A REVIEW OF THE BOULDER DAM PROJECT

THESIS FOR THE DEGREE OF B. S.

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Boulder Dam

Civil engineering   Hydraulic engineer

A Review of The Boulder Dam Project

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FOREWORD

The water in and on the earths surface is of constantly increasing importance to the life and comfort of man. As population increases and civilization advances so will the value of water increase and the struggle over its control will increase in like measure.

REVIEWING THE BOULDER CANYON PROJECT

The Boulder Canyon Project became effective June 21, 1929; six months after it's passage, and money was to be made available at the regular 1929-30 meeting of Congress.

The branch railroad from the Union Pacific railroad, to the damsite is now under construction, most of the work being done by the Union Pacific.

It is expected that highway construction from Las Vegas to the damsite will start immediately. This road may be constructed as part of the project, since it is considered a proper charge against the construction fund, because the government will need prompt and efficient stage service for express, light freight, and labor turnover.

Private corporations will be allowed to bid for furnishing the power necessary for construction, and if these bids are not suitable the government will build it's own plant.

A concrete gravity type dam, curved in plan is proposed.

Excavations must be made to a maximum depth of 125 feet below the river bed to solid rock.

A coffer dam must be built both above and below the damsite and tunnels excavated through the solid rock to divert a maximum of 200,000 second feet of water around the site (according to the "Colorado River Board" report) before excavation may begin.

It is anticipated that approximately 2,500 men will be employed during the construction period,depending largely on the construction methods used.

It is estimated that power will be ready for delivery at the switchboards within five or six years after the first contract is let.

FOLLOWING IS A REVIEW OF THE BOULDER CANYON PROJECT ACT:

1. That the location of the project shall be at the Boulder or the Black Canyon.(Sec.1)
2. That the purpose of the act is to control the floods, improve navigation,and regulate the flow of the Colorado River,to provide for storage and use exclusively within the United States,and to generate electrical energy as a means of making the project a financially solvent undertaking.(Sec.1)
3. That any rights the states may have to water within thier boundaries,or the right to adopt such policies and enact such laws as they deem necessary,with respect to the approiation,control,and use of water within their boundaries,shall not be modified except by the "Colorado River Compact" or other interstate agreement.(Sec.18)
4. That the Secretary of the Interior is authorized to carry out the provisions of this act,subject to the "Colorado River Compact".(Par.(b)sec.8)
5. That there is hereby appropriated $165,000,000 to

carry out the purpose of this act.(Sec.3)

6. That the secretary of the Interior is authorized to acquire by proceedings,eminent domain,and otherwise all rights of way,lands and other property necessary to carry out this act.(Sec.1)

7. That no expenditures shall be made out of the fund for operations and maintenance except from appropriations therefor.

8. That interest shall be at the rate of 4% on all amounts advanced from the fund under provisions of this act, and all amounts advanced from such funds shall be checked by the Secretary of the Interior at the close of each fiscal year.(Par.(b)sec.2)

9. That no person shall be entitled to have the use of the water for any purposes,except by contract made with thr Secretary of the Interior as herein stated. (Sec.5)

10. That after the $25,000,000 set aside for flood control has been replaced from the 62 1/2 per cent of any excess over the amounts due the government,after the amortization period,it shall be placed in the fund to be expended within the Colorado River basin as may be hereafter prescribed by Congress.(Sec.5)

11. That the rights of the United States in,or to,the Colorado River and it's tributaries,shall be subject to and controlled by the"Colorado River Compact"(Par (b)sec.13)

12. That 37 1/2 per cent of any moneys collected by the Secretary of the Interior, above the amounts due the government shall go to Arizona and Nevada, presumably in lieu of taxes, by virtue of their natural resources being taken for a public service. (Par.(b)sec.4)

13. That the power to be sold at a price may be found to be "Justified by competitive conditions at distributing points or competitive centers" (Par.(b)sec.4) Contracts will be made with a view to secure reasonable returns. (Par.(a)sec.7)

14. That the provision of the Feder l Water Power Act, and regulations of the Federal power commission shall be conformed with as far as possible in the operation and administration of the project and for the protection of the investor and the consumer. (Sec.6)

15. That there shall be readjustment periods for the sale price of the power, either upward or downward as the conditions at the distributing points may indicate, the first readjustment after fifteen years and every ten years thereafter. (Par(a)sec.5)

16. That no charge shall be made for water for irrigation and potable purposes in the Imperial and Coachella Valleys. (Sec.1)

17. That the water may be sold for irrigation and potable purposes in all districts other than the Imperial and Coachella Valleys. (Sec.5)

18. That a board may be arranged for, consisting of one member from each of the seven states, to advise with the Secretary of the Interior on the sale price of water and power, and matters relative to the states (Sec.16)

19. That the sum of $25,000,000 set aside for flood control to be replaced out of 62 1/2 per cent of any revenue in excess of any amount necessary to repay the government, and if not entirely replaced during the amortization period, it may, thereafter be paid from the 62 1/2 per cent of the net profits. (Par. (b) sec. 2)

20. That the all American canal may be constructed, and any dam and necessary works, under the reclamation act, which provided that all expenditures be underwritten by the lands benifited, prior to the beginning of construction, and shall not be paid for out of the sale of water or power. (Sec. 1)

21. That a dam be constructed with a reservoir capacity of not less than 20,000,000 acre feet of water. (Sec. 1)

22. That firm contracts be made by the Secretary of the Interior, for the sale of power generated, and the use of water to generate power, and for the storage of water for irrigation and domestic uses, and that will replace the government investment in the dam and power plants in fifty years, before construction shall be undertaken, and the charges for the water for irrigation and domestic purposes shall be for permanent services. (Sec. 5)

23. That the consent of Congress is given to the seven states of Colorado, New Mexico, Wyoming, Utah, Arizona, California, and Nevada to enter into a compact or agreement, supplemental to and in conformity with the "Colorado River Compact". (Par. (a) sec.13)

24. That the consent of Congress is given to any six states of the basin, including California, to enter into a six state compact, if the said six states ratify the Colorado River Compact without conditions except to waive the provisions of the first paragraph of article three of said compact, requiring seven states, provided California limits itself, by leglislative action, to a consumptive use of not more than 4,400,000 acre feet of water from the Colorado River, and in the event of the six state pact, the act shall become operative six months from date of passage. These conditions have been complied with both as to the six state pact and the California limitation as to the use of water(Par.(a)sec.4, par.(a)sec.13)

25. The consent of Congress is given to the three states California, Arizona, and Nevada to enter into an agreement, and especially provides for seven conditions under which this agreement may be made, and not be necessary to return to Congress for reratification, as follows: (Par.(a)sec.4)

(1) That of the 7,500,000 annually apportioned to the lower basin by paragraph (a) of article

three of the Colorado River Compact, there shall be apportioned to the state of Nevada 300,000 acre feet, and to the state of Arizona 2,300,000 acre feet for exclusive beneficial and consumptive use in perpetuity.

(2) That the state of Arizona may annually use one half of the excess or surplus waters unapportioned by the Colorado River Compact.

(3) That the state of Arizona shall have the exclusive beneficial use of the Gila River and it's tributaries within the boundaries of the state.

(4) That the waters of the Gila River and it's tributaries except return flow after the same enters the Colorado River shall never be subject to any diminution whatever by any allowance of water by treaty or otherwise to the United States of Mexico, but if as provided in paragraph (c) of article three of the Colorado River Compact, it shall become necessary to supply water, to the United States of Mexico from the waters over and above the quantities which are surplus as defined by said compact, then the state of California shall and will mutually agree with the state of Arizona to supply, out of the main stream of the Colorado River, one half of any deficiency which must be supplied to Mexico by the lower basin.

(5) That the state of California shall and will mutually agree with the state of Arizona and Nevada that none of the said three states shall withold water and none shall require the delivery of water which cannot reasonably be applied to domestic and agriculture uses.

(6) That all provisions of said tri-state agreement shall be subject in all particulars to the provisions of the Colorado River Compact.

(7) Said agreement to take effect upon the ratification of the Colorado River Compact by Arizona, California, and Nevada. (Par.(a)sec.4)

And further provides that the three states may enter into any compact, or any two thereof may enter into any compact, subject to further approval of Congress. (Par.(b)sec.8)

26. The general and uniform regulations shall be prescrib- by the Secretary of the Interior for awarding contracts and for the renewal of contracts, and providing that no contract shall be of longer duration than 50 years. (Sec.5)

27. That any dispute or disagreement as to the fullfillment of any contract made under this act, shall be determined by arbitration or by court proceeding. (Par.(a) sec.5)

28. That contracts for use of power shall be made with responsible applicants, who will pay the price set by the Secretary, with a view to meeting the revenue

requirements provided for in this act.(Par.(c)sec.5)

29. That in case of conflicting applications for the purchase of power and water, that the Secretary of the Interior shall determine the matter in conformity with the policy expressed in the Colorado River pact as to conflicting contracts for water and power rights, preference being first given to a State.(Par.(c)sec.5)

30. That preference shall be given to a State for the purchase of power within six months after the Secretary has given notice, provided, however, that time shall be given for a State to arrange for bond issues for payment.(Par.(c)sec.5)

31. That any agency receiving a contract for electrical energy equivalent to 100,000 horsepower may be required by the Secretary of the Interior, if deemed feasible, to allow any other agency having contracts for less than 25,000 horsepower to participate in the benefits and to use any transmission line constructed for carrying such energy, upon payment of a reasonable share of the cost of construction, operation, and maintenance.(Par.(d)sec.5)

32. That the Federal Power Commission is hereby directed not to issue or approve any permits under the Federal Water power act upon the Colorado River or any of it's tributaries, except the Gila River, in the Colorado River basin, until this act shall become effective.(Sec.5)

33. That the United States in constructing, managing, and operating the project under this act, shall be subject to, and controlled by the terms of any compact between

the States of Arizona,Colorado,and Nevada,or any two thereof.(Par.(b)sec.8)

34. That all persons who have served in the United States Army during the wars with Germany,Spain,or the inn-surrection in the Philippines shall have preference, for three months,to the right of entry into any public lands thrown open by the Secretary of the Interior. (Sec.9)

35. That,as far as practicable,preference shall be given to persons serving inthe wars with Germany,Spain,or the insurrection of the Philippines,in all construction work authorized by this act.(Sec.9)

36. That the Secretary of the Interior may,at his dis-cretion,lease the use of the water for generating power,deliver power at the switchboard,or build and lease the power plants.(Sec.6)

37. That the Secretary of the Interior,is authorized and directed to make investigation and public reports of the feasible projects for irrigation,and sites for power projects in the States of New Mexico,Col-orado,Wyoming,Utah,Arizona,and Nevada.(Sec.15)

38. That the Secretary of the Interior is authorized to investigate the feasibility and determine the bound-aries of the reclamation project known as the "Parker-Gila valley reclamation project" in Arizona,and determine the most feasible method of irrigation of these lands.(Sec.11)

The project was to become effective when, either the "six-State" or the "seven-State" compact was accepted by the States involved.

The Congress of the United States does not limit the water supply of any State, without that State's consent. In the "six-State" compact, California is the only State in which the amount of water supplied is to have a limit. No attempt was made to limit the supply of either Nevada, or Arizona, hence no principle of State rights has been violated.

The whole purpose of either the six or the seven State compact is, to reserve a fair share in perpetuity in the States where developement will necessarily be slow.

The California Legislature accepted the definite limitations and, Utah entered the "six-State" compact by action of it's 1929 Legislature, therefore the Boulder Canyon Project, became effective on proclamation of the President after June 21, 1929, Utah being the sixth State to adopt the "six-State" compact.

For a period of from eight to ten years before the bill was placed before Congress, engineers were going over the ground, testing the rock strata, determining elevations, selecting and rejecting different sites and locations, trying to determine the most feasible point for the super-dam, somewhere in the lower Colorado, that would hold back in one great lake, the amount of water that would normally empty from the mouth of the river over a period of one and one half years.

Finally two sites were picked,one in the Boulder Canyon and,the other farther downstream in the Black Canyon. Both sites were considered as a feasible location for the dam, but the site in the Black Canyon was decided to be preferable to that in the Boulder Canyon,due to phases which will be discussed later.

After deciding upon the damsite,it was considered to be feasible,from an engineering standpoint,to build a dam across the Colorado River,that would safely impound water to an elevation of 550 feet.

Due to this enormous head of water,the danger to the country below the dam,in case of collapse,was realized,and therefore it was decided that large factors of safty should be used in all phases of the design. It was judged feasible to make the necessary excavations,of approximately 125 feet, but that the plans and the estimated costs should include provision for the control and handling of a considerable volume of water. This on account of any unexpected leakage through the cofferdams during excavation.

The plans for the power house,which must be fitted to a particular site,are considered feasible as proposed.

It was decided that the All-American canal,should be concrete lined through the sand dunes,and be given enough slope to carry away all inblown sand to a suitable place of disposal and removal. Consequently the canal was pronounced feasible with additional cost.

A dam of 550 feet above low water, across the Colorado River at Black Canyon, impounding 26,000,000 acre feet, will be adequate, to so regulate the flow of the lower Colorado as to control ordinary floods, to improve the present navigation possibilities, and to store and deliver the available water for reclamation of public lands and for other beneficial uses within the United States.

After it was determined that the project was feasible, the necessity then arose to select the type of dam most suitable, and to estimate the cost of construction.

The dam will be a curved gravity structure, designed for a maximum stress of 30 tons per square foot. It will be more than 700 feet high and contain approximately three and one half million cubic yards of concrete, of which about one half million cubic yards will be below the low water level, the lowest point of the excavation being approximately 125 feet below low water. After the river has been diverted into the diversion tunnels and the excavation has been completed, the construction problem will be probably the greatest mass-concrete manufacturing job ever undertaken. That is it may be considered the greatest, when the unusual height is considered as over against the horizontal area involved. It is believed that the mass-concrete work will take about three years and eight months.

The stresses are determined by the trial load method, and takes into account uplift at the base of the dam and within the concrete; radial sides of cantilever elements; tangential shear between the arches; temperature changes in the concrete, as produced by both setting heat and exterior air and water temperature variations; transverse shear in both arch and cantilever elements; the effect of twist; and the effect of foundation and abutment deformations in both arch and cantilever elements.

The cost of the dam is estimated at $70,600,000.00

For the discharge and regulation of irrigation water it is proposed to install needle valves in both sides of the Canyon, connected to the reservoir by tunnels and fed from the power intake tunnels.

Also because of the proposed location of the power plant and the great height of the dam, spillways of ample capacity will be provided to prevent damaging the power house by any abnormally large flood topping the dam.

The power plant will be an installation of 1,000,000 horsepower. It will be located immediately below the dam, one half on the Nevada side and the other half on the Arizona side, forming a U-shaped structure with the base of the U resting on the downstream toe of the dam.

The estimated cost of the 1,000,000 horsepower developement is $38,200,000.00

Also there is to be considered the construction of the All-American canal, which will run in a southwesterly direction, to the international boundary line then westerly to a point about ten miles west of Calexico, Calif. The length will be between 75 and 80 miles. Power can be developed at various sites along the canal, principally at

Siphon Drop,Pilot Knob,and possibly three or four places west of the sand hills. The Coachella branch diverts from the main canal at a point about 40 miles from the Laguna dam,runs northwesterly to a point near Indio,Calif.,northwest of the Salton Sea,and thence southerly to a point near the north boundary of the Salton Sea,the length of this branch is about 140 miles. The cost of the All-American canal and the Coachella canal is estimated at $49,500,000

The interest during the period of construction is estimated at $17,700,000 giving a total estimated cost of $176,000,000.00

Up to this time it has been realized that water storage is necessary to supply the demands,but nothing or practically nothing has been said as to the disposal of the water, that is dividing the quantities such that each of the States effected would get thier fair share. This qestion of water disposal necessitated the drawing up of an agreement or compact,which each of the States would have to sign in order that the agreement be effective,such an instrument was drawn up and is known as the "Colorado River Compact".

It provides in substance as follows: The Colorado River basin consists of two great natural sub-divisions,the upper basin and the lower basin. All of the streams and all drainage of the upper basin join together to form a single stream at Lee's Ferry,located at the head of the great Canyon,in the State of Arizona,a few miles southerly from the intersection of the Colorado River with the boundary line common to the State of Arizona and the State of Utah, and is the natural point of demarcation between the upper region and the lower region.

The Compact conforms to this division and the seven States are grouped into two political divisions. Colorado, New Mexico, Utah, and Wyoming constitutes the "States of the upper division", and the States of Arizona, California, and Nevada constitute the lower division.

With the drainage area divided it was considered advisable to apportion a certain annual amount to each division. Seven million five hundred thousand acre feet annually, was apportioned to each division, and by reason of probable future developement along the Gila River, the lower basin is premitted to increase it's developement to the extent of one million acre feet additional annual beneficial consumptive use before being authorized to call for a further apportionment from the surplus of the River.

The States of the upper basin shall not cause the flow of the River to be depleted below 80% of the River flow at Lee's Ferry during the lowest ten year period which is on record.

Navigation is made subservient to all other uses. Power is made subservient to domestic and agriculture uses.

State control of the appropriation, use, and disposition of the water within each State is left undisturbed.

The compact may be terminated at any time by the unaminous agreement of the signatory States.

Most of the items so far covered have dealt with those articles which had to be passed by Congress or by some board appointed by Congress,now the discussion of why the damsite in the Black Canyon was chosen rather than the one in the Boulder Canyon,from the engineer's standpoint.

Approximately seventy different sites were carefully tested,one after the other these sites were rejected as being unsuitable for such an enormous project,due to some defect found by the engineers,testing the foundation,elevations,and canyon walls. After a number of years of testing and discarding,the number of possible damsites had dwindled down to two,one in Boulder Canyon and the other in the Black Canyon.

The Boulder Canyon site was found to be suitable and could be used,provided no better site was located. The foundations are of granite rock of excellent quality. Regular joints and more irregular fractures are numerous,and there was found to be occasional fault zones,however,test tunnels showed that these are of little consequence to within a few feet of the surface.

There is no danger of the rock failing to meet the requirements as a dam foundation.

The site considered to be most suitable for the construction of the dam was in Black Canyon,which is about forty miles from Las Vegas,Nevada and the Union Pacific railroad. At this site the rock formation is somewhat jointed and exhibits occasional fault displacements,which are completely healed. It is almost ideal rock for tunneling, is satisfactory in every essential, and is suitable for use in construction.

The Geologic conditions at Black Canyon are superior to those at Boulder Canyon. The Black Canyon site is more accessible, the walls are steeper, and a dam of the same height here would cost less and have a slightly greater reservoir capacity.

There is no doubt whatever but that the rock formations of this site are competent to carry safely the heavy load and the abutment thrusts contemplated.

It is feasible from an engineering standpoint to build a dam at Black Canyon that will safely impound water to an elevation of 550 feet above low water.

The proposed dam will be by far the highest ever constructed and will impound 26,000,000 acre feet of water. Failure of such a structure would cause immense damage to the country below, and therefore the dam should be constructed on very conservative lines.

In the opinion of the board the maximum calculated stresses should not exceed 30 tons per square foot. Keeping the stress to as low a maximum as 30 tons per square foot, will add materially to the cost of the structure.

Not only was the rock formation an important factor to be studied, but also the reservoir capacity. All of that reservoir which lies between the damsite in the Black Canyon and the Boulder Canyon, is additional capacity to what would be obtained by constructing the dam in Boulder Canyon. A review of the entire reservoir is as follows: At the damsite the reservoir is only about 400 feet wide, from this point it gradually widens until at a point about one and one half miles abowe the damsite the reservoir is four miles wideaand maintains this width to a point about ten miles above the damsite. The average depth is about 330 feet giving a capacity of 8,448,000 acre feet, or 49,065,984,000 gallons of water.

We have now followed the reservoir up to the lower end of the Boulder Canyon, and here the reservoir narrows down from a width of 4 miles to about 3,000 feet. For a distance of seven miles the width gradually becomes less and at the upper end of the Boulder Canyon the reservoir is only 1,000 feet wide. The average depth of this narrow channel is 310 feet, giving a capacity of 863,159 acre feet of water.

It can readily be seen hat all of the water up to this point in the reservoir, is that additional amount which is obtained by placing the dam in the Black Canyon rather than in the Boulder Canyon, or an additional capacity of 9,311,159 acre feet of water.

From the upstream end of the Boulder Canyon the reservoir widens out until at a point 8 miles upstream the reservoir is 9 miles wide. This extreme width id due to a wash extending 7 miles south; the width then gradually decreases until at a point about 28 miles above the damsite the reservoir is 4 miles wide and, at this point the Colorado River branches off continuing on too the east and south as the Colorado River and,northward as the Virgin River.

Suppose now we consider the north fork of the reservoir;first we find that in about five miles it narrows down to two miles wide and,at the forks the depth is about 460 feet,five miles farther upstream the depth is about 400 feet. The reservoir extends northward for about 18 miles with approximately the same width,there it branches out,the right branch continuing on to the north about 10 miles,gradually becoming shallower and shallower until there is nothing left but a muddy creek. If now we observe the left fork, we find that it includes the towns of St Thomas and Kaolin, this branch extends northward for 7 miles,and also dwindles away to a muddy creek. Not only St Thomas and Kaolin but also 7 miles of railroad will be in the reservoir.

The reservoir along the Colorado River maintains a uniform width of about two miles for a distance of 10 miles above the forks. From this point the reservoir narrows down until at a distance of 12 miles upstream from the forks, it is only about 2000 feet across. This is through the Virgin Canyon which is about 6 miles long and will have a depth of about 400 feet. After passing through the Virgin Canyon, the reservoir widens out,covering a sand dune territory and Greggs Ferry,then narrows down again as it enters Iceberg Canyon. The River crosses the Nevada and Arizona line in this Canyon. The depth at the line will be about 380 feet. From this point on the width will rarely exceed 2,000 feet, as the water passes through canyon after canyon,filling the Grand Wash, the Grand Wash Canyon, the Grapevine Wash, the lower granite gorge and, from a point just about 100 miles from the Black Canyon damsite; where the elevation is 1050, upstream to the Bridge Canyon damsite, the river is in a canyon having practically no reservoir capacity due to it's width.

This then is the review of the greatest reservoir ever contemplated, in which there will be stored approximatly 26,000,000 acre feet of water. It can readily be seen that it will take some time to fill and keep filled a reservoir of such an enormous capacity, so at this time we will take up a study of the Colorado River and it's tributaries.

The United States Geological Survey has finished an investigation to determine the possible ultimate development of the States of Wyoming, Colorado, New Mexico, and Utah from the Colorado River and it's Tributaries. It has been determined according to a recent "press release" that approximately 1,198,000 acres are now irrigated from the Green and the Colorado Rivers not including 160,000 acres on the San Jaun River in New Mexico, with a possible ultimate acreage of 2,997,000 acres on the Green and Colorado Rivers, and of 600,000 acres on the San Jaun, making an ultimate irrigated area of 3,597,000 acres; assuming a consumptive water duty of 1.5 acre-feet per acre, which students of the question agree to be liberal, makes a total consumptive use of the water in the upper basin of 5,395,500 acre-feet of possible ultimate transmountain diversions, brings the total possible use to approximately 5,720,000 acre-feet as contemplated by the Colorado River Compact.

The total mean annual run-off at the junction is about 12,500,000 acre-feet of which 6,800,000 acre-feet flows in the Colorado River and 5,730,000 acre-feet in the Green, The available reports discuss in detail the extent to which this flow is now being put to use and outline it's probable future use. The bare facts are presented.

IRRIGATION.- Approximately 1,136,000 acres are irrigated at the present time with water from these drainage basins, and it is estimated that this area may ultimately be increased to nearly 2,997,000 acres.

TRANSMOUNTAIN DIVERSION.- At the present time there are nine conduits that divert water from the Green River basin into the Great Salt Lake basin, claiming about 166,000 acre-feet per year, and six conduits that divert water from the Colorado River above the Green into the Mississippi River drainage basin, with an annual diversion of 20,400 acre-feet. According to estimated that have been made the possible increased diversion into the Great Salt Lake Basin may amount to 50,000 acre-feet and that into the Mississippi River Basin to 262,000 acre-feet.

DEVELOPED POWER.- Not including all special plants such as flourmills and sawmills, which generate hydroelectric power for use incident to their business, there are 48 hydroelectric plants inthe basin having a total installed capacity of about 49,000 horsepower. These plants are distributed by States as follows;Wyoming,one with an installed capacity of 70,Colorado,fourty one having a total installed capacity of 47,350,and Utah six with an installed capacity of 1,780.

UNDEVELOPED POWER.- The amount of the developed power is practicably negligible compared with the undeveloped power resources. The various reports describe some ninety sites at which it would be possible to develope 169,000 horsepower for 90 per cent of the time,311,000 horsepower for 50 per cent of the time,or 1,080,000 horsepower with the flow regulated at described reservoir sites. These sites are located as follows by States and by major and minor drainage basins:

The above figures do not include 7,500 horsepower now in use and ten undeveloped sites capable of producing 230,000 horsepower in New Mexico on the San Juan. The total,then, in the four upper basin States-Wyoming,Colorado,New Mexico, and Utah-is developed 56,700 horsepower,undeveloped 1,360,000 horsepower.

The Colorado River Board,after reviewing in some detail existing records of flow,in it's concluding paragraph on water supply states: It is estimated that the present flow is depleted by water taken for irrigation in the upper basin by approximately 2,750,000 acre feet,which amount if added to the above estimated flow,would increase it to about 15,000,000 acre-feet. This is the amount apportioned by the seven-state compact for the division at Lees Ferry.

SILTING OF THE RESERVOIR.- It is decided that the efficiency of the reservoir will not be seriously impaired during the first fifty years,and is estimated that 137,000 acre-feet of silt will be deposited in the proposed reservoir annually.

It is estimated by engineers familiar with the situation that well within that period other reservoirs will be constructed above which will store a greater part of the silt. Five million acre-feet capacity in the Boulder Dam reservoir is allocated to silt controll

As a closing paragraph for the topic of the water supply I would say that without regulation the river has little value. When the melting snows fill its thousands of little feeders,the lower river becomes a turbulent,dangerous force. Nearly a hundred miles of levees have to be maintained at a great cost to keep the river floods from innundating the farms of Yuma and Imperial valleys. When the snows are gone, the river shrinks to a shadow of what it was two months before. The quick runoff of the river and the absence of summer rains accentuate this wide difference between high and low water. The highest summer floods have exceeded 200,000 cubic feet per second; low flow has dropped to 1,200 cubic feet per second.

These conditions call for a large reservoir to regulate the river's flow as the next step in protecting development already made and in providing for its expansion. To serve all purposes the storage must be large enough to equalize the wide variations in monthly discharges and reduce the variation between years. The larger the storage the more valuable it will be.

During the months preceding the passage of the bill the original purpose of the act,which was to protect the Imperial and Yuma valleys from floods and drought,extend the irrigated area in Arizona and California and furnish additional water for domestic use and other uses in the coast counties of California,had been lost sight of. It had ceased to be a measure to provide water and had become, in the discussion and in popular opinion,a measure for the production and disposal of power.

Enlisted in this controversy were the private power interests,opposed to all government construction of power plants,the believers in state and and municipal ownership and operation of power plants,and the different states which wish to participate in power revenues. It became a struggle between different economic and social policies and for the political advantages of the different states. As a result it is hard to understand just what the bill, as it was passed,means,how far the Secretary of the Interior in the allocation of power is to be controlled by the preference given to municipalities and to states,and how far he can exercise discretion in the protection of public welfare.

One thing the Secretary cannot ignore. The law requires him to secure a contract for the power that will repay the costs of certain parts of the work within fifty years. Without such contract the entire legislation fails and Boulder dam would have to wait until Congress deals with it again.

An opinion widely held that-- Boulder dam is being paid for out of taxation-- is erroneous. It must be paid for out of power revenues and charges for storing water. After the Secretary has secured satisfactory contracts for power, he can then proceed to submit estimates for appropiations and make contracts for the building of the dam and power house.

After a long and careful investigation the power experts employed fixed a price for the power privilege at the dam of 1.63 mills per killowatt-hour as meeting these requirements. Those who pay this price will have to install and operate the machinery. It simply means a fixing of the price to be paid for falling water, with the government having nothing to do with the generating of hydro-electric energy. If the charge is much greater than this, customers cannot be found.

While there have been protests that the price was excessive, two offers for the entire output have been recieved, one from the Southern California Edison and related companies, and one from the department of power and light of the city of Los Angeles. Both of these bidders are in a position to dispose of all the power purchased. There have been other offers, but the ability to dispose of the power is so problematical that the Secretary could not consider them with the facts now before him.

The problem of disposing of the power is complicated by provisions in the bill giving to municipalities and to the three lower states of the basin a preference right to claim power. The act requires that this preference right of the states be exercised within six months. Only Nevada has indicated a desire to acquire any definite quantity of power. Certain municipalities in Arizona and California have also applied for power.

There are,however,certain definite rights which must be protected. The Metropolitan Water District, comprising the southern California municipalities whic are seeking a source of domestic water supply in the Colorado River,will need a large amount of power to pump this water over the mountains. A number of other municipalities have preference rights,as have the states of Arizona and Nevada. It is in every way desirable that these states obtain this power whenever it can be utilized to operate mines or develope latent resources. The Secretary has been very successful in his negotiations with the different interests,in that he has induced the two principal distributors of power to agree that,while they will contract for (and if necessary take) all the power,they consent to surrender to,the Metropolitan Water District one half of the total power generated, or so much thereof as may be necessary for pumping water in the aqueduct. They agree to surrender to each of the states of Arizona and Nevada 18 per cent,or 36 per cent of the total quantity of the power generated,and to municipalities a certain additional percentage,the amount of which has not as yet been definitely fixed.

If all these withdrawal privileges were exercised, it would mean that the original contractors would have less than 10 per cent of the power left to meet their requirements. They are willing to assume this risk because of a confident belief that not all of the withdrawal rights will be exercised,or at least will not be exercised for many years.

If the power privilege is disposed of at 1.63 mills per killowatt-hour,it will pay the entire cost of the dam and leave a very considerable surplus to be divided between the states of Arizona and Nevada,the bill providing for such division. It would appear that each of these states stands to recieve an annuity somewhere between $350,000 and $700,000 a year.

Based on the estimates of the variations of flow of the Colorado River,it is believed that under present conditions of irrigation a continous output of 550,000 horsepower,or 1,000,000 horsepower on a 55 per cent power factor, could be maintained even duming the years of normal low flow. A 1,000,000-horsepower hydroelectric plant fully loaded and operating continously on a 55 per cent load factor,would generate annually 3,600,000,000 kilowatt hours of current. In actual practice this theoretical output might be reduced by approximately 10 per cent.

With the uncertainties of the flow at Boulder Dam it is impossible to estimate closely the average annual output of power which would obtain during a fifty year period but, it will be concluded that with full irrigation development in the upper basin, the 75,000,000 acre-feet can be delivered at Lees Ferry, during any ten year period.

The above supply equalized at Boulder Canyon is equal to approximately 12,000 second-feet of continous flow which in turn will generate, with head available, approximately 559,000 horsepower under ultimate development. For present and near future conditions-- say for the next 25 to 60 years the available water supply will develop 850,000 firm horsepower. These conditions will obtain until full irrigation development in the upper basin.

SEQUENCE OF CONSTRUCTION: Before work can be started at the damsite it will be necessary to build the construction railroad, to provide adequate housing facilities and to secure electric power for construction purposes. The first step in the program will be the construction of the railroad. The next step will be the building of a town with all modern improvements, including sewer and water supply systems, the water being obtained from the Colorado River. Construction of a temporary power plant, or of a transmission line from some outside source, can proceed simultaneously with the building of the railroad and the town.

As soon as transportation, housing and power facilities are available,the driving of the diversion tunnels will be started. On completion of the tunnels,the river will be diverted and the upstream and downstream coffer-dams built so that the foundation of the dam can be unwatered and the foundation excavations made. Stripping of loose rock on the canyon walls,excavation of highway approaches and such abutment excavation as may be required will be carried on while the coffer-dams are being built. As soon as the foundation excavation is made,pouring of the mass-concrete will be started. Concrete work in the spillway,power tunnels and outlet works can proceed simultaneously with the pouring of the mass-concrete in the dam. It is estimated that all work can be completed in seven years.

The construction of the main line of the All-American canal will be a six year program and work will proceed simultaneously with the work on the dam. No estimates of the time required to build the Coachella branch of the All-American Canal have been made thus far.

PREFACE

The object of this Thesis, being a part of the review of the Boulder Dam Project, is to present a comprehensive view of the general conditions confronting those interested in such a project. It is not intended to be a technical report of the subject, but is limited to things of a more general nature. It is hoped that this knowledge may be obtained upon reading the paper as presented.

C. F. Ravell.

CONTENTS

THE FOUNDATION

The investigations of the feasible sites for the boulder Dam included the investigation of two locations; namely the Boulder canyon site and the Black canyou site. The board of Engineers and Geologists appointed under authority of Joint Resolution No. 65, Seventieth Congress, made the following report to Secretary West. At Boulder canyon the foundation rock is granite and associated granitic rock of excellent quality. Regular joints and more irregular fractures are numerous and there is an occasional fault zone. Test tunnels prove that these are of little consequence to within a few feet from the surface. On the whole the rock is strong, substantial, durable, and the whole mass is essentially tight. There is no danger of the rock failing to meet requirements as a dam foundation. The rock in the vicinity is suitable for construction materials, and there are local sourses of good gravel. If no other site were available, The Boulder canyon site could safely be used as far as geological conditions are concerned.

The most favorable site in Black canyon is about 40 miles distant from Las Vegas, Nevada., and the Union Pacific Railroad. A construction railroad from Las Vegas would pass near available gravel deposits and the best quarry sites. The foundation is a volcanic breccia of tuff, a well-cemented, tough, durable mass of rock standing with remarkable steep walls, and resisting the attack of weather and erosion exceptionally well. The rock formation is somewhat jointed and exhibits occasional fault displacements, which are now completely healed. It is almost ideal rock for tunneling, is satisfactory in every essential, and is suitable for use in construction.

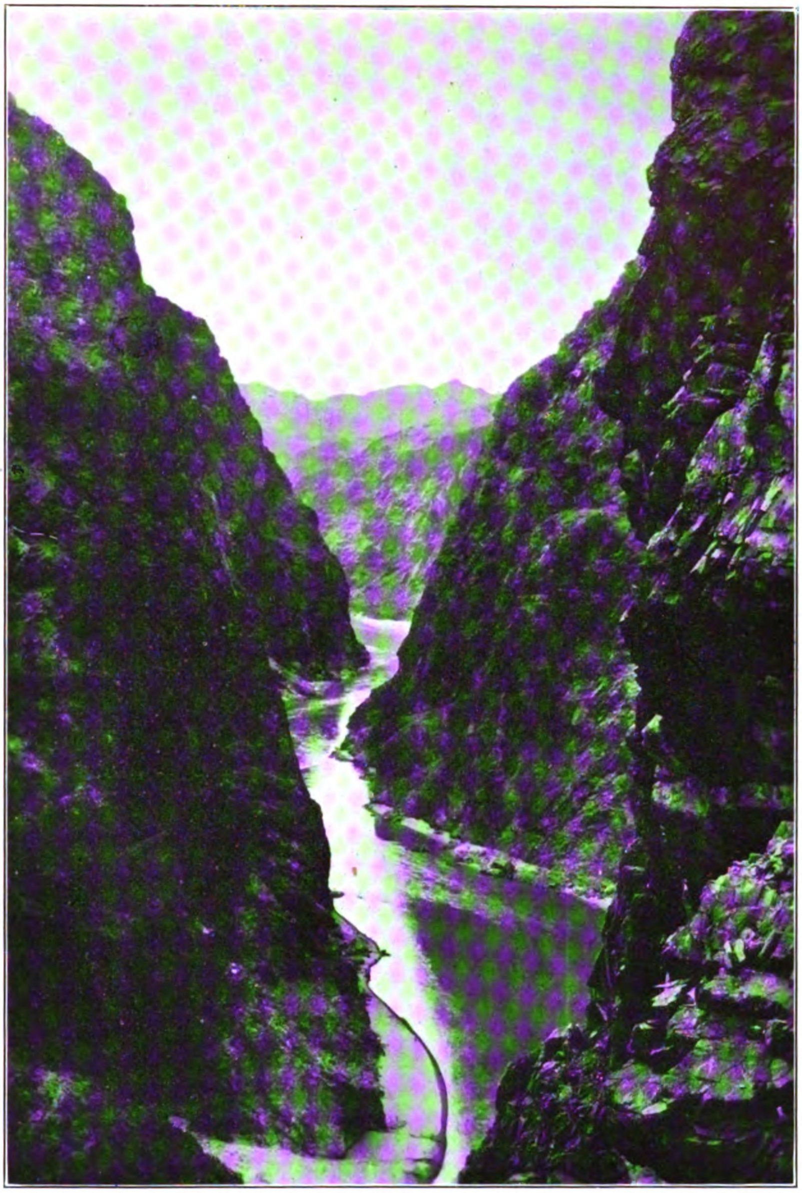
Geologic conditions at Black canyon are superior to those at Boulder canyon. The Black canyon site is more accessible, the canyon is narrower, the gorge is shallower below water level, the walls are steeper, and a dam of the same height here would cost less and would have a somewhat greater reservoir capacity. The rock formation is less jointed, stands up in sheer cliffs better, exhibits fewer open fractures, is better healed where formerly broken, and is less pervious in mass than is the other site.

There is no doubt whatever but that the rock formations of this site are competitent to carry the heavy load and abutment thrusts contemplated. The board is of the opinion that the Black canyon site is suitable for the proposed dam, and is preferable to Boulder canyon.

The Geology of the Foundation

The Muddy Creek formation occupies by far the greater part of the surface within the Boulder canyon Reservoir site. Overlying the Greggs braccia and the Muddy Creek formation is a deposit of well-stratified sand and gravel with intercalated flows of basalt. This has been described by Lee of the United States Geological Survey, who named it the Temple Bar conglomerate. It is variable in thickness and from Lee's descriptions appears to attain a maximum of over 2000 feet. He regarded it as probably of early Quarternary age.

A still younger deposit of gravels forms bluffs and terfaces along the Colorado from the mouth of the Grand Canyon to the Gulf of California. They have been named by Lee the Che-



COLORADO RIVER, NO. 92

Looking downstream into Boulder Canyon from point of rock on Nevada side near the entrance. The lower part of the Arizona abutment for a dam at the upper ("C") site is shown in the lower left corner. A drill barge is shown in the center of the picture, working at the "A" dam site. February 19, 1921 mohuevia gravel and were considered by him as of late Quaternary age. Their maximum thickness is given as about 700 feet.

In addition to the intrusive granite rocks of pre-Cambrian age such as are exposed in Boulder Canyon and the late Tertiary basalt flows, such as occur in the Muddy Creek formation and Temple Bar conglomerate, the region contains two rather complex masses of predominantly igneous rock of considerable volume and extent. One of these lies just north of Boulder Canyon and stretches westward toward Callville Wash and eastward to the valley of the Virgin; the other occupies many square miles on both sides of the Colorado, in the vicinity of Black Canyon. Information concerning these rocks will not be given. For practical convenience of reference in the present report, however, the first of these may be referred to as the Boulder Wash group and the second as the Black Canyon group. The Black Canyon group is the more homogeneous and consists of intrusive masses, flows, breccias, and volcanic sediments that are probably all of Tertiary age. The Boulder Wash group, in addition to volcanic and intrusive rocks, contains some limestone and shale. The volcanic rocks are probably Tertiary but some of the stratified rocks and possibly some of the intrusive rocks may be older than the Tertiary.

At the base of the Boulder Wash group, on the north side of Boulder Canyon, 1,000 feet or more above the river, is a hard, siliceous yellowish limestone which rests directly upon the pre-Cambrian schist and granite. No fossils have been found in it and its age is unknown. This limestone, which is perhaps from 100 to 200 feet thick, is overlain by several hundred feet of coarse breccia composed largely of fragments of pre-Cambrian rock. Apparently some lenses of limestone are interbedded with this breccia. The general dip of the whole is to the north.

The igneous rocks of the Black Canyon group constitute an extensive mass that lies athwart the course of the Colorado, about 3 miles south of the mouth of Las Vegas Wash, and stretches east and west for 2 or 3 miles on each side of the river. Through this mass the stream has cut the deep gorge of Boulder Canyon and flows wholly within it for about 8 miles, to a point where the walls become less precipitous and pre-Cambrian granitic and schistose rocks emerge from beneath the volcanic group. For about 7 miles farther, down to Jumbo Wash, the river flows mainly through mountains of pre-Cambrian crystalline rocks, but members of the Black Canyon group appear at the water's edge. Below Jumbo Wash the Canyon was not traversed, but a reconnaissance suggests that the Black Canyon volcanic group may be generally continuous with the thick volcanic series that makes up most of the Black Mountains farther south, in the vicinity of Oatman, Arizona.

The general form of the entire assemblage of rocks comprising the Black Canyon group is difficult to ascertain and in some respects would remain in doubt even after detailed geologic mapping. It is clear, however, that the rocks are chiefly lava flows and breccia deposits that originally were nearly horizontal. They evidently occupy a basin of which the deepest part is under the present Black Canyon. The shape of this basin and the depth from the river level to the pre-Cambrian crystalline rocks upon which the lavas as a whole rest are not at present determinable. There is some evidence to show that the bottom of the basin subsided after the first eruptions and perhaps continued to sink throughout the period of volcanic activity. Such movement is indicated by the exposure within the canyon walls of layers of volcanic sandstone which now dip at angles up to 65° and have been faulted, wheras the higher flows have generally a much lower dip toward the east-northeast. There is evidence at one locality that the andesite broke through the older rocks in the vicinity of Black Cnayon; in other words, that the seat of eruption was local and that the flows and breccias are not the product of outbursts at some unknown distant point. If this is true, it is probable that in some parts of the basin the andesitic lavas estend downward to their point of origin within the earth.

The basaltic dikes and masses that are exposed in the canyon walls belong to a late stage in the eruptive activity and probably extend downward far below the bottom of the basin. They appear to have risen through branching and irregular fissures which cross the general stratification of the flows and breccias.

From the occurrence of pre-Cambrian granitic and schistose rocks both north and south of Black Canyon it is fairly certain that the Black Canyon volcanic group as a whole rests on these rocks. Such a relation is clearly shown on the river about 8 miles below the head of Black Canyon. Here the andesite rests on the pre-Cambrian. It was not practicable to examine the contact closely at this place but, as seen from the river, it appears to be fairly close. It is certain that loose gravels or breccias are absent at this point, and if any detrital material intervenes between the lavas and the pre-Cambrian it is not of a character to cause any anxiety as regards possible leakage from a reservoir 8 miles away.

RESERVOIR LEAKAGE

In brief, the water of the proposed Black Canyon Reservoir will be confined by mountains of hard rock or by natural dams of softer but not particularly pervious material through which it would have to pass for 20 miles or more before finding an outlet. In other words, there is no point at which escape of water from the reservoir through a relatively thin barrier of pervious material need be feared. The shortest route of escape through the inclosing rocks would be through the mass between Hemenway Wash and Colorado River, to some point of emergence below the dam site. To accomplish this passage the water would have to pass through at least a mile of rock, partly intrusive dioritic porphyry and partly the volcanic rocks of the Black Canyon group. There is no evidence of the existence of any contiouous porous rock member as for example, a layer of conglomerate or loose breccia, through which water could escape by this route.

The possibility of leakage around the dam on the Arizona side of the river, under the gravel-covered slopes that intervene between the Black Canyon volcanics and the pre-Cambrian rocks of the main ridge of the Black Mountains, was also carefully considered. To escape by this general route the water would have to penetrate at least 2 miles of material, mostly solid, impervious rock. As the flows of the Black Canyon group dip mostly northeast, away from the dam site, the water would have to find its way not merely between but across these flows and the possibility of escape by this underground route may safely be dismissed.

BLACK CANYON DAM SITE AND LEAKAGE AROUND DAM

The river here is from 250 to 300 feet wide, and the walls rise so steeply that at the 1,100 contour, or about 450 feet above the river, they are only from 600 to 700 feet apart. For a considerable part of their height they are composed of andesite tuff breccia, consisting of angular fragments of andesite and of other fine-grained igneous rocks in a matrix of finer particles, all firmly cemented to a hard rock of generally reddish gray color. Although not separable into distince beds, the rock exhibits indefinite lines of stratification, emphasized on weathered surfaces by the alignment of irregular pits of cavities which give the rock the superficial appearance of being somewhat porous or spongy. The pits, however, are not original cavities but are due to the disintegration and weathering out of certain fragments in the breccia. In certain spots in the walls the cement of

the breccia, which is partly calcite and probably partly oxide of iron, is more readily acted upon by the weather than elsewhere and the breccia disintegrates so as to produce cavities or shallow caves in the cliffs. This action, however, is superficial and the rock back of a very thin surface layer is apparently nearly or quite as strong, hard, and impervious as elsewhere. The breccia as a whole is a strong, hard, impervious rock and would be excellent material on and against which to construct a dam. There is no deep decomposition and less than 10 feet would have to be removed to secure good anchorage for a concrete structure. The breccia is traversed by some joints, but these are superficially accentuated by weathering. Joints are probably much less abundant than in the granit at Boulder Canyon.

When a dam is constructed on granite there is not likely to be much concern about the foundation. There is reasonable certainty that the granite extends downward far beyond any depth that need be considered in planning an engineering structure. When, however, a dam is built on volcanic rock it is necessary not only to consider the character of the rock in sight but to inquire what may be beneath it. It is possible, for example that a firm massive lava may rest on loose gravel or agglomerate through which water might escape and perhaps in time undermine the foundation of the dam. No one can tell at present what is under the andesite breccia at the lower dam site at Black Canyon, but it is reasonable certain that the breccia extends so far below the river bed at this point to insure an adequate foundation for any properly constructed dam. The lines of stratification in the breccia dip upstream at about 50 degrees. The same breccia extends downstream for at least 1200 feet, with gradually decreasing dip. The average dip can safely be taken at 30 degrees. This would give a thickness of at least 700 feet of breccia below the surface of the river at the dam site. The actual thickness is probably greater than this, as the dip and distance used in the calculation were very conservatively taken. If anywhere beneath the breccia were soft or porous deposits, these nowhere come to the surface and consequently would not be likely to permit the escape of water held back by the proposed dam. Wherever the base of any member of the Black Canyon volcanic group has been seen no considerable quantity of loose or porous material has been found. About 1,700 feet downstream from the lower dam site an irregular intrusive mass of basalt is exposed on both sides of the river and extends for some hundreds of feet above the water. This mass has presumably come up from great depth and constitutes a natural impervious diaphragm which would prevent free passage of water through a buried porous stratum, did such exist. About a mile below the dam site the breccia disappears and an intrusive diotitid rock forms the lower walls of the canyon. The precice piont of change was not recognized in passing up and down the river and the contact between the two rocks is certainly inconspicuous and presumably, therefore, close. In short, there is no reason to apprehend that water impounded behind a high dam at the lower dam site could escape around or under the dam.

SELECTION OF DAM SITE

Two dam sites were investigated in Black Canyon; one about 1400 feet below the entrance, known as the A site and the other about 1½ miles below the entrance, known as the D site. Due to the greater width of river channel at the upper site it was anticipated that bed rock would be found at comparatively shallow depths. However, the shallow depth did not materialize, and this in combination with the character of the rock and the large amount of concrete necessary to build the dam, made the D site preferable.

The river at the D site is from about 260 to 350 feet wide at low water and the walls rise so steeply that at an elevation 450 feet above the river they are only from 550 to 650 feet apart. For a considerable part of their height the walls are composed of andisite tuff breccia, previously described, overlain by flow breccia.

Drilling of site D was undertaken in September, 1922. Due to the fact that the rock is of volcanic origin, usually looked upon as requiring careful investigation before acceptance for a foundation for a high dam, it was desirable to obtain a high core recovery. To accomplish this a core 13/8 inches in diameter and double-tube core barrels replaced the single-tube type.

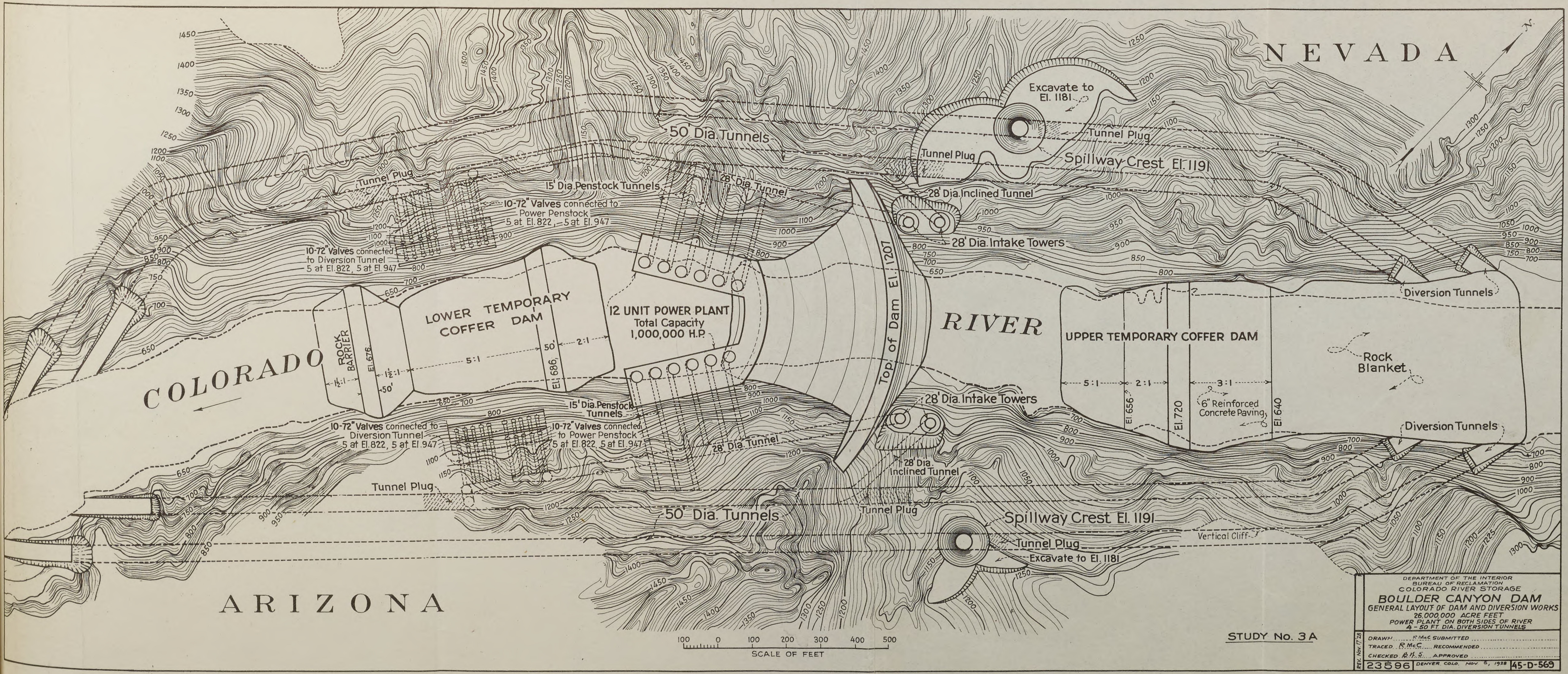
Although geological examinations indicated that the foundation rock extended to a depth of at least 700 feet below river level; that it does rest on a layer of material through which water under great pressure might pass; and that if this pervious layer did exist the passage of water would be prevented by a diaphragm of basalt across the canyon below the dam site, it was thought best to test the rock to a considerable depth. A hole was therefore drilled on the Arizona side, opposite the center of the base of the proposed dam, to a depth of 575 feet (575 feet below low-water surface). Eighty five per cent of the core was recovered. The hole remained in breccia or compact latite of andesite for the entire distance. The rock termed "latite" or "andesite" was encountered several times. It isa smooth, dark red-brown rock, similiar to the volcanic breccia but without the angular fragments. Where the change from one rock to the other occurs there is no definite joint. The change is gradual, one merging into the other, and in all probability the two are essentially the same rock with a different distribution of the angular fragments. Three comparatively soft streaks were encountered, one at depth 305 feet, one at 459 feet, and one at 576 feet. The drill water was lost once when the hole had reached a depth of 470 feet, but it is not known whether the water was lost above or below water level in the river. A great deal of trouble was experienced toward the end on account of lack of proper equipment for so deep a hole. It was necessary to "piece out" with smaller drill rods which vibrated badly. There was danger of sticking the diamond bit, and as the additional information to be obtained was of a nature to satisfy curiosity rather than of practical value, the hole was discontinued.

The entire area of foundation of the largest dam proposed was developed by drilling on lines 200 feet apart as was done at Boulder Canyon. In addition, the sites of the proposed cofferdams for diverting the river during construction of the dam were drilled.

As a usual practice all holes at the lower dam site were drilled into bed rock for a distance of 50 feet. The records show that 100 per cent of core was recovered from several holes and that core recovery seldom fell below 90 per cent. The foundation rock was found to be the same andesitic tuff breccia that appears in the canyon walls at the dam site. At times pieces of core 3 and 4 feet were recovered. In one hole on line D400 and ine on D600 compact latite or andesite without angular fragments was encountered, similar to that found in the deep land hole. Briefly, the drilling proved the foundation to be excellent beyond doubt. The rock is massive, sound, and of a remarkable uniform character.

The maximum depth below low water was found to be 110 feet for 400 feet betwe n lines D-200 and D-200, increasing to 123.3 feet at line D-400 and 132.5 feet at line D-600. There is a point just above line D-200 and another near line D-600, where some slight movement has apparently taken place. Although they are considered as of no practical importance the dam has been placed as to avoid them- thus the downstream toe of the largest dam proposed falls about 50 feet downstream from line D-400 and it is assumed that at this point the maximum depth is 125 feet.

In general the river channel is filled with fine sand and silt to a depth of from 20 to 30 fe t overlying gravel and small boulders with the exception that at line D large boulders, presumably the result of a rock slide from the canyon wall, were encountered. Samples taken at various times show the material below the fine sand to be well graded and suit-


NEVADA
N.
Excavate to El. 1181
Tunnel Plug
Spillway Crest El. 1191
50' Dia. Tunnels
15' Dia. Penstock Tunnels
28' Dia. Tunnel
28' Dia. Inclined Tunnel
28' Dia. Intake Towers
10-72" Valves connected to Power Penstock 5 at El. 822, 5 at El. 947
10-72" Valves connected to Diversion Tunnel 5 at El. 822, 5 at El. 947
ROCK BARRIER
El. 676
LOWER TEMPORARY COFFER DAM
El. 686
12 UNIT POWER PLANT
Total Capacity 1,000,000 H.P.
Top of Dam El. 1207
RIVER
UPPER TEMPORARY COFFER DAM
Diversion Tunnels
Rock Blanket
6" Reinforced Concrete Paving
El. 656
El. 720
El. 640
COLORADO
15' Dia. Penstock Tunnels
10-72" Valves connected to Diversion Tunnel 5 at El. 822, 5 at El. 947
10-72" Valves connected to Power Penstock 5 at El. 822, 5 at El. 947
28' Dia. Tunnel
28' Dia. Inclined Tunnel
28' Dia. Intake Towers
Tunnel Plug
50' Dia. Tunnels
Spillway Crest El. 1191
Tunnel Plug
Excavate to El. 1181
Vertical Cliff
ARIZONA
SCALE OF FEET
STUDY No. 3A
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE
BOULDER CANYON DAM
GENERAL LAYOUT OF DAM AND DIVERSION WORKS
26,000,000 ACRE FEET
POWER PLANT ON BOTH SIDES OF RIVER
4 - 50 FT. DIA. DIVERSION TUNNELS
DRAWN R McC SUBMITTED
TRACED R McC RECOMMENDED
CHECKED B.H.S. APPROVED
REV. NOV. 17. 28
23596
DENVER, COLO. NOV. 6, 1928
45-D-569

able for use in concrete. This has a practical value since the materials excavated for the foundation may be stored for later use in concrete.

Consideration was given to filling the river gorge by blasting from the canyon walls, but such a plan was abandoned as impractical. There is with such an idea a practical certainty of excessive settlement and a resulting menace to the safety of the dam. With a dam of unprecedented high and large pondage no saving in cost should be attempted at the expense of safety.

The Design

The unprecedented height of the proposed dam, roughly twice that of any dam heretofore built, necessitates a conservative design. The concrete gravity dam, built of homogeneous material and depending only on its weight to resist the water pressure, rather than uncertain stresses of thick arches, is best suited to this condition. For enhanced safety the dam is to be built in arch form but no dependence is placedon the arching for strength.

Careful consideration was given in the design of the concrete gravity dams to Cain's theory versus Bouvier's theory for calculating pressures in the concrete. Cain's theory solves for maximum pressures perpendicular to the faces of the dam, while Bouvier's theory solves for pressures normal to the resultant of forces.

Investigation of constructed dams by both theories showed the following stresses with a full reservoir.

design purposes. The weight of 143 pounds per cubic foot will effect a small reduction in the required dam section.

With reference to assumption (f), although uplift is recognized in the design, precaution against its occurrence is taken by extensive drainage and grouting of both the foundation and the dam itself, with resulting increase in dam strength. Further as to assumption(f) the intent is that pressure at either end of the dam will be that corresponding to the height of the water above that point with water at the top of the dam at the upper end and at the low-water level at the lower end. This pressure has been presumed to be effective over two-thirds of the area, the other one-third of the area distributed uniformly from one end to the other of the dam, which is assumed adequately drained to prevent the formation of pressures over one-third of its area.

With regard to assumption(H), it appears that the stresses were computed by assuming a slice through the dam from front to back face 1 foot in thickness; that is, 1 foot thick between parallel planes through the section of the dam. This amounts to assuming a gravity dam with a straight plan instead of an arched plan and wiht such a straight plan the pressure of 40 tons per square foot would be attained. In fact, however, the plan of the dam being an arch, the stresses should enter and leave the dam on radial lines with the result that the stresses entering the dam at the upper end over a width of 1 foot or more would be concentrated in the lower end of the dam over a width materially less, the concentration depending on the shortening of the radius. Offsetting this tendency toward increase in stresses there is a shifting of the center of gravity toward the upstream toe by reaso n of greater thickness at that point. If we now assume that all stresses of the arched dam are carried by gravity only then the maximum stress at the downstream toe, as computed by Mr. B. F. Jakobsen who is associated with Mr. LaRue, at 68.10 tons per square foot. The Government engineers have made a similiar computation and found a stress of 68.3 tons per square foot under the same conditions. It is to be borne in mind, however, that this result could only be obtained if arch action were entirely destroyed. It is the belief of the bureau engineers, based upon the results of careful analyses of other dams, that the fears entertained by Mr. Jakobson regarding the ineffectivness of arch action are largely without foundation. The Weymouth design in not considered as final but was selected from experience as represinting sufficient yardage for a final design in which the question of stresses could be more fully considered.

Further with reference to assumption (b), although investigations indicate that the stress at the toe, reservoir full, is materially increased by this reduction of length if the dam is considered as resisting the pressure by gravity action alone, it is probable that the arch form adds security in even greater proportion since the stress can not exist with-out first developing both horizontal and vertical arch action.

In the event silt accumulates in the reservoir to the top,(an event quite unlikely by reason of upstream storage development) the foundation fressure will be increased materially over that produced by water alone. The resultant of pressures, however, will remain within the middle third of the base at all heights and the sliding coefficient will be less than that required to satisfy uplift assumptions.

Silt and uplift are not assumed to act at the same time.

For this and other dams the computed stresses are as follows:

6

	Res. cap. in acre feet.	Max. height to road way in feet.	Pressures exp. in tons per sq. ft. by Cain's theory. No uplift or silt	with up-lift Res. full	With silt to top of dam.
Max. pressure U.S. face	34,000,000	740	41.3	8.6	19.2
" " D.S. "	34,000,000	740	39.7	39.6	45.6
Max. sliding factor.	34,000,000	740	.51	.71	.74
Max. pressure U.S. face	20,000,000	640	40.4	3.1	9.1
" " D.S "	20,000,000	640	39.7	39.7	49.4
Max. sliding factor	20,000,000	640	.52	.72	.67
Max. pressure U.S. face	10,000,000	523	35.5	-----	-----
" " D.S. "	10,000,000	523	34.9	35.0	41.1
Maximum sliding factor	10,000,000	523	.51	.69	.61

The section chosen for investigation was the maximum that could exist at the lower dam site in Black Canyon assuming that bed rock in the narrow trench is level.

As a mater of fact, at the upstream heel of the dam the rock is 14 feet higher than at the downstream toe.

Over the greater part of the foundation area the rock is at about elevation 600, 30 feet above the lowest point of rock at the downstream toe of the dam. Thus, there is only a very small portion of the dam that is as high as assumed and if the foundation were assumed as being at elevation 600 the maximum designed stress for the highest dam would not be in excess of about 36.7 tons at the downstream side and it is believed that this stress could be reduced to 35 tons without adding concrete by changing the shape of the downstream face slightly. Certainly, the loads would be distributedto the side benches in the riber channel in such a way as to relieve the higher stresses at the toe at the deepest point in the narrow trench. Furthermore, with additional work on the design than is warranted in the preliminary design, the stress could undoubtedly be made to increase uniformly toward the bottom rather than as worked out in this design. The comparatively high stress at the upstream heel with reservoir empty is not of much importance since the reservoir can never be empty-at least not below river level and probably not below the lower set of permanent outlets.

The stresses due to silt are higher than those due to water alone. However, the assumption that the reservoir will at some time be filled to the top with silt is rather extreme and it is questionable if the silt deposit will not relieve the pressures rather than increase them. Authorities do not agree upon this point and experiments are not conclusive.

A study was made of the effect of varying the top width. Reducing the width from 50 to 25 feet did not result in appreciable saving in concrete and for a dam of the size proposed the wider top is believed to be more in keeping with other dimensions.

A design and estimate was prepared of a dam at the lower dam site in Black Canyon to develop a maximum pressure of 30 tons per square foot by Cain's theory. The concrete required to build such a dam would be about 25 per cent in excess of that for a pressure of 40 tons per square foot, and the total estimated cost about 12 per cent more. It might be possible to reduce the pressures and the cost of the dam through the use of some sort of hollow or perforated construction instead of following the usual practice in designing gravity dams, but it is questionable if any "freak design" would be approved where the integrity of the structure is of such great importance.

In all cases the estimates assume that it will be necessary to remove foundation and abutment rock to a depth of 10 feet to secure absolutely sound rock. It is proposed that each dam be built on a curve to best fit the dam site.

In the proposed layout of the dam site, if the power house were moved upstream to shorten the pressure tunnels its cost would be materially increased, and it would be located at the base of the very steep canyon wall where rocks falling from above might damage the machinery as well as the building. It was also found that the saving in cost of the tunnels by moving the dam downstream did not offset the increased cost of the dam due to its greater volume.

CONSTRUCTION MATERIALS

The estimated cement requirements is 4,000,000 barrels for a reservoir of 34,000,000 acre-feet capacity and proportionally less for smaller reservoirs. The Southern California and Utah mills are very favorably located with respect to distance and rail connections to the dam site and their combined daily capacity is about 20,000 barrels, or 6,000,000 barrels annually for 300 working days per year. This is 50 per cent in excess of the total cement requirements for the dam if built in a single year.

The sand found along the river banks and in the upper portions of the river bed with predominating grain diameters of 0.001 to 0.005 inch is too fine for general use in concrete other than to supply a possible deficiency of "fines" in a natural or crushed sand. This sand contains very little organic matter, being finely broken and worn rock fragments of great variety wiht quartz predominating. The coarser sand and gravel found in the lower portion of the river bed are suitable for concrete, and it is proposed to store such material from the excavation for the dam at Black Canyon to be later used for concrete.

Concrete aggregate could be made by crushing the granitic rocks of Boulder Canyon or the glassy lavas at Black Canyon. The "latite" at Black Canyon is very brittle and could readily be made into sand and gravel, but the process would be comparitively expensive.

No large deposits of clean sand and gravel were located in the immediate vicinity of any of the dam sites. The cleanest deposits are found in Callville Wash., but these are not favorably located with respect to the dam sites. In Hemenway Wash are very large deposits of sand and rather angular gravel containing considerable fine material. The most promising deposit lies about 3½ miles from the adopted dam site in Black Canyon on the route of the proposed construction railroad to the dam site. Test pits developed more than sufficient material for the largest dam under consideration.

Samples, ranging in weight from 150 pounds to 1,000 pounds, of various materials in the vicinity of the dam sites which in the field appear to be suitable for concrete aggregate were tested by the Bureau of Standards. The tests show that the Hemenway sand and gravel, although apparently dirty and forbidding in appearance, is the most suitable of any of the materials submitted for test as to concrete strength, workability, and durability. Crushing tests of concrete made from the unwashed material, just as found in the pit, gave nearly the same strength as washed material, and better workability. Twenty-eight day tests of concrete cylinders of this material showed average strength of over 1,500 pounds per sq. inch for the more suitable mixtures, comparing favorably with concrete concurrently made with proven gravels from the Washington vicinity. The weight of Hemenway gravel concrete averaged 143 pounds per cubic foot against 146 pounds for the Washington gravel. With extended research to determine the best proportioning and preparation of Hemenway gravels concrete of the highest quality can be expected. It appears that washing may be found necessary and that screening may be limited to a simple separation of the coarse aggregates from the fine. There was some doubt about the dirty films on the gravel, but microscopic examination showed these to be calcium carbonate and iron oxide, both stable minerals, and dispelled suspicion.

A light-weight concrete without sacrifice of strength would be desirable in that its use would result in a smaller dam section and therefore a less cost, provided the lightweight concrete could be produced cheaply. A possibility in this direction lies in the use of crushed latite which is to be found at the adopted dam site in Black Canyon in a very advantageous position to be quarried cheaply. It is brittle and could be crushed readily. Its apparent specific gravity is about 2.27 and the weight per cubic foot of concrete resulting in its use was found to be 131 pounds against 143 pounds for the Heminway gravel. The crushed aggregate is sharp, and when used alone, results in a harsh mix of poor workability. The subsitution of fine river sand for 25 per cent of the crushed sand improved both the strength and workability of the concrete. It is believed, however, that the saving in concrete with the lightweight latite would be more than offset by the additionalcost crushing aggregate in comparison with Hemenway gravels.

Diversion Works

Balanced 72-inch needle valves were adopted because-

First: They are particularly adapted to working under high heads.

Second: The discharge into open air, which avoids difficulties arising through the creation of vacuum around the contracted jet.

Third: The energy of the jet is destroyed in the river channel where no damage can result.

Fourth: Regardless of the stage of water in the reservoir the valves are under observation and may be repaired or replaced at any time.

The valve conduits are to be lined with semisteel to prevent the water in the conduits from exerting uplift within the dam, to transmit the compressive forces inthe dam and to resist the wear and tear of silt which will in time be carried through the dam.

Each conduit is provided with a 5 by 9 foot hydraulic-operated emergency slide gate near the upstream end operated from a gallery in the dam.

Trash racks have been provided on the upstream face of the dam with provision for mechanical raking.

The trash rack piers contain two grooves to guide bulkheads to position in case it becomes necessary to do some repair work in the conduit upstream from the emergency gate before the water in the reservoir is drawn down. A traveling crane on top of the dam will handle needle valves,-trash racks, and bulkheads.

The maximum irrigation demand is assumed as 30,000 second-feet. In case of the dam to store 20,000,000 acre-feet, the outlet works will operate as follows.

(a) The lower set of valves begin discharging with 2,000,000 acre-feet in the reservoir.

(b) With 5,700,000 acre-feet in the reservoir the discharge is 30,000 second-feet.

(c) The upper set begins discharging at the time the lower set is carrying 26,000 second-feet.

(d) The upper set with full reservoir will discharge 38,000 second-feet under a head of 200 feet.

(e) Both sets will discharge 85,000 second-feet with water surface standing at top of parapets. Maximum head 315 feet. In the estimates it has been assumed that all needle valves for any one dam are of the same design, although the heads on the two tiers are different in order that they may be interchangeable in an emergency.

The only excuse for operating valves in the higher dam under heads greater than 275 feet would be:

(a) It might be desired to discharge the 40,000 second-feet flood-control water before the water surface in the reservoir reached the bottom of the 5,000,000 acre-foot flood-control storage reserve, in which case the lower set would be required to operate under a head of 365 feet. With water surface above this level the upper valves alone would pass the 40,000 second-feet.

(b) At very long intervals of time it might be necessary to operate the lower set of valves under heads as great as 415

feet to prevent water overtopping the parapets on the dam. Even this head is not considered excessive for emergency use during a short period.

The outlets at river level are not a part of the permanent outlet works as they are to be "plugged" when their usefulness has ceased. Their function is to carry the low-water flow of the river during the time the diversion tunnels are being closed and until the water surface in the reservoir is raised to the lower set of valves.

In the event a power house is built as a part of the development a large part of the irrigation requirement, and at times all of it, would pass through the power house thus relieving the outlet works. With the outlets provided it is possible that overtoppong may occur at very long intervals-perhaps once in 500 years if it is attempted to control the flood to 40,000 second-feet. Overtopping could be prevented by opening the gates to discharge at the rate of about 80,000 second-feet at a time when it becomes ecident that overtopping would otherwise occur.

Spillway

Studies of various types of spillways were made. In one the discharge was carried downward into the tunnels used for dicerting the river dueing construction of the dam. In another the discharge was carried at high velocity in large tunnels through the point of rock on the Arizona side and dropped over the cliff downstream from the dam. In another the discharge was carried at comparatively slow velocity through the ridge east of the dam site and dropped into a wash, entering the river about 1½ miles by river below the dam site.

In the case of the concrete dams the plan of carrying the abnormal floods occurring at very long intervals over the dam was adopted as being the most economical and the safest manner in which to handle the discharge. As was considered in making the computations for the dam, the design allows for water to pass over the central portion with the water surface in the reservoir standing 21 feet above the roadway with the resultant forces falling within the middle third of the critical point.

To keep the possible overflow from striking the abutments of the dam the latter has been raised at each end 25 feet above the roadway.

The flow will be at right angles to the crest toward the center of curvature. Any overtopping would be of short duration and the only damage anticipated would be the possible breaking off of the parapets. This, however, might result in a sudden increase in flow downstream and defeat to a certain extent the flod-control.

There was an article published in the Engineering News Record stating that there is a movement to increase the height 25 feet there-by making it more effective in flood-control.

CONSTRUCTION PLAN

Diversion works.

In designing the proposed diversion works the flow of the Colorado River at Yuma between the years 1902 and 1923 was used as a basis for calculating probable discharges at Boulder or Black Canyon.

The relative peak discharge at points widely separated on the river depends upon the magnitude and duration of the flood. Large floods build up gradually and are "ironed out" by the effect of channel storage proportionally less than are the "flashy floods" originating in streams like the San Juan, Little Colorado, and Virgin. The impending danger of losing cofferdams will be due to the flashy floods which are apt to occur at any time during the working season.

As an example of the absorbing power of the river channel the flood of October, 1911 was sited. The discharge at Yuma suddenly rose from 8,000 to 60,000 foot-second, 2,000 second-feet of which came from the Gila and the remainder principally from the San Juan and Dolores Rivers. At Ship Rock, N. Mexico (about 325 miles above Lees Ferry), the discharge of the San Juan River was estimated to be 150,000 second-feet. Assuming that the San Juan and Dolores peaks did not coincide this peak discharge of 150,000 second-feet at Yuma had diminished to 58,000 second-feet or at the average rate of about 100 second-feet per mile. Upon this basis the discharge at Lees Ferry is assumed to have been about 117,000 second-feet and at Boulder Canyon about 90,000 second-feet.

During the years in which records were taken on stream flow the following gives some idea of the working seasons and the quantities of flow that would have had to been taken care of by diversion works. The discharges exceeded 75,000 second-feet a total of nine times in the 19 seasons after work would probably have been started. The flood of Sept. 1923, which is estimated to have been close to 100,000 sec.-ft. at Boulder Canyon, would have overtopped the cofferdams. Only four of these overtoppings would have been serious, since in other instances work would not have been far advanced. The serious floods would have occurred as follows:

October, 1911, estimated peak, 82,000; work advanced 2½ mo.
March, 1916, estimated peak, 8[illegible],000; work advanced 8½ mo.
February, 1920, estimated peak, 96,000; wk. adv. 7 3/4 mo.
Sept., 1923, estimated peak, 100,000; wk. adv. 2 months.

In the season 1909-10 conditions were extremely severe, and even with diversion works of 75,000 second-feet capacity only 7½ months would have been available for completing the seasons work.

The appreciable longer working season and lessened danger from overtopping justifies the construction of temporary diversion works having a capacity of 100,000 second-feet since the loss of a cofferdam after the work was well under way would undoubtedly defer the completion of the dam at least a year.

Temporary diversion of 100,000 second-feet is accomplished by means of three concrete-lined tunnels at 130-foot centers on the Nevada side of the river, and rock-earth fill cofferdams, the tunnels to be later used for power development.

Estimates of tunnels of varying size and the necessary cofferdams for each size indicated that a combination utilizing 33-foot diameter tunnels was the most economical, but since tunnels 35 feet in diameter were best suited to the requirements of power development this size was adopted at very little greater cost. The largest tunnels justified by other conditions are desirable to effectively pass the large quantities of drift and debris carried by the Colorado River. That portion of the tunnels used later for power purposes is lined with 1:2:4 concrete with an average thickness of 30 inches. It is proposed to grout between the concrete and rock under a pressure slightly in excess of the pressure to which the tunnels will be subjected in operation as penstocks.

The portions of the tunnels not used as penstocks are lined with 1:2½:5 concrete having an average thickness of 18 inches, the least thought to be practicable. High rock points would be permitted to extend to within 6 inches of the face of the concrete.

Although horseshoe tunnels would be more easily dug, on account of the flatter bottom, circular tunnels were adopted for the reason that they are better adapted to distributing uniformly the great pressures to which they will be subjected under full reservoir head.

It is proposed to drive and line all tunnels complete before the rock-fill cofferdams are started. All tunnels may be driven simultaneously from both ends, the muck being removed through "muck tunnels" at each end, constructed on a grade of about 5 per cent from the invert of the large tunnels to a point above high water. The muck tunnels, crossing all diversion tunnels below low-water surface in the river and with exits above high water, would permit the driving of the diversion tunnels regardless of the stage of the river. The inlet and outlet ends of the diversion tunnels will have to be completed behind cofferdams during low water.

It is proposed to use rock-fill cofferdams to turn the river, as they appear to be the most practicable type for the situation, having been successfully used at other points on the river and exclusively in recent years in closing breaks on the lower river.

Test holes were put down on the sites of the temporary cofferdams, the location of the lines drilled being based upon the assumption that a percolation factor of 6 would be sufficient for the gravelly material in the river bed below the fine sand. The results of the investigations are favorable for such requirements.

On the other hand in order to insure the safety of the rock-fill cofferdams, they must rest upon a better foundation than is offered by the sand and silt in the river bed. It is believed that great floods scour out the channel filling clear to bedrock while ordinary floods probably scour out the sand and silt down to the more stable gravel and boulders.

It is proposed to start dumping large rock obtained from the canyon walls at the cofferdam sites from cableways spanning the site as soon as the flood begins to recede in July, the diversion tunnels having been completed before the spring flood. It is assumed that at this time the river channel will be scoured out to at least elevation 620, perhaps deeper under the lower cofferdam. The rocks first dropped would be as large as would be practicable to handle. Some of these rocks would be carried downstream beyond the limits of the cofferdam section, but at some stage a part of them would begin to "hang" within the section. At this point smaller rock would be dropped simultaneously which would be caught by the larger rocks and held within the interstices. As the flood receded more rocks would stay in place. The estimates assume that 25 per cent of the rock dropped would be carried away. During the rock placing process the diversion tunnels would be discharging at full capacity, and to reduce the head on the cofferdams these would be built simultaneously, the lower one being kept half as high as the upper one.

Due to the velocity of the overflowing water, the lower side of the rock-fill may take a slope as flat as 1 on 4 or 5 and by the time the rock fill is raised sufficiently high to turn the entire flow through the tunnels, a blanket of sand and silt will, no doubt, have deposited on the upper slope to approximately normal river bed level. Experiments at Boulder Canyon have demonstrated this material to be very tight if undisturbed. Above the top of the sand, and to the top of the rock fill, an earth blanket will be placed on the water side, material for which may be obtained from Hemenway Wash.

For additional safety the channel excavation for the main dam not suitable for making concrete may be dumped on the water side of the cofferdams.

The arguments in favor of using rock-fill cofferdams constructed as proposed, are as follows:

(a) The process and necessary equipment is not complicated.

(b) If the fill is placed during the recession of the flood, the rock will be deposited on a bottom as established by the flood which is unquestionably much more stable than the normal river bed at low water.

(c) A fill built as here planned will effect a saving of time of approximately two months for other work since if built from trestles, or if a type is built requiring caissons, piles, cribs, etc., construction could not be undertaken until about the 1st. of September or until the return of low water in the river.

(d) The rock-fill type placed by cableways is particularly adapted to fighting floods. Any type requiring the building of trestles across the river would be in imminent danger of being destroyed by the flash floods which may occur at any time. Loss of a cofferdam during its construction might result in a year's delay in completing the main dam.

(e) If the rock fill were built at low water stage, its foundation would be such that a blowout of the sand on which it rested would be apt to occur under the head to which it would be subjected.

(f) With the cableways left in place over the crest of the cofferdam it could be raised rapidly if endangered by flood and if the rock fill is partially or entirely lost, it could be replaced without having to wait to rebuild trestles, drive piles, etc.

Behind the temporary cofferdams it is proposed to build portions of the upstream and downstream faces of the dam to the height necessary to permanently divert the river. The work to be accomplished in bringing the whole dam up to the elevation of the river would be entirely too great to be accomplished between seasonal floods. With the river permanently diverted, excavation of the foundation and pouring of the concrete between the permanent cofferdams could proceed without undue haste.

Permanent cofferdams to force 200,000 second-feet through the diversion tunnels were given consideration but the design was not considered practicable and, moreover a flood of that proportion has only occurred once in the 20 year period of record- in 1921- when the discharge at Yuma was about 200,000 second-feet. For the permanent cofferdams the diversion capacity is calculated to be 135,000 second-feet in case of the long tunnels discharging below the power house and 154,000 second-feet if the shorter tunnels are used-sufficient to pass ordinary floods. The cofferdams might be overtopped in a high year, but no damage could result beyond filling the hole with sand, or possibly gravel.

It is proposed to first build a protion of the gravity section at the upstream side of the dam on each bench, leaving a gap about 150 feet wide over the deep trench. The rock excavation on the benches would be under way while the loose material in the deep trench was being excavated and the pouring of concrete would be started at the earliest possible moment.

In order to reduce the immediately needed excavation and concrete quantities across the deep trench to a minimum, a thin arch with short radius has been designed for the cofferdam. The gravity sections have sufficient section to keep the tangential thrust of the arch well within the middle of the section. Both the gravity and arch sections would be stepped and dovetailed on the downstream side and steel bars, or rails, would be left projecting to secure a good bond with the concrete to be later added.

The lower permanent cofferdam is designed as a gravity dam to take water pressure from either side. Its construction would be carried on simultaneously with that of the upper cofferdam. The problem here is less difficult and there is less concrete to be placed. There is a possibility that the lower cofferdam may not be needed, depending on conditions found when the dam site is unwatered. If the leakage through the rock-fill cofferdam and the underlying gravel and boulders can be handled at a reasonable expense and it appears feasable to complete the permanent upper cofferdam on schedule, then the temporary lower rock-fill could be raised to the necessary elevation to avoid overtopping by the spring flood, and the permanent cofferdam dispensed with. On the other hand, if the permanent upper cofferdam can only be completed to river grade, or a little above, it would be better to build the permanent lower cofferdam than to take a chance of losing the lower rock-fill dam during the flood. Since the additional expense of building the permanent lower cofferdam is small, it is probable that it should be built. The only objection to it is the fact that it introduces what may be considered a line of weakness in the completed dam where the stresses are high. However, in the design, an effort has been made to minimize this fault by making the general direction of the joint normal to the direction of pressures. The upstream face would be dovetail and steel "studs" would be left projecting as in case of the upper dam.

The critical time in the construction period is that during which the permanent cofferdams are being built. It will, in an ordinary season, be necessary, in about eight or nine months' time, to build the cofferdams, and place the concrete to at least low-water surface. The cutoff trench in the foundation has been placed just downstream from the permanent upper cofferdam as a timesaver, as with the trench at the upstream side of the dam, construction of the permanent cofferdam would be delayed awaiting completion of the trench excavation.

When it is desired to begin storing water in the reservoir the diversion tunnels will be plugged near the reservoir end with concrete and the river discharge carried by the conduits through the concrete dams at about river grade. After the tunnel plugs have been placed the lower tier of outlets without gates will be plugged with concrete behind a ball to be placed at the upstream end and a low cofferdam built on the dam at the lower end, the water in the meantime being controlled by the outlets provided with gates. After water level reaches the higher valves the conduits at river level are to be permanently plugged with concrete.

CONSTRUCTION PLAN

It is assumed that all construction machinery at the dam site will be electrically operated. Due to the magnitude of the work it is assumed that the construction railroad to the dam site and the plant for furnishing power will be built before work at the dam site is undertaken, the latter either at Las Vegas or the dam site, depending upon whether it would be more economical to transport fuel or transport power. During the construction of the railroad and power plant a construction camp would be built at the dam site, including housing facilities, shops, water supply, etc.

From the detailed studies of various construction plants it appears that a cableway plant is best adapted for use at the proposed dam site. The cableways would span the canyon in positions to handle both the excavation and concrete. Cableways used to build the rock-fill cofferdams would after their completion, be moved to new positions over the main dam. Nine cableways are proposed, each capable of handling a 12-ton rock or five cubic yards of concrete each trip.

The first work to be done is the driving of the three diversion tunnels, involving about 15,500 linear feet of 38 to 40 feet diameter tunnel and lining them with concrete. Electric shovels and muck trains would probably be used, the shovels digging themselves in at both ends of each tunnel through the muck tunnel described under the heading "diversion works," with its portal above high-water surface. The large tunnels would not be "blown through" at either end until the concrete lining had been completed, since otherwise work could not be carried on during high water. Excavation would be started during low water so that the six shovels could be taken to the tunnel portals on barges. To get the shovels from the railroad at elevation 1,375 to the barges, cableways Nos. 1 and 2 would be used. These two cableways and the railroad trestle under them would be the first equipment installed at the dam site. The longest tunnel has a length of 5,700 feet. If it is assumed that work would be carried three shifts per day for six days a week, with an average daily progress of 15 linear feet, it would require about 15 months to complete excavation. Concrete lining would follow the excavation closely. Therefore if work were started in December it should be completed by the middle of the second March, prior to the beginning of the spring flood. Upon completion of the diversion tunnels the shovels would be moved to the rock quarries to furnish rock for the temporary cofferdams.

During construction of the diversion tunnels the camp would have been completed; three cableways would have been erected over each rock-fill cofferdam; cableway No.9 would have been erected over the lower permanent cofferdam; and the quarries above the rock-fill cofferdams would have been opened up. Diversion capacity has been enlarged from 100,000 to 200,000 second-feet, in accordance with a special engineering board's report.

As stated under "Diversion works" the rock-fill cofferdams would be started as soon as the flood began to recede, probably in July. The upper cofferdam is much the larger and would require the longer time in building, requiring 620,000 cubic yards of loose rock, including the 25 per cent assumed to be swept away. The material will be handled in 8 by 2½ foot skips, the loaded skips weighing from 8 to 8½ tons. The skips would be filled by the electric shovels, with some hand work, and taken to the cableways on flat cars. The skips would be dumped automatically without lowering down into the canyon, permitting high speed and large output. The quarry equipment to maintain the pace set by the cableways would have to be efficient. Work would be carried on in three shifts per day without interruption, at least until the river had been turned. The crest of the fill would be kept level in order to avoid concentrated flow at any one point. Allowing 30 seconds for "hooking" each successive skip, each cableway should average 30 trips per hour. On similiar work of this kind these skips averaged 4.3 cubic yards of loose material per load. Assuming this as a basis of computations each cableway would handle 129 yards per hour or 3,100 yards per day. Three cableways would place about 9,000 yards per day, and it would require 69 days to complete the cofferdam or conservatively three months. By the middle of October therefore the rock fill should be completed. The fill would be made water-tight by placing sand and gravel from Hemenway Wash on the upstream face.

The river should be turned at least by the middle of September, at which time the fill then in place could be made water-tight so that unwatering of the dam site could be started. The lower cofferdam would have been completed and cableways Nos. 7 and 8 moved to positions 7B and 8B over the lower permanent cofferdam. As soon as the site was unwatered, excavation of the river bed would be started at both permanent cofferdams-probably about october 1.

The loose excavation for the lower permanent cofferdam is the greater and amounts to 343,000 cubic yards. However, the time element is more important in case of the upper permanent cofferdam where there are 188,000 cubic yards to be removed. By October 1, cableway No. 3 could have been removed to position 3B leaving No. 4A and 5A to finish the upper rock fill cofferdam. There would thus be three cableways commanding each permanent cofferdam site.

Electric shovels or dragline excavators would be used in the hole to load the same skips that were used in building the rock-fill cofferdams. The skips would average 4.3 yards per trip. Allowing 30 seconds for "hocking," each cableway could make 13 trips per hour, lifting out of the hole and dumping into a "dirt trap" at the top of the canyon. Work would be carried on continuously for 24 hours a day. Each cableway would handle 56 yards per hour or 1,340 yards per day, and three cableways would handle 4,000 yards per day. At this rate the excavation would require 47 days or conservatively 2 months. By December 1, therefore, the excavation of loose material at the upper site should be finished. Work of preparing the foundation would take another month and it would be the 1st of January before concreting could be started. Excavated material suitable for use, in concrete would be stored in the spillway basin under cableways Nos. 1,2 and 3 E.

There are 150,000 yards of concrete inthe upper permanent cofferdam and 85,000 in the lower. By December 1, the concrete mixing plant would have been completed and the gravel pit in Hemenway Wash would have been opened up, the shovels used in the diversion tunnels, quarries, and dam excavations, having been moved to the gravel pit. Concrete buckets would be of the bottom-dumping type with capacity of 5 cubic yards per trip. It is assumed that concrete would be placed on two shifts per day only, the third shift being devoted to cleaning up and keeping the job going. Each cableway could make 13 trips per hour allowing 30 seconds for hooking trips. Each cableway could place 65 yards per hour or about 1,000 yards per day. One cableway would be reserved for general service, leaving two outfits to place 2,000 yards per day. If this rate could be maintained it would require 75 days, or until March 15, to finish the work, If concrete were placed at half the rate assumed, the cofferdam could still be finished by the end of May in time to turn the seasonal flood which does not usually occur until late in June.

One of the characteristics of the Colorado is its tendency toward flashy floods of comparatively small volume. Although of small volume and short duration they cause a great deal of anxiety and would be a sourse of great danger. The river may rise from 10 to 15 feet in a few hours at most any time during the working season. During such a time the temporary rock-fill cofferdams would be in danger and in order to be in a position to combat the flood two cableways would be left in position over the upper rock-fill and one over the lower fill until the permanent cofferdams have been completed. After that they would be moved to their new positions over the main dam.

It appears that the work of diverting the river can be accomplished in the time avialable and certainly the permanent cofferdams could be at least be brought up to river level from where they could be completed after high water without rebuilding temporary cofferdams. From the time construction of the railway is started until the permanent cofferdams are finished will be at least 30 months, allowing 3 months to build the railroad.

Any diversion scheme which does not contemplate building the permanent cofferdams in one low-water period will be a very expensive one, since it will involve the partial of total loss of both temporary cofferdams and their replacement, and the excavation of the river-bed material at the dam site for the second time-at least down to the uncompleted structure. While the monetary loss would not be especially serious, the loss of time, necessary shutdown, and the demoralizing of the organization would have a serious effect upon the work.

With the permanent cofferdams successfully completed the construction of the dam would be a comparatively easy matter and would resolve itself, more or less, into the development of a plant to put concrete into the dam at the greatest practicable speed and at the least possible cost comparable with good quality.

Excavation of the remaining loose material between the finished cofferdams and work of preparing the foundation rock would be taken up immediately. By the time this work was done the heat of the summer would slow up operations and concreting on a large scale would not be started until about September 1, three years after beginning construction of the railroad.

The volume of concrete in the dam, exclusive of that in appurtenant structures, is estimated to be 3,560,000 cubic yards. Assuming 250 working days per season and an average daily fate of progress of 3,500 cubic yards, it would require 4 years to place the concrete. As the dam is raised the area over which concrete can be placed becomes less, ao that in order to maintain the average rate of progress it may be necessary to place concrete in the lower portion of the dam at twice the average rate. Work would be carried on for three shifts per day, but one shift would be necessarily be devoted to repairing equipment and getting the work cleaned up in order that concreting onthe other two shifts may not be delayed.

The maximum rate at which concrete would be placed is estimated to be 3,500 cubic yards per shift of 8 hours, which amounts to 438 yards per hour and, considering loads of 5 yards, the requirements of cableway service are 87½ trips per hour. The cableways proposed average 13 trips per hour each, carrying concrete the average distance and lowering to the average depth of the lower two-thirds of the concrete in the dam. Thus it will require seven cableways to do the work. However, nine cableways are proposed partly on account of advantageous spacing of cableways over the work and partly on account of the fact that some of these cableways will be used for handling forms and miscellaneous material. The total time being 7 years after starting.

The plant proposed for building the dam is very simple and is one which should perform the work at a minimum cost. It is proposed to locate the mixing plant on the rim of the canyon in a position to be under the cableways but above the top of the completed dam so that the concrete may be handled by gravity. The mixing plant would be designed to produce 3,500 cubic yards per 8-hour shift or at the rate of 7.3 cubic yards per minute. If 2½-yard mixers were adopted it would require a battery of five mixers with probably a spare mixer to insure the availability of five at all times. The mixer would be set under the material bins and would dump into hoppers holding at least 2 batches. The cableway skips would be carried to the mixing plant on flat cars running on tracks under all the cableways.

The cement, sand, gravel, and cobbles would be brought in on the railroad built over the material bins and dumped directly into the bins. For each yard of concrete 1.44 cubic yards of material exclusive of cement are required, or for the construction of the dam 5,130,000 cubic yards. If 30-yard dump cars are used it will require 171,000 carloads of material from the gravel pits 7½ miles away. Trains will operate three shifts a day so that when runs of 7,000 yards per day are being made at the dam 336 carloads of material will be required at the rate of 14 cars per hour continuously. In operation a 7 car train would probably be brought from the switching yards to the mixing plant every half hour.

Two reciprocating locomotives with one spare could probably handle the trains between the gravel pit and the switching yard. Three geared engines with a spare could handle the cars from the switching yard to the mixing plant. Two switch engines would be required in the yards. A large number of gravel cars would be required not only to insure flexibility in operation but to provide live storage in cars in the switching yards where they could be drawn upon in case of an accident on the railroad.

UNIT COSTS

In July, 1923 letters were written to several large manufacturers of cement requesting quotations on cement shipped in bulk in very large quantities to be used in estimating purposes. The following quotations were received:

	Per Bbl.
Monolith Portland cement Co., Colton, Calif.	$2.50
Colton Portland Cement Co., Colton, Calif.	2.30
Cash 10 days	2.25
Ogden Portland Cement Co., Ogden, Utah	2.10
Southwestern Portland Cement Co., Victoria, Calif.	2.00
Colorado Portland Cement Co., Portland, Colo.	2.00
Cash 10 days	1.90
Riverside Portland Cement Co., Riverside, Calif.	2.00

The assumed costs are as follows:

Assumed cost of cement at mill	$2.00
Freight Riverside to Searchlight, 380 lbs. at 23¼ per hundred-weight	.88
Freight Riverside to dam site, 48 miles at 1½¢ per ton-mile.	.14
Storage and rehandling at mixing plant	.10
Total estimated cost in bins at plant	$3.12

Rock in temporary rock-fill cofferdam

Sourse of material, rock in the canyon walls at the cofferdam sites.

Quarrying and loading into skips on cars:	Per Cu. Yd.
Drilling and blasting	$0.45
Mucking, including derricks, shovels and hand	.70
Power	.05
Repairs and supplies	.10
Plant depreciation	.20
Total by solid measurement	$1.50

It is assumed that 1 cubic yard of solid rock will build 1¼ cubic yards of rock fill dropped from cableways (331/3 % voids).

	Per Cu. Yd.
The resulting cost of rock measures in the fill is	$1.00
Hauling to cableways	.15
Placing by cableways	.15
Total estimated cost in dam.	1.30

<u>Gravel and cobbles for concrete</u>

	Per cu.yd.
Steam shovel operation	$0.15
Hauling to screening plant	.15
Operation of screening plant	.35
Plant depreciation	.15
Hauling to mixing plant	.10
Total estimated cost in bins at mixing plant	$0.90

<u>Sand</u>

Assuming 50 percent natural sand mixed with 50 per cent crushed sand.

	Per Cu. Yd.
Natural sand same as gravel	$0.90
Crushed sand:	
Quarrying and loading rock at $1.50 per cu. yd., solid 35 % voids crushed	.97
Hauling to crushing plant	.15
Operation of crushing plant-	
Crushing	.25
Rolling	.40
Plant depreciation	.20
Transportation to mixing plant	.15
Total crushed sand	2.12
Total estimated cost mixed sand in bins at mixing plant	1.50

With reference to the following estimates it will be noted that the dost of a dam 550 feet high, with a reservoir capacity of 26,000,000 acre-feet, was increased from $41,500,000 to $76,600,000 by the special engineering board.

Three items entered into the increased cost of the dam.

(a) Increased spillway capacity over top of dam.

(b) Decreased allowable pressures on foundation from 40 tons to 30 tons per square foot.

(c) Increase in size of diversion works.

It is not assumed, however, that the board varied the unit costs materially.

Alternative Estimate

Diversion works	$4,331,550.00
Dam	19,409,460.00
Outlet works	4,540,356.00
Spillway	200,060.00
Railroad	1,840,810.00
Construction camp	500,000.00
Permanent improvements	60,000.00
Right of way	250,000.00
Total estimated field cost	$31,132,236.00
Administration, engineering and Construction 22½ %	7,004,753.00
Total estimated cost: Exclusive of power development and interest during const.	$38,136,989.00
ROUGHLY	$38,000,000.00

Preliminary estimate

Capacity 34,000,000 acre-feet. Max. water surface, el. 1,250 feet. Diversion tunnels discharging below power house

To be increased according to Colorado River board report.

Diversion works, same as for 20,000,000 acre-feet res.	$4,258,200
Foundation excavation 1,112,000 cu. yds.	1,840,500
Grouting and drainage	113,434
Conc. in body of dam 3,560,000 cu. yds. @ $7	24,920,000
Parapets, lighting, rimming roadway at abutments, railing, and extra conc. on abutments	134,415
Outlet conduits	2,097,556
Outlet works, trash racks	1,304,159
Valves and gates	2,082,140
Closing sluiceways	388,915
Track, crane, and elevators	250,193
Const. R.R. as per 20,000,000 acre-foot RES.	1,840,810
Const. camp	500,000
Permanent improvements	60,000
Right of way	500,000
Field cost.	$40,423,064
Administration, engineering and contingencies 22½%	9,077,706

Total, exclusive of interest during const.	$49,423,064
Roughly	$49,500,000

Capacity 10,000,000 acre-feet; maximum water surface, elev. 1,033 feet. Diversion tunnels discharging above power-house site.

Diversion works, total length of tunnel 10,500 ft.	$5,516,700
Foundation exc,,total 800,000 cu. yds.	1,198,500
Grouting and drainage.	71,594
Conc. in body of dam, 1,320,000 cu. yds.	9,240,000
Parapets, roadway, lighting,etc.	51,881
Outlet conduits	1,511,284
Trash racks	571,460
Valves and gates	1,905,696
Track,crane, & elevators	286,937
Construction railroad	1,826,646
Construction camp	500,000
Permanent improvements	75,000
Right of way	200,000
Total field cost.	22,955,698
Administration, Engineering and Contingencies 22½%	5,165,032
Total estimated cost	$28,120,730
Roughly	$28,000,000