are built above the water-plane; the concrete is allowed to cure for a couple weeks; and the curb is then sunk by excavating thru the interior, usually with shovels and buckets, but in one instance with a dredge and orange-peel bucket. As the caisson is lowered, new rings of concrete are added at the top. The reinforced concrete has greater strength and integrity than the brick and masonry walls used previously. An important advantage of caisson curbs is that the equipment required is not elaborate, and many farmers have been entirely successful in sinking caisson curbs without employing skilled help. So far as known, the first reinforced-concrete caisson wells were sunk about 1906. In 1913, a well was sunk by the U. S. Indian Service near Banning, California, by means of a shield, on the principle used in driving tunnels beneath rivers. The well reached a depth of 100 feet (30.5 m.) below the water-table, an achievement of note for a dug well.

The second type of well, drilled or bored from the surface, has steadily increased in favor during the past decade. The method most commonly employed for these wells is the drop-drill method or its modification, in which a mud-scow, that is, a heavy sand bailer with a circular cutting edge, replaces the ordinary drill bit and stem.[9] In California and in Arizona the

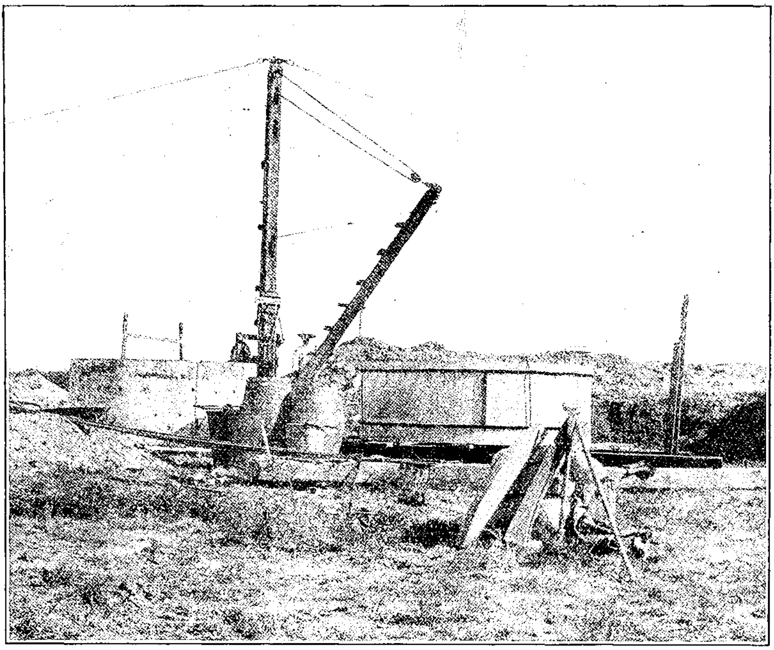

Fig. 2. Inside and Outside Forms for Reinforced Concrete Caisson Well Curb.

The pit has been excavated to water level and the outside forms are shown ready to be lowered. This type is recommended where the water-table is at shallow depth and the first water-bearing stratum furnishes the largest and main supply.

typical irrigation well is a 12-, 14-, or 16-inch (30.5-, 35.6- or 40.6-cm.) cased well, drilled to a depth of from 150 to 300 feet (45.7 to 91.4 m.). Portable rigs are used almost exclusively, and "stove-pipe" casing is preferred because of its smooth exterior and its low cost.

Another method, however, is threatening to supplant the familiar drop drill. The new method is the modern hydraulic

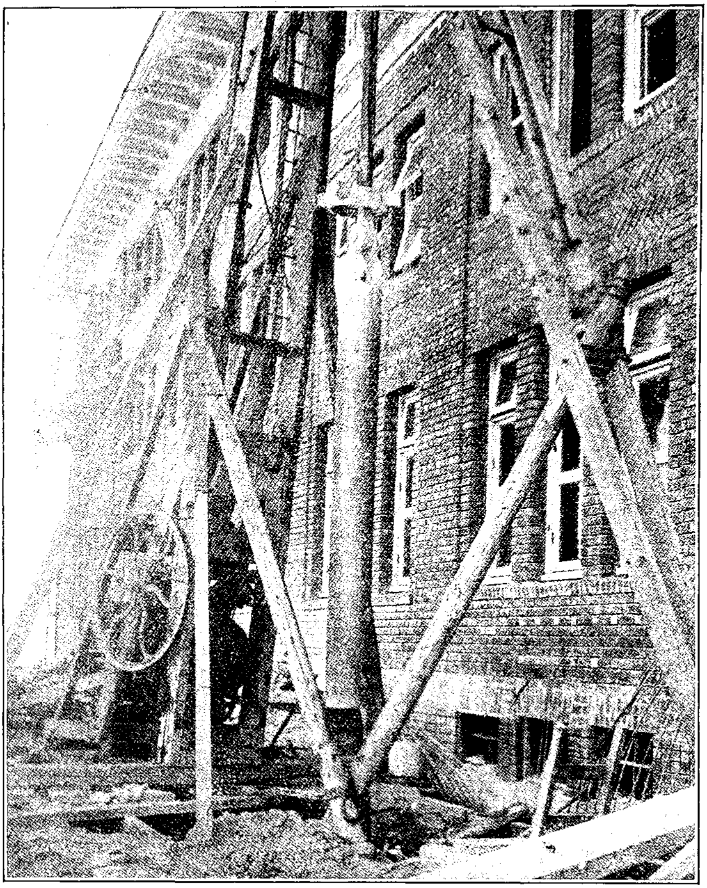

Fig. 3. **A California Mud-scow, Driving Collar and Jars for Sinking 16-inch Wells.**

The circular shoe serves to cut the formation in place of the ordinary drill bit. Good samples of the formation are obtained.

rotary—not the process formerly employed, wherein the well casing with a toothed cutting shoe was rotated, but a new process, which omits the casing and uses a line of heavy drill rods to rotate a fish-tail bit. Instead of clear water, the fluid used is clay mud, the consistency and specific gravity of which are maintained or changed according to the formations encountered. The walls of the hole are sealed with mud and are thus kept intact. Even coarse, running gravel can be held by using heavy mud, and frequently the mud is thickened until its specific gravity reaches 1.1. By means of a duplex reciprocating slush pump, the fluid is forced down thru the rods to the drill. It then returns upward, outside the rods, bringing the drillings with it. On reaching the surface it is led thru a circuitous ditch, in which the drillings settle out, to a small sump, from which it is pumped again into the well. When the final depth is reached, the drill rods are withdrawn and screw-joint well casing is set in the hole. The log of the well being known, a well screen—either wrapped, or shutter, or plain perforated—can be placed in the column so as to set opposite the water-bearing strata, or well casing can be used for the whole column and then perforated. Finally the well must be "developed" with clear water to bring out all the mud and open up the sand and gravel strata.

This latest rotary method originated about 1890 in Louisiana, where it was used in an obscure way. But when the first gusher of the Spindle Top oil district was obtained in 1901 by the use of this method, immediately the method sprang into notice everywhere. It came into general use in the rice and oil districts of Texas very quickly, and remarkable records of fast drilling in Texas sands have been reported. In 1906 rotary rigs were introduced into the California oil fields, and on account of the greater depths of wells, the rigs were built much heavier than those previously used. About 1910 it was adopted extensively in northwest Texas for water wells, and since then has been tried out in many locations in New Mexico, Arizona, and southern California. It has demonstrated its applicability under the conditions of our Western valleys, despite the greater difficulties to be met in gravelly formations. In the oil fields of California it has replaced cable drilling to a considerable extent; but drilling for water is still done largely by the old system, especially where the formations are known to contain boulders. The relative cost of drilling deep oil wells in California by the two methods, rotary and drop drill, is still a subject of debate; but for wells of less than 400 feet (122 m.) depth in boulder formations, the unit cost by the standard method is unquestionably less than by the new hydraulic rotary method.

However, it is claimed that sufficiently larger supplies can be obtained from the same formations to justify the extra cost, and much evidence has been adduced to sustain this claim. The author knows of three localities where only wells of less than 500 gallons (1893 litres) a minute had been drilled prior to the coming of a rotary rig, but with the rotary, yields of from 1200 to 2000 gallons (4543 to 7570 litres) a minute have been developed from shallow wells, in each of the three districts.

The State of Arizona has appropriated funds for deep wells in four counties, the avowed purpose being to determine whether or not there are artesian waters in those counties. One of the wells has been completed. It is in the Sulphur Spring Valley, in Cochise County. Generalized specifications were prepared and bids were called for on the basis of depth, since the fund, $7500, was a fixed amount. A rotary driller guaranteed 1500 feet (457 m.) depth and received the contract. The drillers with drop-drill rigs bid on various depths from 900 to 1200 feet (274 to 366 m.).

The well was sunk rapidly to 1135 feet (346 m.), at which depth semi-indurated and cemented gravels were encountered. The ordinary fish-tail bit was quite inadequate; freshly sharpened bits became blunt in three hours' time. Much time was lost, also, in removing and setting in the long string of drill rods. The situation was saved by the purchase of a rotary rock-drill bit, the invention of H. R. Hughes, of Houston, Texas.[10] It consists of two cone-shaped hardened-steel cutters, carried on the arms of a heavy stem and rotating at right angles to each other. The cutters run on bronze bearings and are lubricated, with the heaviest possible lubricating oil, from a small storage pipe inside the drill rod. With this bit, 3 feet an hour could be made, and the contract depth of 1500 feet (457 m.) was soon reached. The rock-drill bit will have much influence in extending the range of usefulness of the rotary process.

The perforation of well casing and the "developing in" of the well after perforation have been much neglected in the past. Many cases are known in which wells supposed to have been perforated have been found to be almost water-tight; the perforator knives frequently dent the casing instead of cutting it; and well contracts have called for little or no "development" after the perforations were made. Rotary drilling, however, requires that the mud forced into the walls of the drill hole must be removed.

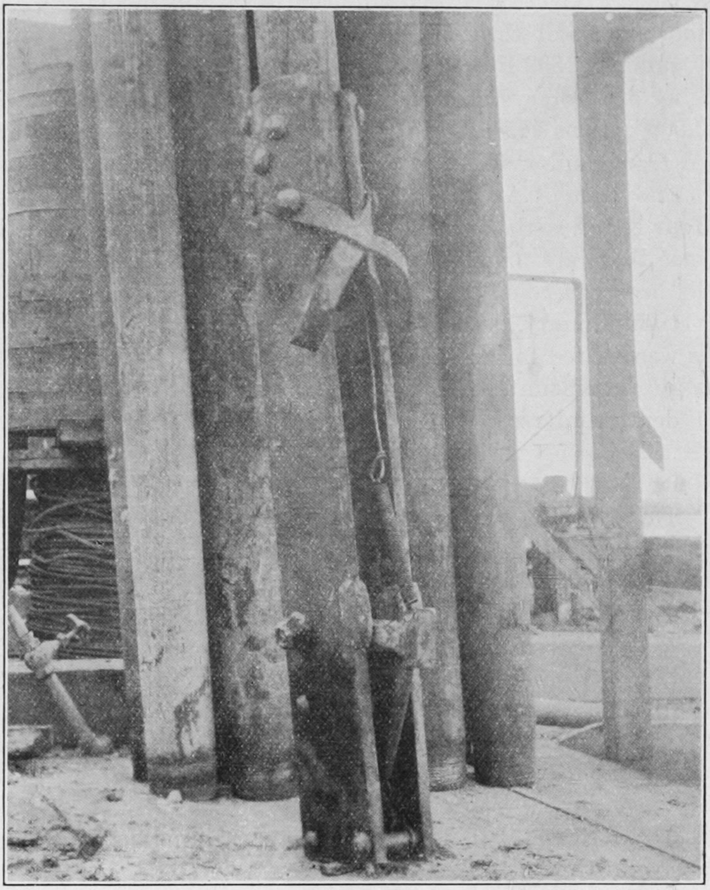

Fig. 4. A Stack of 4-inch Drill Rods and a Single-cut Perforator used at the State Artesian Well at Servoss, Arizona. The Perforator Was Made by the Driller at the Site of the Well.

Great ingenuity has been displayed in the various processes of washing, jetting, churning, and pumping, with water and with compressed air, by means of which the water-bearing strata are opened up, not only close to the hole but for a considerable distance back from the casing. It has been possible sometimes to remove from the hole an amount of sand equal in volume to four or five times the volume of the hole. One of the most effective

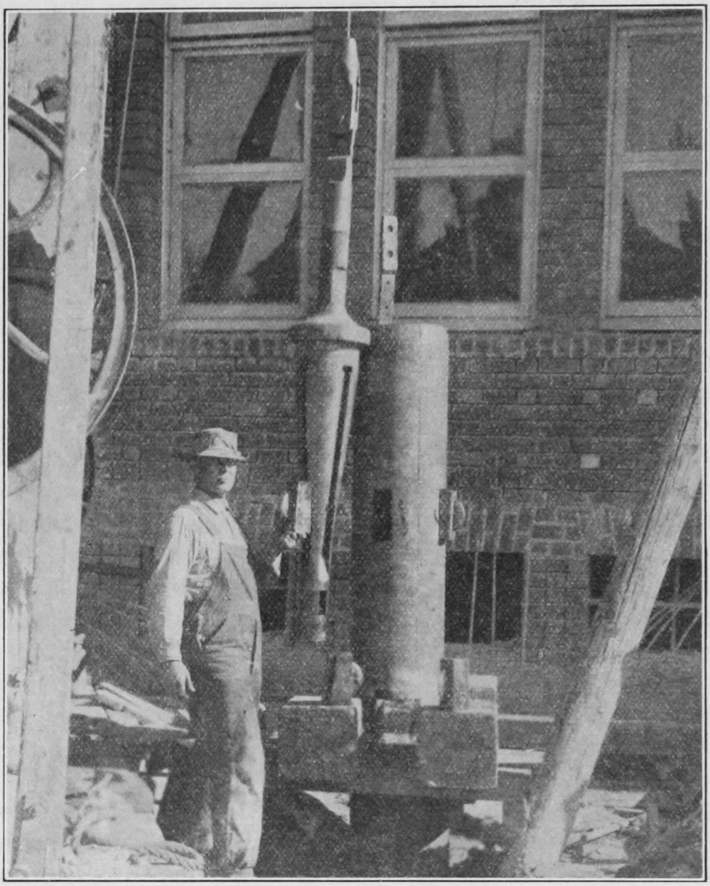

Fig. 5. The Mackey Four-way Casing Perforator, Showing the Four Roller Knives and the Grooved Knife-frame Removed from the Main Shell.

methods is "rawhiding" the well. This consists of alternately starting and stopping a centrifugal pump, the bowl or bowls of which are set 30 to 60 feet (9.1 to 18.3 m.) below the ground-water level. There should be neither foot valve nor check valve, for it is essential that when the pump stops, the column of water should return suddenly into the well. In the author's opinion, the superior yields obtained by rotary drilling are due, not to the method of drilling but to the ingenious and long-continued processes of "developing", processes which drillers with cable rigs can learn and are learning, to use with equal effectiveness.

Another accomplishment of the rotary method is the reaming out of the upper portion of the hole to 26 or 30 inches (66 or 76 cm.) diameter, so that turbine pumps of large size can be lowered to position sufficiently deep below the water-plane to give a heavy draw-down. The 26-inch (66 cm.) casing and 24-inch (61 cm.) pump bowl have become very common during the last five years.

The third type of well, dug to water level and drilled below water level, is still preferred in many localities. This type permits the installation of large-bowled centrifugal pumps, horizontal or vertical, and it is undeniable that until within two years such pumps were giving much better efficiencies than were obtainable from pitless turbine pumps. Wells of this character are now favored where the fluctuations of the water-table are slight, where the draw-down during pumping is moderate, and where electric power is available for direct-connected units. A fine well of this type, with concrete-lined pit, has just been completed at the University of Arizona. Any kind of pump whatsoever can be installed in this well for testing purposes, and it is hoped, thereby, to contribute materially to our common knowledge of the action and the merits of the many types of pumps now in use or proposed.

Newell and Murphy[11] consider that a caisson curb sunk as far as practicable below the water-table, with two or more drilled feeder wells in the bottom, is the most desirable form of construction. Wells of this type are common in Arizona.

Miscellaneous other well types are found in various localities according to local conditions. As an illustration, there are in the neighborhood of Willcox, Arizona, numerous wells consisting of an unlined pump pit to near water-level and an uncased hand-auger hole thru the clay to the first water gravel. These wells yield from 300 to 700 gallons (1136 to 2650 litres) per minute, and their cost is insignificant. Machine augers, also, are used in a few localities, with indifferent success.

The attention of engineers should be directed to the necessity of assisting well drillers to report the logs of wells correctly. Three instances have come to the author's attention recently, in each of which the log was wrongly reported. In this connection, the California mud-scow method provides the surest means of ascertaining the character of the formations, for chunks of the materials in their original condition are almost sure to be brought up in the bailer.

PUMPING MACHINERY.

Economically, pump irrigation is dependent in large measure upon the machinery used. Altho this fact has been realized, yet there has been a lack of appreciation of the benefit to be derived from engineering design and supervision of the individual pumping plant. Usually the buyer is a farmer with little or no familiarity with pumping machinery, and he could well afford to expend 5 percent of the cost of his plant for engineering advice. Ordinarily, however, plants costing less than $10,000 are designed by salesmen, and salesmen, of course, have other interests to serve besides that of the prospective purchaser. The author has seen many instances of stranded farmers whose sad failures were due to the unwise selection of pumps or engines. One man of this class remarked recently, "I bought talk". Herein is a promising field of usefulness for engineers. In every pump irrigation district there should be consulting engineers prepared to write specifications and contracts and to supervise the purchase and installation of pumping machinery, and also to have similar charge of the development of wells. At the present time, contracts are drawn in optimistic vein by the salesmen and the liberal efficiency guarantees are so worded that the farmer cannot check them up.

In the design of farm pumping plants, it should be recognized as a principle that reliability and simplicity are of equal, if not greater, importance than efficiency and fuel economy. A power plant on a farm is at a disadvantage, often it is from ten to fifty miles from a machine shop where lathe work can be done, and the farmer himself is not a mechanic. Plants of less than 30 horsepower should operate without attendance for several hours at a time, and a breakdown at a critical time, when the crops need water, is likely to prove fatal financially.

Pumping machinery will be discussed under the three heads: pumps, oil engines, and electric power.

PUMPS.

The pump that is preeminently adapted to irrigation use is the centrifugal pump. Probably 80 percent of the irrigation water lifted from wells is delivered by centrifugal pumps. The advancement in recent years in the design of pumps of this class has been most gratifying. So late as 1905 very little interest was taken in the scientific treatment of centrifugal pumps; little was known regarding their characteristics, except possibly in three or four factories, where even their meagre knowledge was guarded jealously. But, in the intervening ten years the design of these pumps has advanced from the "whittling" stage to a scientific basis, and pumps are now available, which in construction and in efficiency are on a plane with hydraulic turbines. The excellent works of Loewenstein and Crissey[12] and Dougherty[13] offer a safe foundation for all irrigation engineers.

The plain centrifugal pump with open volute continues to be used much more than pumps with fixed vanes. Plain pumps of high efficiency can be built at low cost, and they are the least of the irrigators' troubles. The proportion of vertical-shaft pumps is increasing, owing to the greater depths at which groundwaters are being developed; yet where conditions admit of its use, the horizontal pump is rightly preferred. Improvements have been made in the adaptation of impellers to the conditions of head and discharge, in the methods of balance, in the lubrication, in the reduction of clearance, and in the accessibility to the impeller. Greater backward curvature of the impeller vanes and increase of speed give flatter efficiency and input characteristics. The old open-impeller has practically disappeared. A few of the primitive style of pumps are still on the market, but with the growing appreciation of good machinery, they are being driven out.

Vertical-shaft pumps operate best on heads of from 30 to 50 feet (9.1 to 15.2 m.) per stage. The practice of using a single stage on lifts from 90 to 110 feet (27.4 to 33.5 m.) was tried extensively in 1913 and 1914, but it was found to be impracticable to run the long shafts at the high speed required. Horizontal pumps, on the other hand, can be accurately aligned, and recently-designed pumps speeded at 1800 to 2000 R. P. M. appear to operate successfully.

Vertical turbine pumps designed to go into cased wells have come into wide use. Their problem has been that of the vertical shaft bearings. Separate bearings at the joints of the discharge pipe, protected in various ways from sand and grit, have not proven successful, for enough sand could find its way into the bearings to cut them out rather quickly. But the vertical shaft fully enclosed in a line of oil tubing is long-lived and free from troubles. No longer is it deemed necessary to support the oil tubing from the discharge pipe, but the tubing is put under considerable tension in order to give it supporting power. Until recently these pumps have been built with ball or roller thrust bearings in the pump head, but they can now be obtained with hydraulic balance, a feature of design which is distinctively Californian. The latest improvement is the use of a seal just above the pump bowl, so that the well casing can be used for the discharge column.

During the early years of development of the vertical turbine pump, scant attention was given to the impellers, and the efficiencies shown in tests were uniformly low. During the last year or two, however, great advancement has been made. In a test of a new 5-stage turbine pump, with 14-inch (35.6 cm.) bowl, at the University of Arizona, in May of this year, a maximum combined efficiency of 58.2 percent was obtained for pump and motor belt-connected, the test being based on the static lift. The maximum efficiency was given with a discharge of 340 gallons (1287 litres) per minute and a lift of 26 feet (7.9 m.) per stage of pump. Chas. H. Lee, Assoc. M. Am. Soc. C. E., has reported on tests, made at Los Angeles on a 4-stage 14-inch (35.6 cm.) pump. He found the pump efficiency in excess of 70 percent for a range of discharge from 450 to 750 gallons (1704 to 2840 litres) per minute. So it is established that good performance is possible from medium-sized turbine pumps.

Vertical turbine pumps are more costly than pit pumps and are not likely to displace them on lifts of less than 100 feet (30.5 m.), except in cases where a heavy draw-down is required. The field for the pitless turbine seems to be on lifts from 75 to 250 feet (23 to 76 m.). For developing new wells, the pitless turbine has no equal.

The propeller type of pump which has short helical vanes attached at intervals of about 5 feet (1.5 m.) along the shaft has been purchased considerably by farmers, and at least a few engineers have been attracted to it. With this type, too, the designers' efforts have been concentrated upon finding shaft bearings which would exclude the grit usually found in well water. Felt packing has been tried, as well as dead-water tubes and caps, and impellers enclosed in short slotted tubes, thru which slots water is forced to form a cushion or lubricant between the tube and the discharge column. Bronze, composition metal and lignum vitae have been tried for bearing surfaces. At present, straight guide-vanes are used, either above or below the runners. No authentic tests of these pumps have been reported; but from the fact that large engines are required to operate them, it is believed that their efficiency is low. The problem of the bearings may be solved in time, and it is likely that attention will be given to the curvature of the impeller blades and of the fixed guides, in order to increase the efficiency of the pump. Propeller pumps have an advantage in obtaining a large discharge from well casings of 10-inch (25.4 cm.) size or smaller. A peculiar feature, too, is that the speed required is not dependent upon the lift.

The reciprocating type of pump continues to find a field in irrigation pumping. The conditions, however, requiring a large discharge from a pump set deep below the surface have necessitated the development of entirely new designs. Double-acting pumps with one rod enclosed within the other and pump heads with heart-shaped cams or gears or walking-beam motion effect an overlapping of the power strokes which quite eliminates any pulsations in discharge or in power. And the triple-acting pumps recently introduced, the Glendora pump and the triple-cam Luitwieler, give continuous operation that is practically perfect. Notwithstanding their high cost, the double-acting pumps are much in favor in the foothill regions of southern California, where the lifts vary from 100 to 400 feet (30.5 to 122 m.). For the higher lifts, they are used exclusively.

Mention should be made of other types occasionally met with. The bucket elevator is still used to a small extent, as is air-lift also. It is generally recognized, however, that the air-lift is not an irrigation pump, and their number is decreasing. Freak pumps appear frequently, but after a few installations they are seen no more. The first installation in this country of the Humphrey direct-explosion pump, an English type, is being made at Del Rio, Texas, to lift water from the Rio Grande, but this type is not suitable for pumping from wells.

An approximate estimate of the pumping practice in southern California, based on the quantity of water pumped, is as follows:

Reciprocating pumps	20	percent.
Horizontal centrifugal pumps	30	"
Vertical centrifugal pumps in pits	30	"
Vertical turbine pumps	15	"
Other types	5	"
Total	100	percent.

In Arizona and New Mexico the percentage of reciprocating pumps is much less, while that of vertical turbines is more than 15.

OIL ENGINES.

Irrigation pumping plants serving single ranches are operated by internal-combustion engines or by electric motors. Thruout large areas, electric power is not yet available, at least at low rates, and a gasoline or oil engine is the most feasible power.

The development of the gasoline engine during the past ten years has been more in the direction of multiplicity of design than in real improvements. Just now there is a movement, among manufacturers, looking to the standardization of important parts—a most worthy object. One improvement of great value has been the general adoption of the magneto for ignition and the perfecting of the magneto. The low tension magneto continues to be the most used.

But the revolutionary feature in the engine trade has been the introduction of oil engines, which are designed to burn low-gravity distillates. When, in 1912, it was realized that the cheap, abundant distillates of 35° to 45° Beaume, costing 2¾ cents per gallon in carloads, F. O. B. Los Angeles, could be utilized for fuel by slight modification of the standard gasoline engines, manufacturers and purchasers turned immediately to the oil engine, as the promised land in the power world. Necessity had much to do with the change, for the production of gasoline has not kept pace with the increase in the number of stationary engines and automobiles. In 1913 it was shown that the supply of gasoline was sufficient to operate the engines then in use only one-half

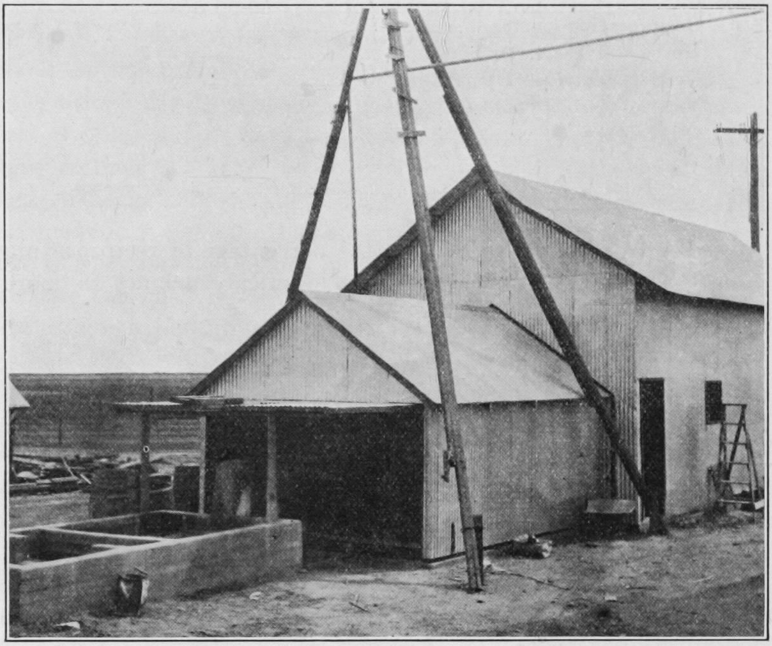

Fig. 6. Engine House, Pump House and Fore-bay of Plant in Salt River Valley, Arizona.

The Pump House is on rollers running on a track and telescopes back into the engine house.

hour per day, and the price of gasoline was tending upward rapidly.

The new oil engines have followed two lines of design: First, the Otto, or 4-cycle type; and second, the two-cycle type. The four-cycle oil engine is referred to sometimes by its detractors as "a made-over engine". The only important difference between it and the gasoline engine is that the oil engine preheats the charge or introduces a slow water feed into the charge, or does both. Preheating is done by passing the intake air thru a jacket on the exhaust block or by passing a part of the exhaust thru a tubular generator between the carburetor and the cylinder. The humidifying water is introduced into the carburetor thru a needle-valve in the same manner as the fuel oil. These engines require a throttling governor; the time of ignition should be advanced more for distillates of low gravity than for gasoline, and it is desirable that the compression pressure should be increased somewhat. Many farmers have altered their gasoline engines by arranging a water feed for the carburetor or on the air intake pipe.

The effect of adding water to the charge is far-reaching. Indicator cards taken on engines, first without the water feed and then with it, show a Dieselizing effect due to the water. Instead of sudden violent explosions with high initial pressures, the gases burn more slowly and the cards show a flat combustion line for about a tenth of the stroke. With the water feed, the combustion appears to be perfect; with distillate of 40° Beaume, the exhaust, even from small engines, is absolutely colorless and invisible. Carbon deposition is reduced, and the cylinders and valves of made-over engines burning the low distillate keep cleaner than they did formerly with 50° distillate and no water feed. Also, the engines heat up less, there is less loss of heat in the circulating water, there is no preignition, and the lubrication of the cylinder is improved. As an example of the excellent service given by these oil engines, a heavily loaded engine has run steadily thru a 14-hour day without a visit from the attendant. There was no muffler, and thereby the farmer, in whatever place he might be, had the assurance that the engine was running all right. The author's tests on oil engines indicate that the fuel economy is fully equal to that of gasoline engines.[14] In Arizona the new distillates, called Tops or Gas Oil, retail at 7 cents a gallon, as against 17 cents a gallon for gasoline. Hence, the introduction of oil engines has stimulated pump irrigation greatly and has made possible the utilization of groundwaters of greater depth than was economically possible with gasoline as a fuel. Oil engines of size up to forty and sixty horsepower are becoming quite common for individual farm pumping plants.

Another type of oil engine has been developed from the two-cycle gasoline engine. The important changes have been the separate injection of the fuel oil at the end of the compression stroke, the introduction of water in the air charge, and the substitution of a hot ball or hot plate for electric ignition. The engines are prepared for starting by heating the hot ball with a blow torch for from ten to thirty minutes. The ignition being automatic, the temperature of the cylinder requires to be controlled closely, and this is done in most engines by hand regulation of the feed-water valve. Pump lubricators and friction-clutch pulleys are required, even on small engines. In California and Arizona, engines of this type have not proven entirely satisfactory, possibly on account of the asphaltic character of California oils. The difficulties have been due largely to imperfect combustion of the fuel oil. Possibly they will be remedied when more effort is made to adapt these engines to oils having an asphalt base.

Large pump-irrigation enterprises permit of large power-units. Many mutual water companies of southern California and the owners of large irrigated tracts operate plants of from 100 to 500 horsepower. Multiple-cylinder oil engines are used in some instances, but Corliss steam engines are found, frequently, in small central stations or in air-lift plants, and steam turbines and producer-gas engines have been selected in a few instances. The community pumping project at Avondale, Arizona, includes two units, one with a 2-cylinder 100-horsepower oil engine, and the other having a 3-cylinder 150-horsepower engine driving a horizontal centrifugal pump, the suction line of which is connected to 12 wells. Steam power has been handicapped by the high cost of attendance and the low fuel economy; for irrigation pumping, the transition from steam to internal-combustion engines is now almost complete.

An installation of the highest type of power machinery has just been completed at Tucson, Arizona, to furnish power to the pumping plants of the Tucson Farms Co. It consists of two 500-horsepower 4-cycle Diesel engines and 2300-volt generators. The fuel used is crude oil of 15° Beaume. It burns perfectly clean, and the consumption is but slightly over 0.4 lb. (0.18 kg.) per kilowatt-hour at the switchboard.

ELECTRIC POWER.

As early as 1900, pump irrigation in southern California had become so important as to warrant a few transmission lines thru the pumping districts. Since then, many additional lines, some of them of great length, have been built. In a few cases, the power is derived from oil-burning power plants, but to a greater extent it comes from the hydro-electric plants of the west slopes of the mountain ranges. Competition, together with the desirable character of the pumping load, has made the power rates to irrigators reasonably low. The prices paid range from 1½ to 3 cents per kilowatt-hour. In some localities a fixed annual charge is made, the amount of power used at each motor being based on a few trial measurements. In the vicinity of Bakersfield and Tulare, California, this charge is about $50 per horsepower per year. It is customary for the user to purchase the installation, including the transformers. Frequently, farmers are found taking out their motors and installing oil engines, in the belief that the engine power is the cheaper. This is true, undoubtedly, unless the farmer, thru carelessness, brings on serious engine troubles, but it is also true, oftentimes, that the inherent convenience of motor power is worth the extra cost.

In Arizona the high rates for electric power stipulated by the Corporation Commission make the use of power from public service corporations prohibitive for small farmers. The Salt River Valley project of the U. S. Reclamation Service, as now operated, includes nine pumping plants, with capacities of 10 second-feet each, all electrically driven. The Reclamation Service furnishes power also, for irrigation outside of the project. The rates paid for the power are based on a sliding scale. In the case of one company, which had three pumping plants, the average cost of the power, in 1914, was 2.46 cents per kilowatt-hour. The lateral transmission lines and all electric equipment are furnished by the consumers.

In the Grand Canyon of the Colorado there is abundant hydro-electric power for the entire state of Arizona, and doubtless some of it will be developed. Two projects, one near the Bright Angel trail and the other near Peach Spring, have been designed and efforts have been made already to finance them.

Smaller projects in the mountains of the eastern part of the state are also feasible. So it is evident that soon Arizona will follow the example of California in the utilization of hydro-electric power for irrigation pumping.

There is a close correlation between hydro-electric power development on the mountain streams and pump irrigation in the valleys lying below. The water can be used first for power and afterward for irrigation. In one instance, in Placer County, California, the water is to be used six times for power and then for irrigation.[15] In cases where only the natural flow is used for power, there can be no possible interference with the rights of irrigationists below. And in case of storage, the loss of water by evaporation is inconsiderable—quite out of proportion to the saving of floodwaters which, if not stored in reservoirs, would find their way to the sea. On years of light rainfall, however, the natural distribution of groundwater supplies along the lower courses of a river tends to disarrangement, but it is well within the functions of engineers to effect an equitable distribution of the tail waters from power plants. Irrigation, then, and the development of ''white coal'' power are mutually advantageous.

In designing practice, the changes during the last fifteen years have been of very little moment. The tendency has been toward higher voltages, so as to effect greater economy in the use of copper. 2300-volt motors are selected more frequently now. Motors are built somewhat lighter than formerly, and the efficiencies are just a little higher. The rating is considerably closer, but the motors are better protected against overloads and accident. Induction motors are used almost universally, most of them being of the squirrel-cage type.

ECONOMICS OF PUMP IRRIGATION.

Published estimates on the cost of pumping have been based, usually, on data collected at some selected pumping plants. LeConte,[16] Tait,[17] and Gregory[18] have contributed valuable estimates of this kind. But, the controlling factors, such as cost of wells, character and cost of machinery, rate of fixed charges, lift, acreage irrigated, duty of water, and cost of fuel or electric current, and of attendance, are so variable that every

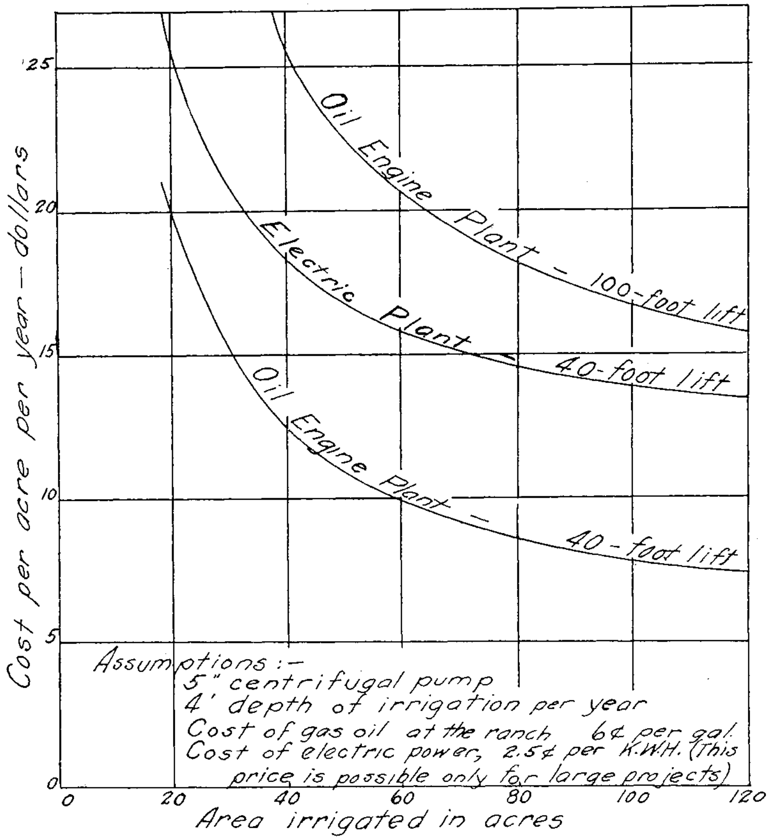

Fig. 7. The Influence of Fixed Charges on the Cost of Pumping in Arizona.

plant presents a special problem, and it is difficult to find plants that are truly representative. Fleming published general cost data for small pumping plants in New Mexico, in 1909.[19] Etcheverry, in 1913, published an analysis of the cost of pumping in California;[20] and the author has recently published a similar analysis based on hypothetical averaged conditions in Arizona.[14]

The most surprising fact revealed by a study of cost of pumping is the importance of fixed charges. In the oil-engine plants now in use, the item of fixed charges is greater than the items of fuel, lubricating oil and attendance combined. With motor-driven plants, too, in many instances, the fixed charges exceed the operating costs. The cause for this condition is usually not that an inordinately expensive plant has been purchased, but that the plant serves too small an acreage. There are many plants in Arizona costing over $4000 and serving less than 40 acres (16.2 hectares). To install smaller plants is a poor solution, for it is difficult and costly to irrigate with a stream of water less than 500 or 600 gallons (1890 to 2270 litres) per minute. The only rational escape from the high fixed charges per acre is to serve a larger acreage under each plant, and to use the plant continuously instead of only 30 or 40 hours a week. Since the individual rancher is limited in energy and resources to a modest area, then three or four ranchers should make use of one plant, either cooperatively or as leasers. The greatest fallacy connected with pump irrigation, at the present time, is the idea that each farmer must have his own pumping plant. As well might it be said that each ranch should have its own ditch from the river. The mutual water companies in the pumping districts of southern California are cooperative in principle; they are successful and beneficent. The further extension of cooperative pumping thru Arizona and New Mexico, and probably in California, is the highest desideratum.

In addition to reducing the cost of pumping per acre, cooperative plants offer other advantages: the groundwater supply can be developed at more strategic points, with less interference between wells and less possible litigation; competent men can be secured to have charge of the plants; and the first cost of the investment by each farmer is reduced greatly.

Comparison between the cost of pumping under various conditions and the cost of irrigation under gravity projects indicates higher cost for the former, in general. Yet this is not true universally. There are many localities of low-lift pumping where the total cost of pumped water is less than $3 per acre-foot, an amount that is exceeded frequently under gravity ditch or reservoir systems. Pumping for irrigation does not compete directly with the utilization of surface waters. Gravity projects of economic cost are developed first; pumping then follows, either to enlarge the irrigated area, or to provide water during seasons of low stream flow, or to irrigate lands not covered by the canals.

There are several other important features of pumping which should be mentioned in the present discussion. There is nothing in pump irrigation which corresponds to a reservoir dam failure. A pump may be out of commission for a week, as may a canal, but a well cannot become a menace to a village, nor can it allow the groundwater supply to be wasted suddenly. Pump irrigation, in flexibility, approaches that of reservoir projects; it is not necessary to irrigate in winter to save the water, nor at other undesirable times. And, too, pump irrigation has a far-reaching influence for higher duty of water; for reduction of water losses, as by means of ditch linings and the use of deep furrows; for clean cultivation; and, in general, for more efficient irrigation. Water-logging of land and drainage projects are not concomitant to pumping districts. Pump irrigators are never humiliated by a 45 percent loss of water in their ditch systems.

There are limitations to the lift at which pumping for irrigation is profitable. Six years ago the limit of lift for economical pumping in Arizona was less than 40 feet (12.2 m.). Today, due to the recent introduction of low-gravity distillates and the improvement in pumps, it is close to 100 feet (30.5 m.) for general farming. Etcheverry states that in California 400 feet (122 m.) may be taken as the limit for citrus fruits, olives, apples, and other orchard products; while for alfalfa, the limit is from 40 to 100 feet (12.2 to 30.5 m.), depending on the pumping conditions and the selling price of the alfalfa.

PROBABLE FUTURE DEVELOPMENT.

Except possibly in southern California, pump irrigation is still in its early stages. There are large areas where no other type of irrigation is possible. Most gravity projects, at present, need more population; but as soon as these projects are developed to the point where surface water supplies are utilized, then will the groundwaters be drawn from to extend the agricultural growth. Exceptions occur, of course, where the groundwaters are too saline even for admixture with river supplies. But the outskirts of gravity projects are especially favorable for pump irrigation, on account of the positive and constant recharge of the groundwaters due to the canal systems and downward percolation from fields. The great possibilities for development by irrigation pumping in the Sacramento Valley have been pointed out just recently by Kirk Bryan.[21] Even in southern California Tait anticipates an increase in irrigated area in the eight southern counties from 745,486 acres (302,000 hectares) to 1,950,000 acres (788,000 hectares), in part from the development of pumping.[22] The growth of pumping will occur faster in States like Arizona and Nevada, where surface supplies are meagre or unfavorable to development, but will extend to States such as Idaho and Montana later on.

A large field of usefulness is open to engineers in furthering and directing the development of pump irrigation. Engineering geologists can point out the areas of economic and permanent supplies and their estimates of safe yield are of great value. Farmers need the help of consulting irrigation engineers, and there are many farmers, well-to-do, who will gladly pay the price as soon as the engineers have demonstrated, in a few cases in each locality, their ability to solve pump irrigation problems in a superior manner.

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