Hoover Dam: Evolution of the Dam's Design

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ABSTRACT: Hoover Dam was a monumental accomplishment for its era which set new standards for feasibility studies, structural analysis and behavior, quality control during construction, and post-construction performance evaluations. One of the most important departures was the congressional mandate placed upon the U.S. Bureau of Reclamation (Reclamation) to employ an independent Colorado River Board to perform a detailed review of the agency's design and issue recommendations that significantly affected the project's eventual form and placement. Of its own accord Reclamation also employed an independent board of consultants which convened twice yearly several years prior to and during construction of the project, between 1928 and 1935. Reclamation also appointed a special board of consultants on mass concrete issues, which had never been previously convened. Many additional landmark studies were undertaken which shaped the future of dam building. Some of these included: the employment of terrestrial photogrammetry to map the dam site and validate material quantities; insitu instrumentation of the dam's concrete; and consensus surveys of all previous high dams to compare their physical, geologic, and hydrologic features with those proposed at Hoover Dam. The project was also unique because the federal government provided of all materials, except the concrete aggregate, to minimize risk of construction claims and delays.

EARLY INVESTIGATIONS

Background

Investigations along the lower Colorado River which eventually led to the construction of Hoover Dam were initiated by the U.S. Geological Survey's Hydrology Branch in 1901-02 when hydrologist J. B. Lippincott identified dozens of potential dam sites along the Colorado River, including the bedrock narrows in Black and Boulder Canyons. In 1904 the newly formed U.S. Reclamation Service began evaluating potential dam sites along the Colorado River. The seminal event that eventually led to the dam's construction began with the unintentional flooding of the

Imperial Valley that commenced in March 1905 when the headworks of a privately constructed diversion canal were overwhelmed along the lower Colorado River, about four miles south of the Mexico-California border (Davis, 1907; Grunsky, 1907; Sykes, 1937). The Southern Pacific Railroad attacked the break throughout 1906, eventually closing off the channel at midnight on February 10/11, 1907, after the Colorado River had discharged its waters into the enclosed basin for just under two years, creating the Salton Sea, with a surface area of 500 square miles (Orsi, 2005).

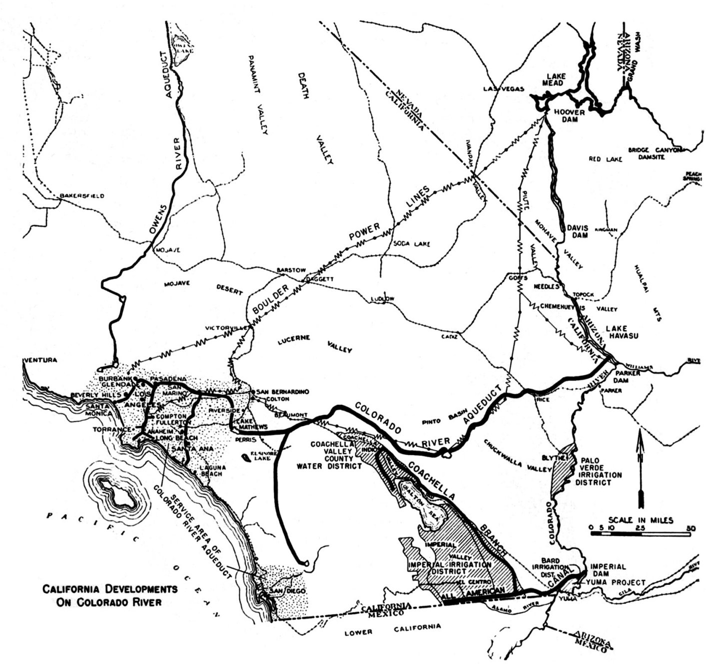
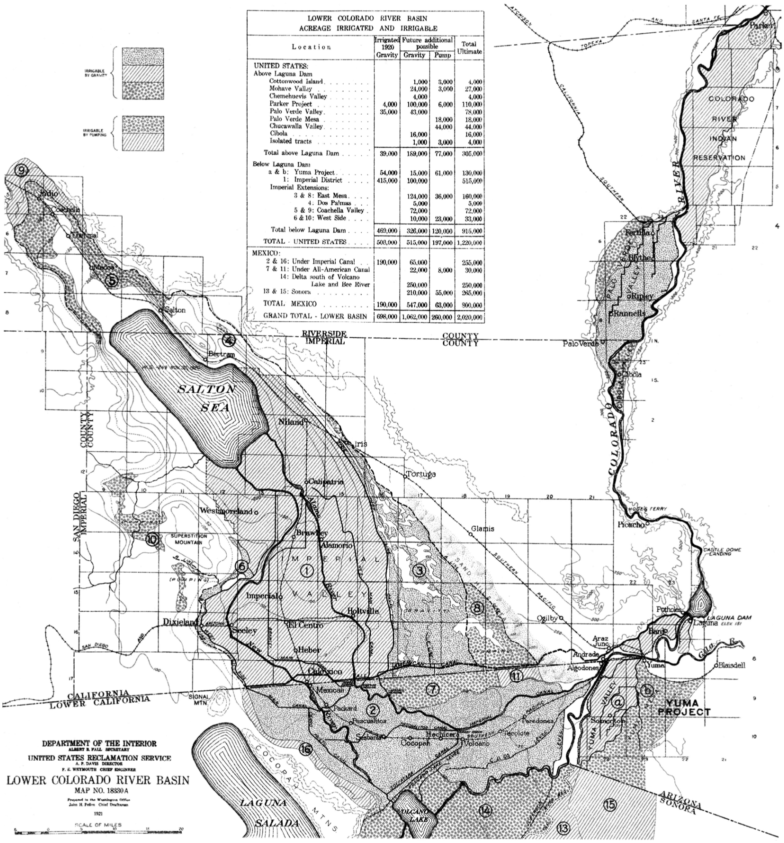


FIG. 1. Location of Hoover Dam, agricultural areas that received irrigation water from the dam, the Colorado River Aqueduct, and the Boulder Canyon Project transmission lines serving southern California (USBR).

The disastrous flooding of the Imperial Valley bankrupted the massive commercial scheme for reclaiming this inland basin of southeastern California. During the winter of 1909-10 the Colorado River once again jumped its banks, this time filling Volcano Lake south of the border and, once again, threatening crops in the Imperial Valley. Congress appropriated $1 million to provide additional flood control along the lower Colorado River.



LOWER COLORADO RIVER BASIN
ACREAGE IRRIGATED AND IRRIGABLE

Location	Irrigated 1920 Gravity	Future additional possible: Gravity	Future additional possible: Pump	Total Ultimate
UNITED STATES:				
Above Laguna Dam				
Cottonwood Island		1,000	3,000	4,000
Mohave Valley		24,000	3,000	27,000
Chemehuevis Valley		4,000		4,000
Parker Project	4,000	100,000	6,000	110,000
Palo Verde Valley	35,000	43,000		78,000
Palo Verde Mesa			18,000	18,000
Chucawalla Valley			44,000	44,000
Cibola		16,000		16,000
Isolated tracts		1,000	3,000	4,000
Total above Laguna Dam	39,000	189,000	77,000	305,000
Below Laguna Dam				
a & b: Yuma Project	54,000	15,000	61,000	130,000
1: Imperial District	415,000	100,000		515,000
Imperial Extensions:				
3 & 8: East Mesa		124,000	36,000	160,000
4: Dos Palmas		5,000		5,000
5 & 9: Coachella Valley		72,000		72,000
6 & 10: West Side		10,000	23,000	33,000
Total below Laguna Dam	469,000	326,000	120,000	915,000
TOTAL - UNITED STATES	508,000	515,000	197,000	1,220,000
MEXICO:				
2 & 16: Under Imperial Canal	190,000	65,000		255,000
7 & 11: Under All-American Canal		22,000	8,000	30,000
14: Delta south of Volcano Lake and Bee River		250,000		250,000
13 & 15: Sonora		210,000	55,000	265,000
TOTAL MEXICO	190,000	547,000	63,000	800,000
GRAND TOTAL - LOWER BASIN	698,000	1,062,000	260,000	2,020,000

FIG. 2. Map from the 1922 Fall-Davis report showing the non-alkali valleys within and adjacent to the Lower Colorado River Basin that could be irrigated by a dam in Boulder Canyon. These included the Palo Verde, Yuma, Mexicali, Imperial, and Coachella Valleys. At that time about 700,000 acres were under cultivation using irrigation over an area farmed by almost 100,000 people. The reservoir in Boulder Canyon had the potential to bring 2,020,000 acres under irrigation, including areas irrigated by gravity flow and those that would require pumping. (USBR)

This second brush with disaster ignited a growing desire for federal assistance, principally through the U.S. Reclamation Service, which had been established in 1902 to develop irrigation and water conservation projects across the semi-arid west. Political representatives from southern California began lobbying for a Reclamation scheme that would provide reliable sources of irrigation as well as dependable flood control.

In 1914 Congress authorized the Reclamation Service to make an inventory of possible dam sites and irrigation project that would benefit thereof in the Colorado River Basin. In January 1916 a fierce flood swept down the Gila River, inundating the Yuma Valley. This flood damage broadened support for a larger scheme that would address the needs of the lower Colorado River Basin as well as the Salton Sink, which drained the Mexicali, Imperial, and Coachella Valleys. In 1918 Reclamation Service Director and Chief Engineer Arthur Powell Davis proposed that the Colorado River be controlled by a dam of unprecedented height in the granite narrows of Boulder Canyon, east of Las Vegas Junction, which were summarized in the Whistler Report of March 1919. Surveys of the Colorado River by the Reclamation Service through contracts with the U.S. Geological Survey began in 1916 and continued through 1925.

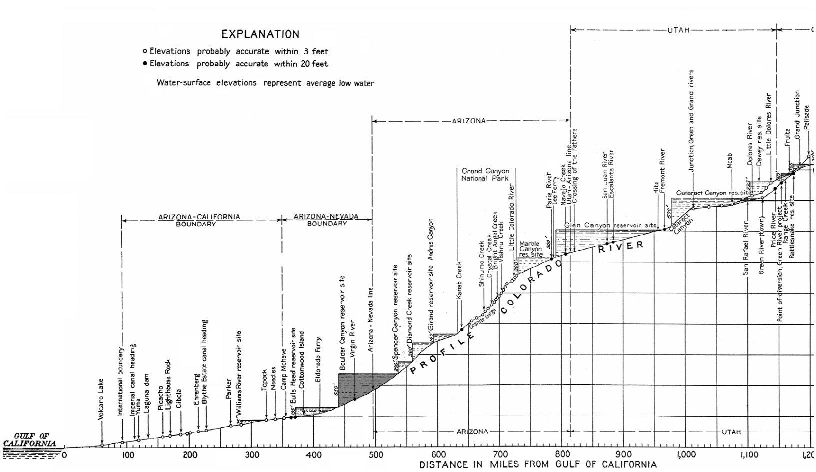


FIG. 3. Stair-stepping series of dams and reservoirs proposed along the Colorado River below its confluence with the Green River by the Reclamation Service in the 1922 Fall-Davis report. The shaded reservoir is the high dam in Boulder Canyon. Only four of the 12 dams shown here were eventually constructed: Hoover (1935), Parker (1938), Davis (1953), and Glen Canyon (1964).

The Imperial Valley interests and their southern California investors vigorously lobbied for the Reclamation Service's Boulder Canyon scheme, which envisioned a substantial reservoir that would provide flood control for the lower Colorado River Basin and supply irrigation water for the Palo Verde and Yuma Valleys of the Colorado River, as well as the Imperial and Coachella Valleys, west of the Colorado River (Figures. 1 and 2).

In 1919 the All-American Canal Board recommended construction of a canal on the American side of the international border that could convey water from the Colorado River to the Imperial Valley. This was intended to circumvent the loss of 50% of the water then being conveyed through the Mexicali Valley within Mexico before it reached the Imperial Valley. That same year Congressman Phil Swing introduced a bill seeking to authorize construction of the All-American Canal (Moeller, 1971).

The Reclamation Service was reorganized into the Bureau of Reclamation (Reclamation) in 1923 and the newly empowered agency began developing grandiose plans to construct a string of dams along the Grand, Green, and Colorado Rivers, from the headwaters down to the Gulf of California (Figure 3).

Boulder versus Black Canyons

Working for the Reclamation Service as a consulting engineer, former Los Angeles City Engineer Homer Hamlin supervised the first surveys of dam sites in Boulder Canyon and Black Canyon in March-April 1920. Educated as both a civil engineer and geologist, Hamlin was the first to designate the site in Black Canyon that was eventually chosen for Hoover Dam in 1928. He died in May 1920 while attending the congressional hearings accompanying passage of the Kinkaid Act which authorized the Secretary of the Interior to begin studying problems with flooding in Imperial Valley and report on possible solutions. At that time Reclamation envisioned the dam at the head of Boulder Canyon where granite outcrops would provide firm abutments (Figure 4) with a minimal cross section for either an earth-rockfill dam (Figure 5) or a masonry gravity-arch dam (Figure 6).

The Kinkaid Act provided funds for a 1-1/2-year-long feasibility study that examined the entire Colorado River watershed with specific emphasis on the development of irrigation of the Imperial Valley region. Reclamation crews began drilling the three principal dam sits in Boulder Canyon between January and May of 1921, under the direction of Walker R. Young. Their camps were destroyed that spring by unusually high flows, which reached about 210,000 cubic feet per second (cfs) in Boulder Canyon. Young marveled at how "*such a great volume of water*" could pass through such a dry thirsty desert without being harnessed for any "*worldly benefit to mankind*."

The Reclamation Service's preliminary design team was comprised of A.J. Wiley, James Munn, John L. "Jack" Savage, and Walker Young. They envisioned that water storage and flood control would originate from a massive dam as much as 740 ft high rising to an elevation of 1310 feet above sea level in Boulder Canyon, about 33 air miles due east of Las Vegas, Nevada.

The feasibility study was unveiled at a conference titled "*Construction of Boulder Dam*" convened in San Diego in November 1921. The Reclamation findings and the proceedings of the San Diego Conference were jointly published by the Government Printing Office in March 1922. It was thereafter referred to as the "Fall-Davis Report," because it was submitted by Albert B. Fall, Secretary of the Interior and

FIG 4. Between 1916 and 1929 most everyone assumed that the Granite Narrows shown here at the head of Boulder Canyon would be the logical site for a mighty dam controlling the lower Colorado River. This was how the scheme came to known as the Boulder Canyon Project (USBR).

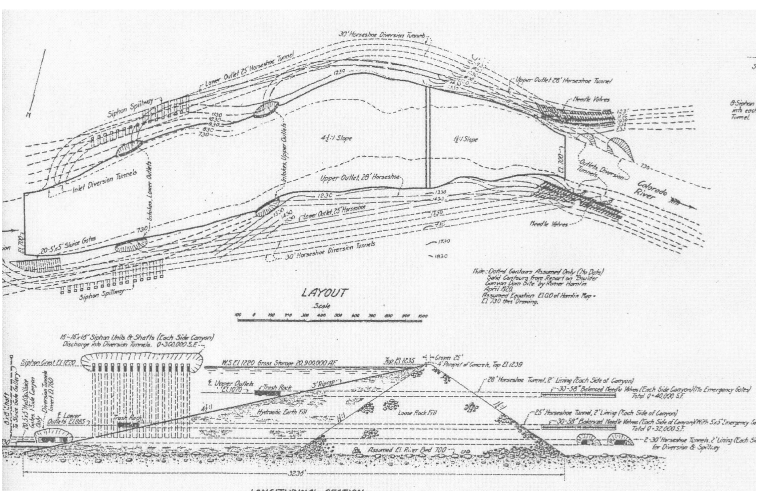


FIG. 5. Schematic plan and section view through a combination earth-rockfill embankment dam in Boulder Canyon, rising 535 feet above river level, as envisioned by the Reclamation Service in 1920. Note that the channel gravels would have been left in-place and the absence of seepage filters between the upstream hydraulic fill and the downstream rockfill (USBR).

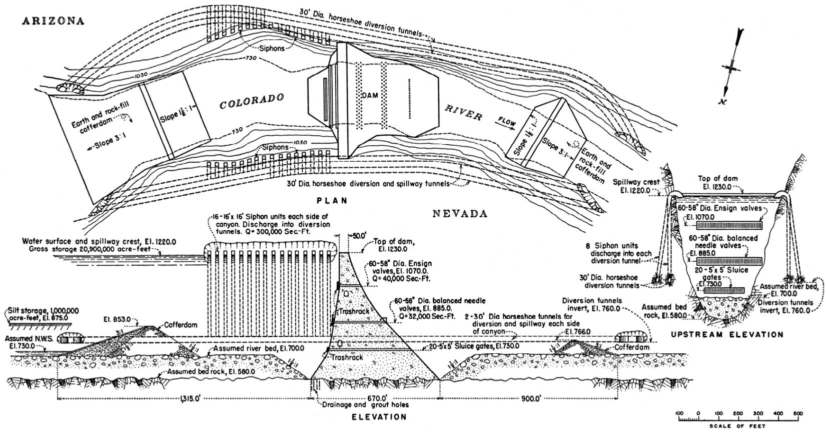


FIG. 6. Schematic plan and section view through a 650 feet high concrete gravity masonry dam in Boulder Canyon, 23 river miles upstream of Black Canyon, as envisioned in 1920. The additional height was necessary to remove all the channel gravels to secure a foundation capable of bearing 35 tons per square foot bearing pressure (Fall and Davis, 1922).

Arthur Powell Davis, Director of the Reclamation Service (USBR, 1922). The study examined four possible dam sites in Boulder Canyon with crest elevations between 1230 and 1310 feet. The largest alternative could store 34 million acre-feet of water, about 26 times the largest reservoir (California's Lake Spaulding) in the United States at the time. These developments were so ominous for the upper basin states that the Colorado Legislature voted to change the name of the Grand to the Colorado River in 1922, as a ploy to bolster their claim to the river's waters.

In January 1922 the Reclamation Service began examining alternative sites for a high dam about 23 miles downstream, in Black Canyon (Figure 7). A survey camp was established at the head of Black Canyon on a sandspit known as "Cape Horn," about 1-1/2 miles below the ferry operated by Murl Emery, who provided boat access to Black Canyon throughout the 1920s. This camp was vacated in May to avoid the summer heat, then re-occupied between September 1922 and late April 1923. During those encampments dozens of diamond drill holes were made from barges anchored to cables attached to the sheer canyon walls (Figure 8), in order to ascertain how much gravel filled the bedrock channel. To their dismay they learned that the channel gravels in Black Canyon extended to an average depth of 120 feet, because of a deeper "inner gorge" caved out of the andesite bedrock. Much of this inner gorge was filled with coarse angular boulders, from rockfalls and debris flows. The depth to granite bedrock in Boulder Canyon had varied from 25 to 150 ft, but the average depth at the favored dam site was only about 65 feet.

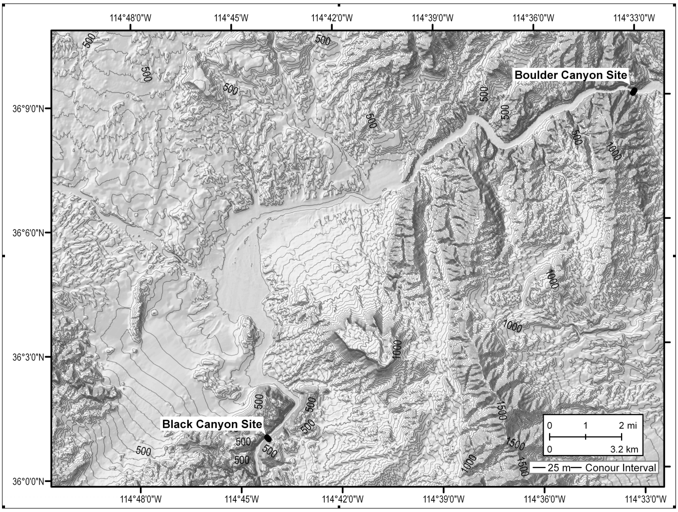


FIG. 7. The geomorphic settings of Boulder and Black Canyons were similar in that both of them were tectonically-controlled by geologically recent faulting, juxtaposing blocks of dramatically different age against one another. The dam sites downstream of Grand Canyon lie within bedrock narrows rapidly excavated by paleo outbreak floods which drained large bodies of water (data supplied by USBR staff).

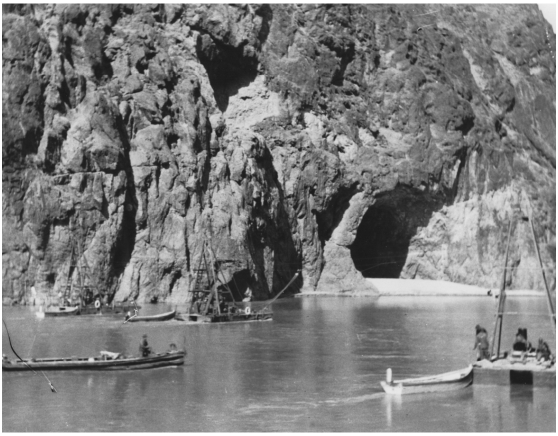


FIG 8. Drilling a line of three AX-size diamond drill holes in upper Black Canyon on October 31, 1922. This image shows Munns' Cave, developed within a basaltic intrusion of the Dam Breccia, which weathered more easily (USBR).

Colorado River Compact

While the Reclamation Service was studying dam sites in Boulder and Black Canyons, the Colorado Basin states began fearing that California would succeed in laying a legal claim to the river's waters by the doctrine of prior appropriation by swallowing the river's average annual flow for three years behind the massive dam being proposed in Boulder Canyon. Everyone recognized that it would be the kingpin structure of any water resources development with the seven-state basin.

In 1921 Congress authorized the seven basin states to enter into a compact for allocation of the river resources. The acrimonious negotiations were chaired by Commerce Secretary Herbert Hoover, who was appointed as the federal representative to the Colorado River Commission by President Harding. Hoover exercised his considerable political skills to force compromises that eventually resulted in the partitioning of the river's watershed into Upper and Lower Basins, with each basin having the right to develop half (7.5 million ac-ft) of the river's 15 million acre-feet average annual flow volume (this figure was overly optimistic, the average flow being closer to ~13.5 million ac-ft/yr after 1930). The upper basin supplied the majority of the water, but the greatest demand was in the lower basin, where the river flowed through an arid landscape.

The resulting agreement signed in November 1922 was the Colorado River Compact, which came to be known as the "Law of the River," upon which all subsequent water resources development in the western USA would be based (Anderson, 2004; Hobbs, 2008). The compact did not become law until June 1929, when 6 of the 7 basin states ratified the agreement, six months after passage of the Boulder Canyon Project Act (Arizona was forced to accede to the agreement after the Supreme Court dismissed their case in May 1931). The Compact has been amended on numerous occasions since that time, most notably, in 1931, 1944, 1948, 1956, 1964, 1968, 1970, 1973, and 1974.

1924 Weymouth Report

Surveys, foundation investigations, and preliminary structural and hydraulic analyses of the entire Colorado River Basin were carried out by the Reclamation Service throughout 1922-23 and were summarized in a massive document known as the "Weymouth Report" (Weymouth, 1924) because it was submitted by Reclamation Chief Engineer Frank E. Weymouth to the Secretary of the Interior in February 1924. The Weymouth Report contained a preliminary design for an arched concrete gravity dam in Black Canyon, which utilized concrete cofferdams that became integral portions of the completed dam, involving about 235,000 yd^3 of concrete. Outlet works were all run through the main dam structure, as shown in Figure 9.

This preliminary design was subsequently adopted as representative of the yardage and material costs for estimates so crucial to the project in securing approval and appropriations from Congress. The maximum bearing stress of 41.3 tons per square foot (tsf) beneath the upstream heel at maximum section was about twice as high as any dam then in existence or even contemplated. At this stage in the design process the concrete dam was also designed to survive flood overtopping 21 feet deep! This is why both ends of the dam crest were sloped 25 feet upward, to train the overflow over the center of the dam, sparing erosion of the rock abutments.

When the 1924 design was released the issue of generating hydroelectric power had not been decided, so was altogether omitted. All of the Bureau designs for this stage forward were made with an eye towards their being retrofitted to accommodate hydroelectric generation, even if these were not shown on the plans (Raphael, 1977).

Between the fall of 1922 and spring of 1928 California Congressman Phil Swing (representing the Imperial Valley) and Senator Hiram Johnson jointly sponsored Boulder Canyon Project bills at each congressional session (twice per calendar year), but without success (Moeller, 1971). The proposed project cost of $125 million was the largest federal appropriation ever approved up to that time and it was difficult to marshal sufficient political support by the other 47 states, being viewed as a project seeking to benefit one particular area of southeastern California.

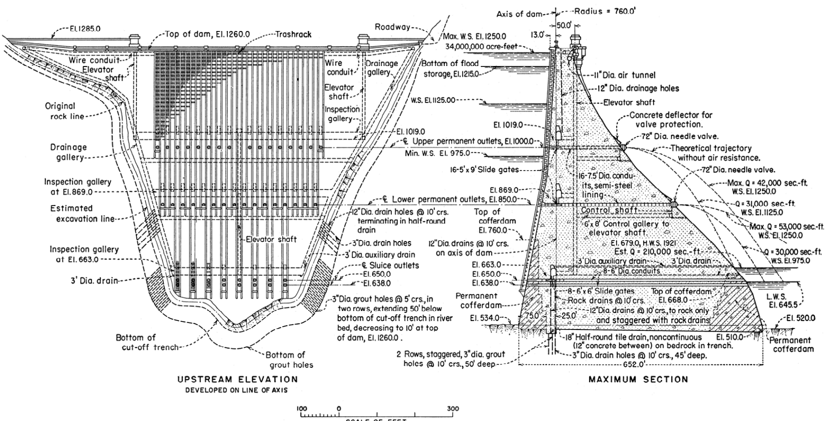


FIG. 9. Plan for a 740 ft high arched concrete dam in Black Canyon from the Weymouth Report in 1924. This design assumed a crest elevation of 1260 ft, 28 ft higher than Hoover Dam. Note the dipped crest to accommodate overflowage at left and the hachured zones in the elevation at right, which were concrete cofferdams wrapped into the dam's heel and toe. (USBR)

THE BOULDER CANYON PROJECT

Congress Debates the Boulder Canyon Project Act

The California delegation labored diligently over the next six years. Spurred by a water crisis Los Angeles entered the fray in October 1923 after its voters approved a bond measure to perform feasibility studies for a Colorado River Aqueduct. In July 1924 Los Angeles filed for rights to one million ac-ft of Colorado River water.

In September 1924 ranchers in the Imperial Valley watched their crops wither as near-record low flows of the Colorado River precluded the necessary diversions for irrigation. The following month President Coolidge announced his support of the Boulder Canyon Project during his election campaign. In April 1925 Los Angeles concluded that a 268-mile-long Colorado River Aqueduct was technically feasible. That fall voters approved a $2 million construction bond for a new aqueduct. In April 1926 San Diego filed for 110,000 ac-ft per year of Colorado River water.

That same month (April 1926) Reclamation Commissioner Elwood Mead issued a statement asserting that the unprecedented price tag associated with the proposed Boulder Canyon Project could be financed through a bond issue that would not interfere with the operations of the federal government, but would generate income through the sale of electricity. These funds would pay the interest on all the monies advanced by the government for construction, and provide a sinking fund for repayment of project costs. This would eventually become the model for countless Reclamation projects for years to come.

Each year the proposal evolved into a larger and more multi-faceted project, providing irrigation to an enlarged area while providing flood control and electricity, but the direct benefits were still limited to the Colorado River Valley and southern California, and were vigorously opposed by Arizona and Utah.

In March 1927 Interior Secretary Hubert Work appointed a Board of Advisors to make an extended survey of the Colorado River watershed to study the problems that might be associated with its development, posing five specific questions that the administration wanted answered because so many criticisms and alternative schemes were being proposed. This board was chaired by former Interior Secretary James R. Garfield, Wyoming Governor F. C. Emerson, former Nevada Governor and State Engineer James G. Scrugham, Colorado Senator Charles W. Waterman, and the board's secretary, Professor W.F. Durand of Stanford University. Durand's name had been suggested to Secretary Work by Stanford President Ray Lyman Wilbur (who succeeded Work as Interior Secretary in March 1929, when Herbert Hoover became President), because he had served on the Consulting Board of Engineers appointed to review the expansive system of aqueducts, reservoirs, and hydroelectric powerplants constructed by the City of Los Angeles from 1906 onward, and had authored an objective article about the various engineering problems posed by development of the lower Colorado River (Durand, 1925; 1953).

The Board of Advisors made a reconnaissance of the Colorado River between Lee's Ferry and the Gulf of California, with particular attention to the potential dam sites in Boulder and Black Canyons (Emerson et al., 1928). Each of the five members wrote their own separate reports, which were compiled together and published in January 1928. Durand's portion was the most comprehensive, occupying 56 of the report's 70 pages.

The political situation changed with the record flooding that struck the lower Mississippi River Valley in the spring and summer of 1927, which wrecked havoc on all the states adjoining the great watercourse, which drains 41% of the continental United States. Commerce Secretary Hoover provided stirring testimony before the House Committee on Irrigation during the 69th Congress (fall 1927) urging them to approve the Boulder Canyon Project (Committee of the Irrigation Division, 1929). The

1927 flood enabled Congressman Swing to forge new alliances and political partnerships with his Midwestern and Southern colleagues, and he brought sweeping support from the California delegation for the precedent-setting federal Flood Control Act approved in May 1928 by the 70th Congress (Moeller, 1971, Nadeau, 1974).

With these new political allies, Swing's Boulder Canyon Project Act bill passed through the House on May 15th, but failed to make it through the Senate before the session concluded. It's likely passage was temporarily derailed by the collapse of the St. Francis Dam on March 12-13, 1928, which killed upwards of 435+ people, making it worst American civil engineering failure in the 20th Century (Rogers, 1995). St. Francis Dam had been built in 1924-26 by the Los Angeles Department of Water & Power, one of the most vociferous proponents of the Boulder Canyon Project. The Arizona and Utah delegations were quick to point out that St. Francis was the same sort of concrete gravity arch dam being proposed at Boulder Canyon (although much smaller, about 200 ft high). Boulder Canyon Dam would be 3-1/2 times higher and would contain 26 times more concrete than the ill-fated St. Francis Dam. The senators from Utah and Arizona succeeded in filibustering passage and the question of safety had to be answered to most everyone's satisfaction before the Senate would approve the measure.

Colorado River (Siebert) Board

As a compromise measure Congress passed House Resolution 5773/Senate Resolution 65 on May 29, 1928, directing Interior Secretary Ray Lyman Wilbur to appoint "a board of five eminent engineers and geologists," of which at least one was to be an Army Engineer, to examine the proposed sites for the Boulder Canyon Dam, and report on "the safety, economic, and engineering feasibility, and the adequacy of the proposed structure and incidental works," such as all the electrical generating equipment, the structures associated thereof, and the proposed scheme for selling electrical power to pay off the project with interest over a term of 50 years (a major criticism of the proposed project by some members of Congress).

The review also included a critical examination of "appurtenant structures," such as the Imperial Dam about 300 miles downstream of Hoover (completed in 1940), the All American Canal (completed in 1940) to be built along the international boundary, and the 123-mile- long Coachella Canal, north of the Salton Sea (completed in 1948). They were given exactly six months to perform these reviews, with a written report due no later than December 1, 1928.

This panel was officially named the Colorado River Board (CRB), but was referred to at the time as the "Siebert Board," because it was chaired by retired Corps of Engineers Major General William L. Siebert, famous for his role in constructing the Panama Canal and as the first chief of the Army's Chemical Warfare Branch during the First World War (Clark, 1930). Board member Robert W. Ridgway had worked on New York's New Croton and Catskill Aqueducts and as chief engineer of New York's Board of Transportation. He had recently served as the president of ASCE in 1925. The other engineer was Professor Daniel W. Mead of the University of Wisconsin, a respected expert in hydraulics who had considerable experience with dams. He subsequently served as ASCE president in 1936.

FIG. 10. The 'Siebert Board' appointed by Congressional Resolution in May 1928 to review the Bureau of Reclamation design of Boulder Canyon Dam. From left: William L. Siebert, Elwood Mead, Warren J. Mead, Charles Berkey, Daniel W. Mead, and Robert Ridgway. The three Meads were unrelated. (USBR)

The CRB was unusual in that it also included two geologists, because the St. Francis Dam failure had been blamed on faulty foundation conditions, not on the engineering of the structure itself (Committee Report for the State, 1928). The two geologists were Columbia University Geology Professor Charles P. Berkey and University of Wisconsin Professor Warren J. Mead.

Reclamation Commissioner Dr. Elwood Mead served as the board's technical advisor and principal liaison with the Bureau of Reclamation. The board members are shown in Figure 10. They were given six months to review Reclamation's designs and make recommendations on where to site the great dam along the Colorado River.

On December 3, 1928 The Colorado River Board issued its 15-page report (CRB, 1928). Under the section titled "Review of Plans and Estimates; The Dam and Incidental Works," the Board's initial comments were blunt and succinct:

> *The board is of the opinion that it is feasible from an engineering standpoint to build a dam across the Colorado River at Black Canyon that will safely impound water to an elevation of 580 feet above low water…*
>
> *The proposed dam would be by far the highest yet constructed and would impound 26,000,000 acre feet of water. If it should fail, the flood created would probably destroy Needles, Topock, Parker, Blythe, Yuma, and permanently destroy the levees of the Imperial District, creating a channel into the Salton Sea which would probably be so deep that it would be impracticable to reestablish the Colorado River in its normal course. To avoid such possibilities the proposed dam should be constructed on conservative if not ultra-conservative lines.*

The Board felt that Reclamation should place the dam in upper Black Canyon, not in Boulder Canyon. The reasons given were: 1) superior geology; 2) narrower canyon, steeper walls; 3) site more accessible from existing rail lines and highways near Las Vegas; 4) river channel not as deep, less volume of excavation to competent rock [even though deeper]; 5) a dam of equal height would cost less and store greater volume of water than at Boulder Canyon; 6) rock less jointed; 7) few open fractures; 8) rock appears less pervious than at Boulder Canyon site; and, 9) rock easier to drill and excavate than at Boulder Canyon (one deep hole was advanced to a depth of 557 feet below the low water surface at the Black Canyon site which only encountered andesite). The Board also pointed out that the Black Canyon site was also much more favorably situated for the development of rail and highway connections to the job site, which were crucial to the project's estimated costs, as the government would be supplying all of the construction materials, with the exception of the concrete aggregate.

The Board also recommended a series of important changes in the dam's design and construction. They recommended that the Bureau of Reclamation reduce foundation contact pressure from 40 to 30 tsf; doubling the design capacity of river bypass diversion tunnels from 100,000 cfs to at least 200,000 cfs (25 yr flood); increasing the spillway capacity from 110,000 cfs to something greater than 160,000 cfs; and increasing the volume of flood storage to 9.5 million ac-ft; increasing the reservoir's maximum storage from 26 million to 30.5 million acre-feet (an increase of 31%). They also felt that the depth of water behind the upper cofferdam should be limited to no more than 55 ft (elevation 700 ft). The Board also affirmed their confidence that an All-American Canal could be built north of the Mexican border and that the electricity generated by dam could be absorbed by the expanding market of greater Los Angeles. The proposed changes increased the estimated cost of the project by 32%, from $125 million to $165 million.

Passage of the Boulder Canyon Project Act

The Boulder Canyon Project name was retained because Swing and Johnson had been trying to push the bill through Congress every year since 1922. The favorable and thorough report by the CRB resulted in rapid approval of the fourth version of the Boulder Canyon Project Act by a vote of 63-11 in the Senate on December 14th, 1928. The House approved a similar version, but with specific amendments requested by Utah on December 18th, and President Coolidge approved the act on December 21st. It was the largest government appropriation ever approved up to that point and its successful prosecution initiated a string of significant appropriations to the Bureau of Reclamation for western water projects from the general funds of the United States over the succeeding three decades.

Appropriations were delayed until a hard fought debate about the pros and cons of publicly generated versus privately generated electrical power, and setting the prices the Bureau of Reclamation would charge for water and electricity generated by the project. These agreements and the power allotments were not agreed upon until late March 1930. The sale of electricity would be the impetus for economic justification of every major Reclamation project (for dams over 200 feet high) for the next half century. The first appropriation of $10.66 million was authorized on July 3, 1930, which was earmarked for the construction of the government rail spurs and highways to the dam site.

A contract was also let for detailed surveying of the Black Canyon dam site and surrounding area, at a scale of 50 ft to an inch with 5-ft contour intervals. Final surveying of dam site continued throughout 1929-30 and into the spring of 1931, when Claude Birdseye (Chief Geographer of the USGS) and Heinz Gruner used terrestrial photogrammetry to construct a detailed topographic map of the dam site in Black Canyon, which was of unprecedented severity of slope (Gruner, 1972). They took stereopair photographs from ground stations tied in by triangulation. The Boulder City town site was laid out by Brock & Weymouth of Philadelphia.

Walker R. Young was appointed to be the Construction Engineer for the Bureau of Reclamation and he would remain on-site as the senor government representative throughout the project. Young was a logical choice, as he had been one of the principal authors of the 1922 Fall-Davis Report and he had supervised the Bureau's surveys and subsurface explorations carried out in Boulder and Black Canyons since 1921.

PERFECTING THE DAM'S DESIGN

Responses to expert advice (1928-31)

The Colorado River Board (CRB) continued to review the various design amendments made by Reclamation before the project went to construction. In April 1930 the CRB recommended that Reclamation increase the height of Boulder Dam by 25 ft, from 557 to 582 feet, with crest elevation increasing from 1207 to 1232 ft. The purpose was to provide 4,500,000 ac-ft of additional flood storage with a minimum freeboard of three feet, increasing the maximum seasonal flood storage to 9,500,000 ac-ft. This decision was influenced in great part by the 1884 flood, a recurrence of which would require Hoover Dam to spill 160,000 cfs downstream, even with maximum flood storage (ENR, 1930). The CRB recognized that this capacity should likely diminish to 4,000,000 ac-ft by 1988, if or when additional reservoirs were emplaced upstream. This decision increased the combined reservoir storage capacity to 30.5 million ac-ft.

The board also warned that flows over 75,000 cfs could cause considerable damage to training and control structures downstream. They recommended that the dam's radius of curvature be reduced from 740 to just 505 ft, and that Reclamation construct physical models of the arched gravity dam to test the new theories of stress distribution using the Trial Load Method of analysis, which Reclamation was using (USBR, 1940).

The board felt that the downstream water demand could be met with a minimum discharge of 8,355 cfs at the dam, apportioned as follows: 55 cfs to southern Nevada; irrigation needs between Black Canyon and Yuma 2,800 cfs; Los Angeles Aqueduct 1,500 cfs; All American Canal 2,000 cfs; and base flow into Mexico 2,000 cfs. The entire system could be self sustaining in terms of power demands and regulation by constructing additional dams with hydroelectric generation at Parker (Parker Dam) and Bulls Head (Davis Dam).

On September 17, 1930, Herbert Hoover's Secretary of the Interior Ray Lyman Wilbur, went to southern Nevada to presides over the project's initial construction at what came to be known as the "Silver Spur" ceremony, because he drove a silver spike at the foot of the Union Pacific Railroad spur that would provide a strategic connection with the dam site (Stevens, 1988). In his dedication speech, Wilbur announced that the dam would be named Hoover Dam, in honor of President Herbert Hoover.

In accordance with the recommendations of their Colorado River Board, in December 1930 the Bureau of Reclamation issued Specifications No. 519, which fixed the dam's crest elevation at 1232 feet, with the maximum reservoir level approximately 586 feet above expected tailwater elevation at the powerhouses. The dam's crest would be about 730 feet above the lowest point in the foundation (this figure turned out to be 726.4 ft). They abandoned plans for glory hole inlet spillways and chose to employ side channel spillways on either abutment (above the outboard diversion tunnels), controlled by 50 ft square Stoney Gates, and four dual bank valve houses on opposing canyon walls, one above another.

Reclamation's Consulting Boards

On January 10, 1931 Reclamation solicited bids for the construction of Hoover Dam and Power Plant. The Bureau also appointed a special Concrete Research Board in November 1930, which began meeting in January 1931. This board was comprised of P.H. Bares, W.K. Hatt, H.J. Gilkey, F.R. McMillan, and R.E. Davis. On March 11th (the same day the construction contract was awarded to Six Companies, Inc.) the Bureau of Reclamation's own Board of Consulting Engineers (BCE) approved its plans and specifications for Hoover Dam. The original board was comprised of: David C. Henny of Portland, Louis C. Hill of Los Angeles, and A. J. Wiley of Boise. All three were former Reclamation engineers actively engaged in private consulting. A.J. Wiley passed away on October 8, 1931 and Dr. William F. Durand of Stanford University was appointed to fill his slot. Reclamation's BCE remained in-place for approximately 10 years thereafter, providing peer review of subsequent projects, including Grand Coulee, Shasta, and Friant Dams, as well as many smaller projects in the American Southwest (subsequent members included geologist Charles P. Berkey, and engineers Joseph Jacobs and C. H. Paul).

ASSUMING RISKS TO REDUCE PROJECT COSTS

Hoover Dam was the first federal project to assume a broad spectrum of risks that had previously been the burden of contractors. These factors, known in the construction industry as "contingencies," were the principal unknowns that drove bid prices up or down. Many concerns were voiced about problems that would be associated with a project of such unprecedented size and duration (up to that point in time most dam construction projects had only taken between one and three years to construct). Risk of flooding might cause great uncertainties, while unforeseen changes in materials and labor costs during the unusually long term of the contract (seven years) was a very real proposition during the Great Depression, which had witnessed unprecedented fluctuations in materials costs.

The government's solution to these concerns was innovative and unprecedented:

1. The bid bond and construction surety to be advanced by the winning bidder were fixed at the moderate amounts of $2 million and $5 million, respectively. An incredible bargain for a $50 million project, but it was difficult for anyone to come up with $5 million dollars in early 1931.
2. Once the cofferdams were accepted by Reclamation, it accepted responsibility for flood damage to all property, except the contractor's plants.
3. Military veterans and U.S. citizens would have preference to being employed on the project.
4. Government was to supply ALL materials, except the concrete aggregate.

The federal government also contracted directly to provide:

1. Construction of a Union Pacific Railroad spur line 22.6 miles long from Las Vegas to Boulder City, then the U.S. Construction Railroad to the rim of Black Canyon overlooking the Nevada powerhouse, at an elevation just 138 feet above the dam crest (elevation 1370 feet).
2. Contracts with Southern Sierra Power Co., to deliver electricity to the dam site no later than June 25, 1931 via a 222-mile-long power transmission line from San Bernardino, California.
3. Awarded a contract to construct a paved highway to the dam site from Boulder City.
4. Awarded separate contacts for construction of Boulder City, to be administered by the Department of Interior.

Government Administration of Housing

It was initially envisioned that Six Companies would house 2,000 workers and their families in a temporary work camp that the government named "Boulder City," nine miles from the dam site. This number eventually swelled to 5,200, although the average number was closer to 3,500. Six Companies began by constructing wooden dormitories for 500 workers at a "river camp" at the head of Black Canyon, on the Nevada side of the river. Additional "family housing" was badly needed to replace the derelict abodes that characterized the unofficial settlement of "Ragtown," along the Colorado River in this same area. The town that became Boulder City was built in just 15 months to house 5,000 government employees and contract workers and their families. Boulder City remained a federal reservation under control of the U.S. Department of Interior until 1959, when it became self-governing. No alcohol was sold within the city until 1969 and no gambling has ever been allowed within the city limits.

HYDRAULICS AND HYDROLOGY ISSUES

Estimating Flood Frequencies with a Paucity of Hydrologic Data

Prior to the construction of federal dams and reservoirs, the Colorado was a river of extremes like no other in the United States. The flood-of-record along the lower Colorado River was 384,000 cfs measured at Topock, Arizona in February 1884, and the historic low flow about 500 cfs in 1911 at Lava Falls, in the western Grand Canyon. The 2.5 yr flood was believed to be about 120,000 cfs, while scour lines in Boulder Canyon suggest floods as great as ~500,000 cfs in prehistoric past.

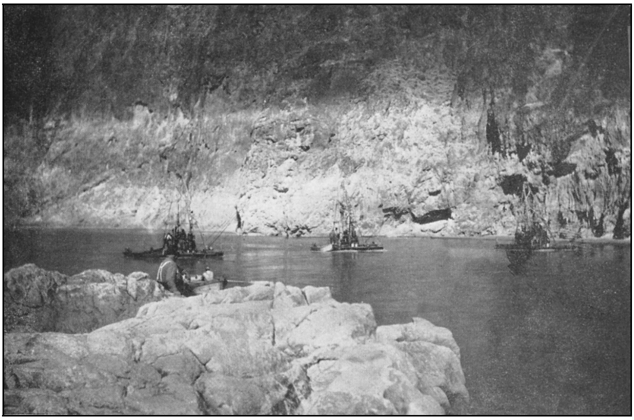


FIG. 11. The Colorado River Board exercised considerable alarm upon their observance of high water marks 80 feet above low water level at the Boulder Canyon dam site (shown above behind rafts supporting three exploratory drilling rigs). This site was near the head of Boulder Canyon. These water marks dropped to about 40 feet above low water by the time the river passed out of the mouth of Boulder Canyon, about five miles downstream.

Table 1. Probable Frequency of Flood Discharges at Black Canyon Assumed in 1930

Discharge, cubic feet/second	Frequency With Which Discharge May be Equaled or Exceeded
130,000	Once in 5 years
160,000	Once in 10 years
190,000	Once in 20 years
230,000	Once in 50 years
260,000	Once in 100 years

320,000 cfs Once in 500 years
450,000 cfs Once in 10,000 years

When Reclamation revised their designs in 1928 the available data consisted of just 26 years of flow volumes recorded at Yuma, Arizona, 312 river miles downstream of Hoover Dam. Flow heights had been recorded at Yuma since 1878, but no velocity measurements had been recorded until 1902. Reclamation had only six years of flow measurements at Lee's Ferry, (346.6 river miles upstream), where a gauging station had been established in 1922; five years of flow volumes at Bright Angel (260 miles upstream, in Grand Canyon), and five years of reliable data at Topock (111 miles downstream). The largest dam in history was being sized with less than 10 years of reliable flow records, a very low figure considering the magnitude of the project.

During their review in 1928 the CRB exercised concern about how large the maximum probable flood might be after observing high water marks 80 feet above low water level at the head of Boulder Canyon (Figure 11). They concluded that a flow of 320,000 cfs every 500 years and 450,000 cfs every 10,000 years were altogether likely, and the frequencies shown in Table 1 were adopted for the project in 1930.

The board recommended that Reclamation increase the spillway capacity from 110,000 cfs to something greater than 160,000 cfs. At that time (1929) the general assumption employed by most designers was to build dams strong enough to withstand *double the largest flood that ever been observed*. The highest recorded flow Reclamation had to work with was 200,000 cfs at Yuma in 1902 (they were not apparently aware of, or did not trust, the estimate of 384,000 cfs at Topock, Arizona in January-February 1884 by W. A. Drake, Chief Engineer of the Atlantic & Pacific Railroad), so they doubled this figure and assumed this to be a conservative estimate (Debler, 1930).

After publication of Gumbal's flood probability triparte diagram in 1941 Reclamation appears to have used that plot to justify their estimates. By using Yuma gage flows for the period 1878-1929 (51 yrs) they used their design flood of 400,000 cfs to back out a recurrence frequency of once-every-3,950 years (Rogers, 2008).

In 1990 Reclamation retained Morrison-Knudsen Engineers (1990) to perform meteorological studies of the Colorado River Basin above Hoover Dam. Just prior to letting this contract the Bureau of Reclamation and the U.S. Geological Survey performed a paleoflood analysis of the 1884 high water marks in the Black Canyon, using flood observations at Lees Ferry; and gage observations at Grand Junction, Colorado and Yuma, Arizona. They estimated that this flood reached a peak flow of about 300,000 cfs in Black Canyon (Hoover Dam) in July 1884 (Swain, 2008).

Estimates of Annual Flow and Flood Storage

In their November 1928 report the Colorado River Board expressed these concerns:

> "*The information on which this flow has been estimated is inadequate to furnish an accurate or sound estimate on which to base an important project without using factors of safety sufficiently great to make such estimate conservative and safe.*"

The Board also noted problems with using Yuma gage readings taken between 1902 and 1922, bereft of reliable volume calculations. Reclamation had extrapolated these data to estimate the average annual flow volume of 16,200,000 ac-ft at the dam site (Debler, 1930). USGS estimated an average annual flow of just 13,600,000 ac-ft for the period 1878-1922, a much longer, and, therefore, more reliable sampling. The Board then made their own estimates of the average annual flow, based on the available data. They concluded that for the period 1887-1904 the average annual flow may only have been 9,360,000 ac-ft/yr, not the 15,000,000 ac-ft/yr assumed in the Colorado River Compact. 75 years later the Board's skepticism was somewhat justified insofar that the actual annual runoff since 1930 has been about 13,500,000 ac-ft/yr (Anderson, 2004).

The Board also recommended that the volume of flood storage of the Boulder Canyon Project reservoir be increased to 9.5 million acre-feet of the total reservoir capacity of 30.5 million acre-feet, a startling 31% of the total storage. This was an unprecedented conservative figure for that time, which drew considerable ire on the part of some Reclamation engineers.

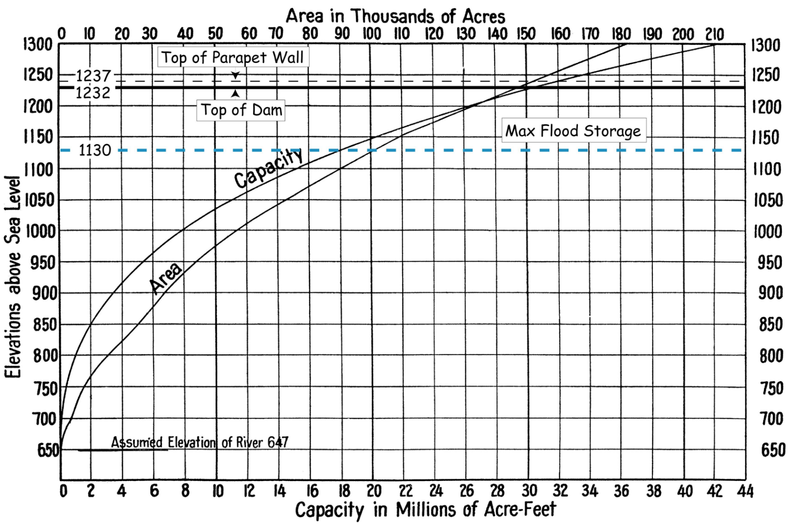


FIG. 12. Reservoir area and capacity curves for a dam in upper Black Canyon, prepared by the Bureau of Reclamation in 1928. The respective levels for Hoover Dam, as constructed, are indicted (USBR).

In April 1930 the decision was made to raise the dam 25 feet to increase flood storage (Debler, 1930). The dam's height was increased to 730 ft above the assumed deepest point of the foundation, with a crest elevation of 1232 ft. This was intended to provide 30,500,000 ac-ft of total reservoir storage, equal to two years cumulative flow of the Colorado River. The reservoir area and capacity curves constructed by the Bureau of Reclamation in 1928 are presented in Figure 12. Of that total, 9,500,000 ac-ft of seasonal flood storage between April 1st and September 1st of each year was intended to accommodate spring runoff from the mountainous interior (in accordance with the recommendations of the Colorado River Board). June and July typically see the greatest volume of runoff, while Reclamation normally targets July 1st as the optimal date for "topping off" their storage reservoirs. Over the years the flood storage has gradually been reduced to just 1,500,000 ac-ft between January 1st and August 31st as more reservoirs have been completed upstream of Lake Mead (Swain, 2008).

In 1930 Reclamation assumed a design flood inflow of 300,000 cfs with a 60-day volume of 23,200,000 ac-ft (Debler, 1930). In 1990 Morrison-Knudsen Engineers (1990) re-examined the hydrologic models for the Colorado River Basin, utilizing a much greater volume of data than was available in 1930, along with considerations of the various reservoirs that now dot the basin. It assumes that most critical situation could occur in August, when a Pine and Cedar Mountains centered storm follows a San Juan Mountains centered storm by seven days. This storm sequence would produce a probable maximum flood (PMF) at Hoover Dam with a peak discharge of 1,130,000 cfs and a 60-day volume of 9,300,000 ac-ft. This peak discharge is nearly four times that assumed in 1930, with a flood volume of about 40% that estimated in 1930 (Swain, 2008).

Spillway Design Evolution

The spillways at Hoover Dam went through a remarkable design metamorphosis. In 1920 the Reclamation Service envisioned the use of 32 siphon spillways, each 16 x 16 ft, splitting these with 16 on each side of the canyon, each group connecting to two 30-foot-diameter horseshoe-shaped diversion tunnels. Their aggregate capacity was 300,000 cfs.

The 1924 Weymouth Report presented conceptual designs for a concrete gravity arch dam (Figure 9) capable of passing 80,000 cfs through interior outlet works, with any excess passing over the dam's crest to a maximum depth of 21 ft. The rockfill dam alternative (Figure 5) envisioned seven drum gates on the Arizona abutment connected to seven tunnels along with an excavated channel that conveyed spillage back into the Colorado River about 1.5 miles downstream. The bypass flow capacity of this scheme was between 180,000 and 300,000 cfs.

Between 1924 and 1928 there was a turnover in staff at Reclamation because of political battles over funding and Chief Engineer Frank Weymouth and a number of his key subordinates, such as Julian Hinds, resigned. The new staff began concentrating on how large bypass flows could be safely passed around a dam of unprecedented height. They chose massive glory hole spillways similar to that which was then being constructed at Owyhee Dam in Idaho (which employed a 60-foot diameter glory hole spillway necking down to 28 ft. With a design capacity of 41,730 cfs, it was the largest of its kind till 1957, when a slightly larger version of the same design was built for California's Monticello Dam). Massive 50-foot-diameter shafts would be connected to two of the four the diversion tunnels, as shown in Figure 13.

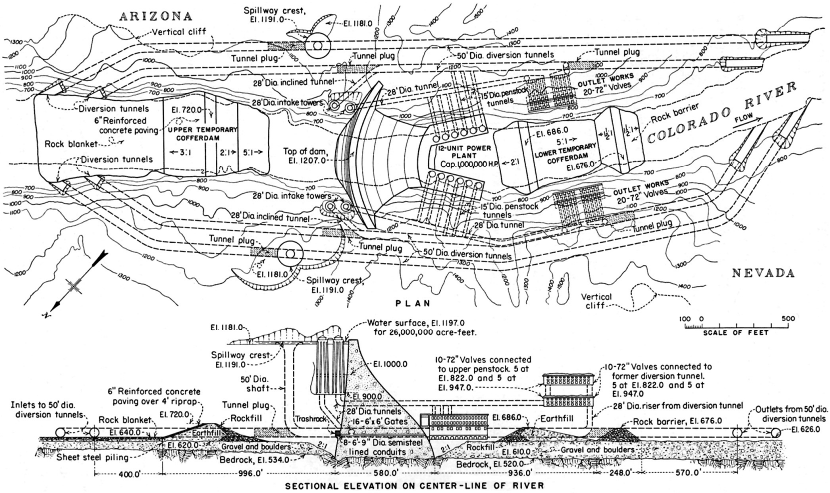


FIG. 13. 1928 design for Boulder Dam at the Black Canyon site, which employed 50-foot-diameter glory hole spillway inlets and a dam with a radius of curvature of 740 ft. This was the design reviewed by the Colorado River Board, which was extensively revised before actual construction began in 1931.

These could accommodate spillage of up to 200,000 cfs. The problem with these was the flow velocities approached 180 ft/sec (fps), far above any other glory hole spillways then in existence. Reclamation engineers brought this figure down to 100 fps by employing risers at the downstream end of the diversion tunnels, but this greatly reduced the outflow capacity.

Reclamation undertook extensive 1:60 scale model studies with the University of Colorado to examine the velocity issues and ended up concluding (erroneously) that smooth high strength concrete could be employed at the elbow transitions between the glory hole shaft and the diversion tunnel to avoid any problems with "erosive action of water" (cavitation). The crest of the spillway was surrounded by an 11-foot-high Ogee crested weir, 234 ft in diameter, in the familiar morning glory shape. Further model studies which included the impacts of the sloping canyon walls showed that the massive glory hole spillways would fill asymmetrically, causing undesirable suction and pulsation when the depth of water approached design levels. For these reasons it was decided to employ open side-channel spillways.

In the fall of 1930 Reclamation altered the spillway design to employ massive side channel, or trough, spillways on either abutment, connected to the two outboard diversion tunnels (Figure 14). These spillways were to be controlled by using 50 x 50 ft steel Stoney Gates at either end (entry and point of discharge), similar to those seen today at the mouths of the two inboard diversion tunnels. The Stoney Gates at the upstream entries allowed the reservoir to be controlled between elevations of 1173.6 and 1223.6 ft, and could theoretically spill 270,000 cfs at a maximum reservoir level of 1232 ft (the top of the dam, without considering the parapet wall, at el. 1237 ft). This is the spillway design that was included in the original plans and specifications bid in early 1931.

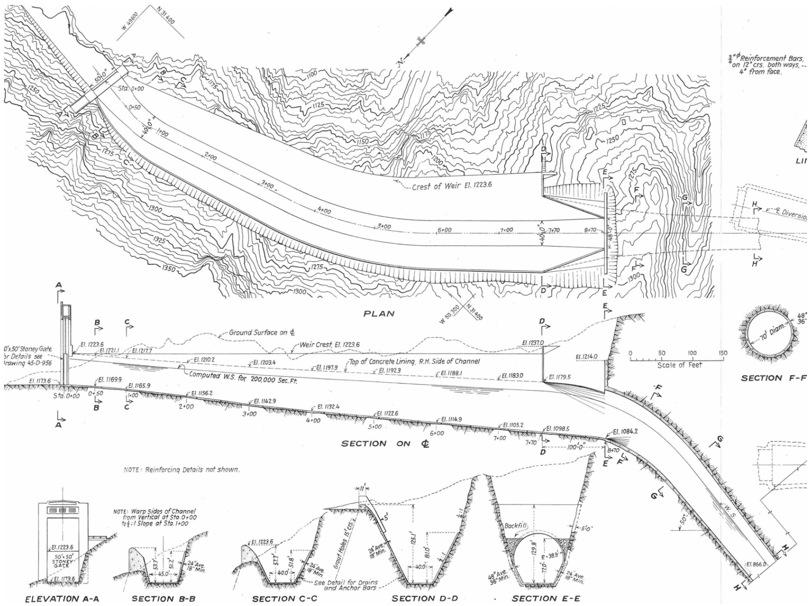


FIG. 14. Reclamation's December 1930 design for side-channel spillways controlled by 50 x 50 ft Stoney Gates. These massive spillway troughs were 870 ft long, passing into 70-foot-diameter throated inlets (Wilbur and Mead, 1933).

The Decision to Employ Drum Gates on the Side Channel Spillways

Model tests on the free crested side-channel spillways showed that they exhibited considerable loss of economy due to turbulent mixing and that an extensive array of training vanes would be needed to alleviate the turbulence, which would entrain air and thereby increase the risks of cavitation. It was then discovered that in order to pass 200,000 cfs at acceptable velocities, they would need a net spillway crest length of about 3,000 feet, which was out of the question because each spillway trough was 650 ft long.

After the winning bid had been submitted, but before the contract was let (mid-1931) Reclamation changed the design of the spillways to full gate control, using floating drum gates. These would be the largest drum gates in the world, allowing spillage of 63,000 cfs with the reservoir at an elevation of 1229 ft, to a maximum discharge of 400,000 cfs with the reservoir at elevation 1232 ft (top of the dam). These side channel spillway troughs are 650 feet long, 150 feet wide, and 170 feet deep on each canyon wall. More than 600,000 cubic yards of rock were excavated for the spillways. The troughs led into inclined shafts 50 feet in diameter and 600 feet long.

The spillway crest elevation is controlled by four 100 x 16-foot hollow drum gates on each spillway, each drum weighing 250 tons. By allowing water into their nested chambers, the hollow drum gates are lifted upward, to a maximum height of 17 ft above the spillway sill. Maximum discharge velocity in the voluminous spillway shafts is about 175 feet per second, or 120 miles per hour. The flow over each spillway would be about the same as the flow over Niagara Falls, and the drop from the top of the raised spillway gates to the river level would be approximately three times as great. The general layout of the main spillways, outlet valves, and penstocks feeding into the powerhouses are shown in Figure 15.

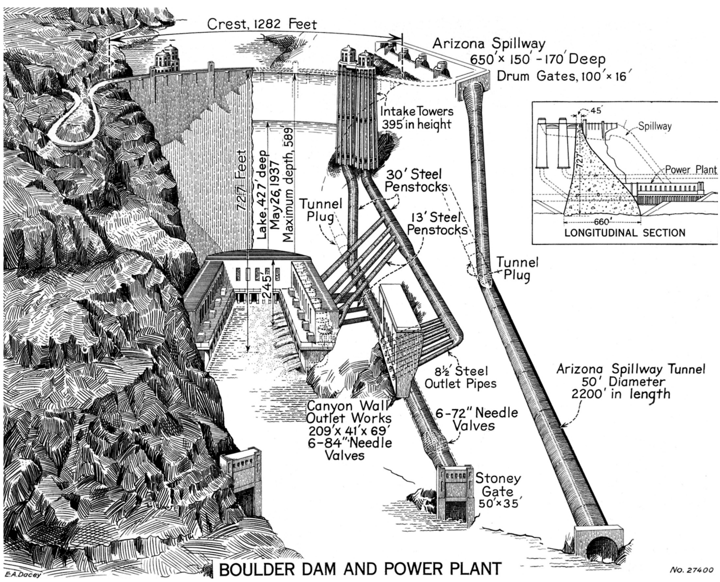


FIG. 15. Cutaway view showing the layout of the main side channel spillway, canyon outlet works, needle valve outlets in the inboard diversion tunnel, and penstocks leading to the powerhouse, all on the Arizona abutment. A similar array exists on the Nevada side (USBR).

Construction access to the higher elevations on the dam's left abutment were accommodated by constructing high catwalks (Figure 16) with the workmen using equipment that had to be driven 237 miles, south through Searchlight, Nevada to Needles, California, and another 10 miles to cross the Colorado River at Topock (about 10 miles downstream of Needles, California). From Topock workers followed old Route 66 through Oatman to Kingman, Arizona, before turning northwest, along the old mining road connecting Kingman to the mining town of Chloride. From Chloride an unimproved road extended up the Detrital Valley to Householder Pass.

From here a new road had to be blazed across White Rock Canyon to the dam's Arizona abutment. A new high-speed highway was graded a year or so later between Kingman and the dam, which became U.S. Highway 93.

As completed in 1935 the total spillage capacity of the dam was about 491,200 cfs. This was broken down as 400,000 cfs in the main side-channel spillways; another 48,000 cfs through the canyon wall outlet works; and 43,200 cfs through the diversion tunnel plug outlet works. An additional 28,800 cfs capacity was gradually absorbed as the powerhouse turbines were added between 1938 and 1961. The canyon wall outlet works were removed in 1954. Today up to 50,000 cfs can be passed through the powerhouses, so the aggregate spillage capacity is assumed to be 493,000 cfs.

FIG. 16. This daring catwalk suspension bridge situated 650 feet above the river allowed workers to cross from the Nevada side to the opposite side to work on the Arizona spillway (USBR).

Valve House Outlet Works

When Hoover Dam was designed valve houses (Figure 17) were originally situated 180 feet above the river on both canyon walls. The first steel penstocks and outlet works pipes began to be placed in 1934. There were 4,700 feet of 30-foot-diameter pipe and 2,000 feet of 8 1/2-foot-diameter pipe. The maximum thickness of the largest pipe was 2-3/4 inches. Each of these canyon-side valve houses was originally configured with six 72-inch-diameter needle valves.

At this same time four 68-inch jet flow gates were installed as "plug outlets" within the inner diversion tunnel plugs. The gates are designed to bypass water around the dam under emergency or flood conditions, or to empty the penstocks for maintenance work.

Between 1956 and 1964 Glen Canyon Dam was constructed along the Colorado River 370 river miles upstream of Hoover Dam and began storing water in March 1963. The erection of Glen Canyon Dam provided significant flood control benefits for Hoover Dam and greatly diminished the rate of sediment accumulation in Lake Mead. In 1979 Reclamation removed two needle valves from each of the tunnel plug outlet works and replaced by a pair of 90-inch- diameter jet flow gates (total of four), which discharge into the river. They also removed six needle valves from each of the canyon wall outlet structures. The abandoned outlets were permanently sealed with high-pressure steel bulkheads and new valves replaced the worn valves in the remaining outlet conduits.

FIG. 17. Water being discharged from the Nevada and Arizona valve houses during the spillway tests in the late summer of 1941, looking downstream (USBR).

STRUCTURAL DESIGN ISSUES

Design of the Mass Concrete Mix

Reclamation's Concrete Research Board (P.H. Bates, W.K. Hatt, H.J. Gilkey, F.R. McMillan, and R.E. Davis) met throughout 1931-34 to provide advice on the many challenging issues posed by the proposed construction, which involved considerable research and innovation. Reclamation's Chief Designing Engineer John L. "Jack" Savage specified four sacks of cement per cubic yard for the mass concrete in all of his dams (Raphael, 1977). Each sack weighed 96 lbs, so 376 pounds of cement were included in each cubic yard, which was the weight of one barrel of cement. The cement used in the early 1930s was much coarser than that used today and the 1931 mix employed more water than would be used today. For these reasons engineers of that era were obliged to use more cement to obtain the desired strength (this was an era before the use of internal vibrators and air entrainment).

Low heat cement was used for the main dam after a small portion of the base was poured (low heat cement not yet being available in large quantities). During the winter months they used a blend of 60% low heat and 40% standard Portland cement.

The mass concrete allowed rock aggregate up to 9 inches in diameter, which was unusually large for mass concrete at that time (this would be equivalent to an 8-inch size using modern aggregate screens). A fairly ‘dry mix’ was specified, allowing for a 3-inch slump (Figure 18). Standard 6 by 12-inch test cylinders, removing the aggregate greater than 1.5 inches in diameter, were used.

FIG. 18. Slump test on dam concrete, using 4-sack per cubic yard mix (USBR, 1947).

Higher strength structural concrete (with a greater proportion of cement) was used in the powerhouses, inlet towers, and tunnel linings (all with steel reinforcement). The daily cement demand during construction of the dam was from 7,500 to 10,800 barrels per day. Reclamation had used only 5,862,000 barrels in its 27 years of construction activity prior to June 30, 1932.

Between 1932 and 1935 10,000 concrete test specimens were made and tested for Hoover Dam. The materials and included cements represented a wide range of chemical composition and fineness. These specimens included: (a) cement paste, (b) mortar, and (c) mass concrete. For economy, most of the concrete specimens were 4-by -8 inch test cylinders with ¾-inch maximum size aggregate. Some large diameter cylinders were also poured to evaluate other properties, such as modulus of elasticity and Poisson’s Ratio, and long-term creep of the actual mix using 36 x 72-inch test cylinders, which allowed the full range of aggregate sizes (Blanks and McNamara, 1935; USBR, 1947).

Chilled Water to Absorb Concrete Heat of Hydration

Hoover Dam was of unprecedented height and volume. Jack Savage and his design team at Reclamation determined that the concrete would remain warm for hundreds of years due to the cement's heat of hydration (Savage, 1936). This was the first time that internal heating of a concrete dam was viewed as a major design problem. At first, it was thought that the solution would be to develop cement with sufficiently low heat liberation that the increased temperatures would be tolerable. Low-heat cement was indeed developed and used in the dam, but even with the low heat cement, the internal temperature still reached 150 degrees F in Hoover Dam.

In 1931 Professor Raymond E. Davis, a member of Reclamation's Concrete Research Board and Director of the Engineering Materials Laboratory at the University of California (Berkeley) began a concerted research program funded by Reclamation to examine the cement chemistry, heat of hydration, maximum aggregate size, most favorable mix proportions, design of an artificial cooling system, the most favorable dimensions of monolithic pour blocks comprising the dam, grouting methods and materials, and the methods employed in the manufacture and handling of the mass concrete (Davis, 1932).

The first step of his research was to devise a cement composition that would produce a low heat of hydration because Reclamation had recently measured the heat of hydration produced by curing concrete on Gibson (1929) and Ariel (1930) Dams (Townsend, 1981). There had also been widely reported problems with heat of hydration causing undesirable tensile stresses and cracking of Rodriguez Dam near Tijuana, Mexico (Noetzli, 1934), described later.

As the dams grew increasingly higher in the late 1920s to early 1930s engineers demanded higher strength concrete, which required additional cement (mixes using 4 or more sacks per cubic yard). The increased heat of hydration was recognized as a potentially troubling aspect of employing higher strength mass concrete. The higher strength concrete was deemed necessary to handle such factors as long-term loading (creep), natural variations in strength, and the requirement that design strength of test cylinders be significantly higher than the maximum design stress, and so forth. No corresponding compensations were made for favorable factors, such as the automatic transfer of stress from highly stressed regions to those adjoining regions of lower stress.

Tests of arch dam models suggested that large stresses develop at the downstream haunch which diminishes to near-zero at the upstream face. Failure only ensued when the average stress over a section reached the compressive strength of the concrete. When the elastic limit was exceeded, a redistribution of stress occurred, transferring stress away from highly stressed regions. Unfortunately, such favorable transfer did not appear to occur in the case of tensile stress. For these reasons, the most noticeable adjustments in Hoover Dam's final design were made along the upstream face, which was sloped noticeably upstream, to reduce the likelihood of the dam developing tensile stress at its upstream toe.

The calculated heat of hydration for the final design of Hoover Dam was 40 degrees F with 125 years to cure and cool, absent any artificial cooling. The Concrete Research Board felt that this volume of concrete would set off thermal stresses that would certainly crack the dam. It was therefore determined that various measures should be employed to reduce the heat of hydration, which were being tested on Owyhee Dam, then under construction near Boise, Idaho (Scott, Nuss, and LaBoon, 2008).

At that time it had been determined that cement contained four principal compounds: tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetra-calcium aluminoferite. For convenience, these were referred to as C_3 S, ~ C_2 S, ~C_3 A, and C_4 AF. The two silicates produced most of the cement's strength. Cement with a low heat of hydration could be fabricated by increasing the amount of ~ C_2 S and decreasing the amount of ~C_3 A. This became the formula used in producing "Modified Low Heat Cement" for Hoover Dam (Davis et al., 1933; Savage, 1936). The heat of hydration of normal Portland Cement is between 85 and 100 calories per gram, while that for the low-heat cement at Hoover Dam was 65 (at 7 days) to 75 (28 days) calories per gram, with an average 28-day strength f_c' = 2,000 pounds/square inch (psi) (Savage, 1936). In retrospect, there was actually no need for low-heat cement because the internal heat of hydration was removed by circulating cooling water in embedded pipes.

In addition to using low-heat cement, two other measures were adopted to help alleviate problems with internal heating of the mass concrete during hydration. One was to cast the concrete in blocks small enough so that they would shrink as a monolithic block, and thereby avoid development of uncontrolled shrinkage cracks. In 1931 Reclamation let a three-year contract with the University of California to carry out extensive tests to ascertain the heat of hydration from cement curing (Davis and Troxell, 1931; Davis 1932; Davis et al., 1933). These tests found that about 90% of the heat is generated in the first 28 days, but that this heat could not be dissipated adequately if the concrete was insulated by warmer concrete above and around it. Hoover was the first mass concrete dam to receive this level of analysis, although research and adjustments to mass concrete mixes for dams continued for many years thereafter (Liel and Billington, 2008).

Dry mixes were specified to reduce shrinkage from moisture change. The dam was built in blocks or vertical columns varying in size from about 60 feet square at the upstream face of the dam to about 25 feet square at the downstream face, using steel forms. Adjacent columns were locked together by a system of vertical keys on the radial joints and horizontal keys on the circumferential joints (Figures 19 and 20). Lift heights in each block were limited to five feet in 72 hours, and 35 feet within 30 days. After the concrete was cooled, grout was forced into the spaces created between the columns by the contraction of the cooled concrete to form a monolithic (one piece) structure. Shrinkage was about 0.5%.

Water stops were employed near the up and downstream faces of block joints. Vertically serrated joints were used between blocks in the dam. These joints were grouted after the blocks had shrunk. Horizontally serrated joints used against the abutments. All joints between blocks were to be grouted in 100-foot lifts, after cooling occurred. All cooling pipes were grouted as well, after water circulation ceased.

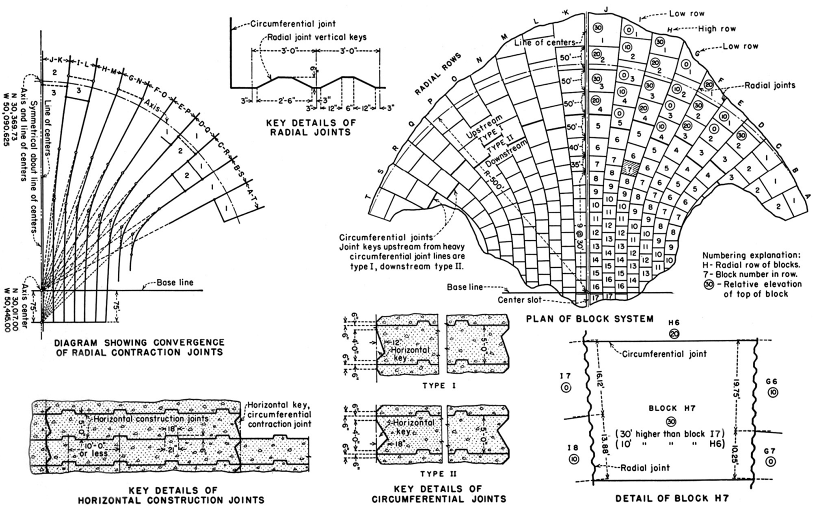


FIG. 19. Plan illustrating the block system used by Reclamation to isolate concrete shrinkage and heat of hydration. The spaces between the blocks were grouted after most of the expected shrinkage and curing had occurred (USBR, 1947).

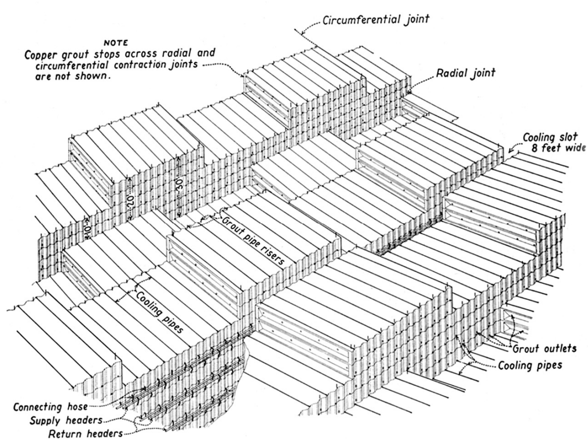


FIG. 20. Detail showing the offset nature of the monolithic blocks comprising the dam, intended to avoid the formation of random shrinkage cracks within the dam. Note beveled shear keys between blocks and the cooling pipes, which were laid parallel to the dam's radius (USBR, 1947).

Designing the Embedded Instrumentation

In 1925, a group of engineers led by Swiss engineer Fred Noetzli conceived the idea of building an experimental arch dam along Stevenson Creek a few miles below Shaver Dam, in the western Sierra Nevada of California (Veltrop, 1988). The test dam was a thin arch 60 ft high and just 7.5 ft wide at its base. The purpose was to test the evolving theories of arch and cantilever loading in a constant radius arch dam. The structure was fitted with every sort of measuring instrument available at that time, including carbon-pile telemeters, which were a kind of strain meter which could be embedded in the wet concrete at the time it was poured. This was the first time that meters were used to measure internal strains of a dam. A young physicist from Caltech named Roy Carlson was placed in charge of the strain measurements, a consultation that proved providential for Carlson as well as dam engineering, world-wide.

The carbon-pile telemeters used at Stevenson Creek did not exhibit long-term stability. After the project concluded Carlson took a position testing materials for the Los Angeles County Flood Control District (LACFCD) began devising a better device for measuring internal strain, and then set about developing a companion device to measure internal stress. Carlson soon determined that the measurement of strain was far easier than measuring stress, and he searched for a suitable sensing element. He found that carbon-steel wire, when drawn down to smaller and smaller diameter kept increasing in tensile strength, reaching up to 700,000 psi. He found that for each one percent change in length, the wire's electrical resistance changed 3.6 percent. This was the physical attribute that allowed the development of the modern strain gage (Davis and Carlson, 1932).

Carlson then experimented with various schemes of mounting the elastic-steel wire to the sensing element, settling on two coils of the steel wire, initially stressed and mounted in such a way that one would increase in length when the ends of the meter were brought closer together and the other would decrease. The beauty of his device lay in its simplicity, which overcame concerns with temperature effects because the ratio of the resistances of the two coils would be affected to double degree when the gage length was increased. The current resistance was independent of temperature change because the temperature effects were compensating. Since the total resistance changed only with temperature, the device could also be employed to measure concrete temperature.

While working at Stevenson Creek in 1926, Carlson observed that concrete increased in temperature while hardening. He set about measuring the temperature rise in concrete poured for the Pacoima and Big Tujunga concrete arch dams built by LACFCD in the San Gabriel Mountains. He used an adiabatic calorimeter to study the heat generated by concrete during its curing.

At the same time (1928-30) a chemical engineer for the Riverside Cement Co. named Hubert Woods was trying to measure the heat of solution of dry cement and compare it with that of the hardened cement paste. Woods succeeded in demonstrating that the difference between the two was the cement's unique heat of hydration. This method proved to be reliable and far more efficient than Carlson's adiabatic calorimeter. However, it was also discovered that the heat-of-solution method was inaccurate when applied to cements containing pozzolan admixtures.

In 1929 Woods began collaborating with Carlson at his LACFCD lab on solving the puzzle posed by fresh cracks that had appeared at Rodriguez Dam near Tijuana, Mexico, where they were using a 5 sack/yd^3 mix (Noetzli, 1934). The cracks appeared within a few days of placement and were being blamed on Riverside Cement, the supplier. Hubert suspected that the cracks were ascribable to the temperature change induced by concrete curing. Carlson had noted significant cracks that developed in the Stevenson Creek Test Dam, which he ascribed to thermal stresses when the concrete warmed significantly during the first 48 hours after placement.

Carlson had been fabricating electrical-resistance thermometers by winding enameled copper wire on insulating spools and dipping them in hot tar to protect the wire from the corrosion (Carlson, 1938a). By embedding some of these thermometers in Rodriguez Dam they recorded a temperature rise of about 120 degrees F. over two days, which then decreased. A 120 degree temperature drop could trigger tensile stresses of more than 300 psi, sufficient to crack the dam's concrete (a five sack mix with 28-day compressive strength f_c'= 2,650 psi). Although assuming zero stress at maximum temperature initially seemed questionable, it was later found that this was very nearly the case (Davis and Carlson, 1932).

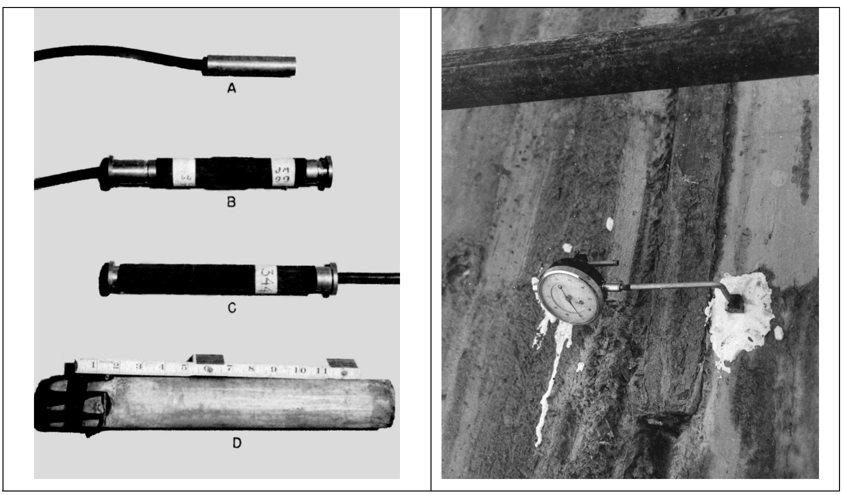


FIG. 21. Left image shows the four basic instruments invented by Roy Carlson that were used to instrument Hoover Dam. These included: A – resistance thermometer; B- joint meter; C – strain meter; and D- strain meter packed in protective tube for embedment. Image at right shows the conventional instrumentation used at exposed locations, in this case a radial dial gage placed across a horizontal joint (USBR).

Carlson's unique experience and his instruments were perceived as vital to Reclamation's needs and interests in developing a state-of-the-art protocol for concrete placement at Hoover Dam, because of its unprecedented scale (Carlson, 1977). Reclamation Chief Designing Engineer Jack Savage tried to hire Carlson to work at their Denver office, but this possibility fizzled when it was learned that Carlson's degrees were in mathematics and physics, not civil engineering (so he was not eligible to take the civil service examination required by Reclamation). In May 1931 the impasse was solved by Professor Davis at Berkeley, who talked Reclamation officials into funneling the concrete research, testing, and instrumentation development aspects of Hoover Dam to Berkeley's Engineering Materials Lab in a three-year contract (June 1931 to June 1934), with the understanding that Davis would hire Carlson as a research engineer (Carlson subsequently earned his master's and Sc.D. degrees in civil engineering, at Berkeley and MIT, respectively).

By the time Six Companies began pouring concrete in June 1933 Carlson had developed and tested the electrical instruments that could be embedded in the dam's concrete to measure strain, joint opening, and temperature (Figure 21). These included 450 of his electrical-resistance joint meters, which provided crucial instrumentation of the dam's expansion joints (although some of the joint meters were rendered inoperative by being carried beyond their design range, as described previously).

Carlson's resistance strain meters (Figure 22) were used to measure the strains engendered by the cement heat of hydration, dead weight accumulation (as the dam rose higher and higher), and, through inference, validate the design assumptions about cantilever and arch stress distributions in the Trial Load Method of analyses employed in the dam's design (Savage et al., 1931; USBR, 1939; 1940).

These measurements were continued on a regular basis up through the end of 1941, when the reservoir filled and the spillways were tested. Instrument readout banks were established inside the dam's galleries, as shown in Figure 23.

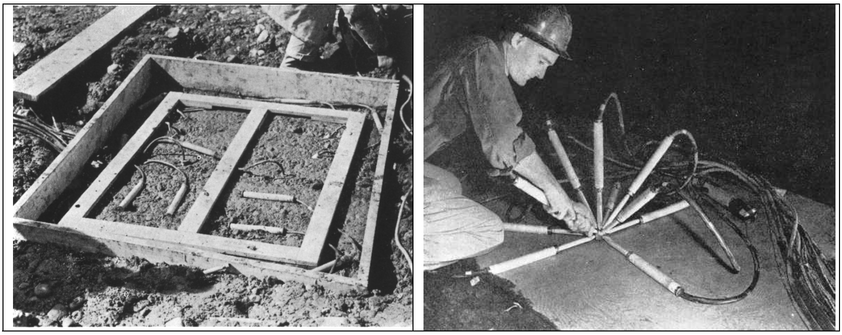


FIG. 22. Left image shows an array of resistance strain meters being embedded in a block, just prior to removal of the template and barrier. This array would record the strains in a horizontal plane. Right image shows an 11 strain meter spider array being assembled just prior to embedment. Spider arrays allowed a three dimensional assessment of the stresses developed within a dam for the first time (from Raphael and Carlson, 1965).

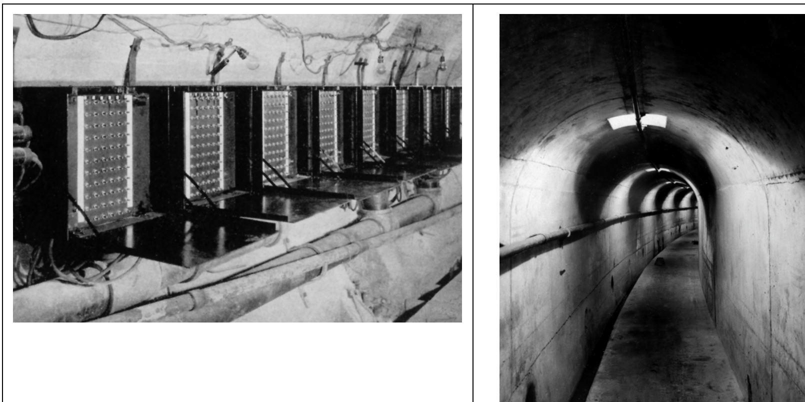


FIG. 23. Left image shows a battery of terminal boards in the Arizona Radial Gallery near elevation 705 ft. Each bank contained copper wire leads to 55 strain meters, which could be plugged into a portable Carlson strain meter testing set. Right image shows one of the dam's internal radial inspection galleries (USBR).

Measurements made during construction were used to control the cooling of the mass concrete and grouting of the dam's joints. These data and measurements were also used to validate the loading assumptions used in the design of the dam and to record its structural behavior. The measurements and resulting analyses validated most of the pre-construction modeling (Carlson, 1938b). The dam and abutments were also fitted with 64 triangulation stations to allow precise external monitoring of deflections. The interior of the dam was also fitted with tilt meters, plumb lines hung in special instrument shafts, recording thermometers, and three strong motion accelerographs. A system of pipes was also placed in connection with the base of the dam to measure the hydraulic uplift against the base of the dam.

The results of the instrumentation program were so successful they became standard practice for all of Reclamation's significant concrete dams thereafter, many of which received substantially more instrumentation, as improved devices, such as Carlson's mercury filled pressure meters, became available (Raphael, 1948; 1953; 1955). This 'second generation' of instruments was sufficiently sensitive to actually measure plastic flow of the dam's mass concrete (ENR, 1942).

Roy Carlson's association with Reclamation would continue for years thereafter. After his work on Hoover Dam concluded he accepted a faculty position at MIT in the fall of 1934. While teaching at MIT he recorded numerous patents for his measurement devices, including the elastic-wire strain meter (in 1936) and an electric-resistance pressure meter (in 1939). The strain meter came to be widely used and a modification of the pressure meter called the "pore pressure cell," was used to a lesser degree by Reclamation on a number of projects, moistly notably, on Grand Coulee, Shasta, and Friant Dams (Raphael, 1953). Three decades later Reclamation was still installing his instruments on their largest mass concrete dams. 2,000 Carlson strain meters were used at Glen Canyon Dam in 1958-64 and 1,600 strain meters were installed in Flaming Gorge Dam in 1958-64 (Raphael and Carlson, 1965).

CONCLUSIONS

The scale of the Boulder Canyon Project was so massive that it gave rise to an unprecedented volume of scientific research and engineering analyses, which was of inestimable value to the civil engineering community. Most of the technical aspects of the dam's planning and design were subsequently summarized in what were collectively known as the "Boulder Canyon Project Final Reports," 21 volumes released by Reclamation between 1939 and 1950.

At the time of its design Hoover Dam was already recognized as one of the greatest engineering feats of the 20th Century. The unprecedented size of the dam led to studies in almost every aspect of dam design and construction of mass concrete dams, including concrete composition and cooling, stress analysis, hydraulic design, and hydraulic and structural modeling.

ACKNOWLEDGMENTS

The author is indebted to retired Reclamation engineer Richard Wiltshire, who appreciates civil engineering history and organized this symposium commemorating the 75th anniversary of Hoover Dam's completion. In 2008 the author served as one of the speakers participated in a Conference on The Fate and Future of the Colorado River, sponsored by the Huntington-USC Institute on California & the West and the Water Education Foundation at the Huntington Library. This led to many valuable contacts which led to a myriad of sources for information and photographs relating the Boulder Canyon Project and subsequent water resources development in the Lower Colorado River Basin.

In 2009-10 the author received a Trent Dames Civil Engineering Heritage Fellowship and was a Dibner Research Fellow at the Huntington Library in San Marino, California. This fellowship and the residency it afforded allowed the author to review of numerous serial publications, collections, archives, and ephemera that provide invaluable to understanding the engineering decisions and political pressures influencing those decisions, not just during construction (1931-35) but during the decade preceding and following the dam's completion. Huntington Archivists Dan Lewis and Bill Frank proved to be particularly valuable in ferreting out rare or obscure accounts from the Huntington's civil engineering and scientist manuscript collections, as well as rare map and historic photos. The author is also indebted to engineering geologist James Shuttleworth, a volunteer in the Huntington's manuscripts department, well versed in the history of the lower Colorado River, who provided innumerable suggestions.

Between 1976 and 1988 the author conducted interviews with Roy W. Carlson (1900-1990), Milos Polivka (1917-1987), Jerome M. Raphael (1912-1989), and George E. Troxell (1896-1984), all professors in the civil engineering program at U.C. Berkeley. Carlson had been an ex-officio member of the Hoover Dam Concrete Research Board. Jerry Raphael had worked for the Bureau of Reclamation from 1938

to 1953 and had been trained by Reclamation Chief Designing Engineer Jack L. Savage (1879-1967). He inherited many of Savage's files on mass concrete behavior and had served as head of Reclamation's Structural Behavior Group between 1949 and 1953, when he supervised the evaluations of crustal deformation at Lake Mead and reservoir-triggered seismicity. Troxell, Carlson, Polivka, and Raphael were all protégées of Professor Raymond E. Davis (1885-1970), Director of Berkeley's Engineering Materials Lab between 1928 and 1953, which carried out the concrete research for Hoover Dam during its final design and construction (Raphael had taken Davis' faculty position at Berkeley when he retired in 1953). These professors supplied the author with countless documents relating to the concrete research carried out at Berkeley for Hoover Dam, which continued for many years after the dam's completion (e.g. creep studies).

Sincere appreciation for assistance is also rendered to the following people and their respective organizations: Reclamation GIS specialist Steven Belew; Dr. Brit Allan Storey and Christine Pfaff, historians with the U.S. Bureau of Reclamation at the Denver office, Dianne Powell of the Bureau of Reclamation Library in their Denver office; Reclamation archivists and staff Bonnie Wilson, Andy Pernick, Bill Garrity, and Karen Cowan of Reclamation's Lower Colorado Region (LCR) office in Boulder City; Boulder City Library Special Collections; Eric Bittner at the National Archives and Records Service Rocky Mountain Region depository at Denver Federal Center; Paul Atwood and Linda Vida at the University of California Water Resources Center Archives in Berkeley; Su Kim Chung of the University of Nevada-Las Vegas Libraries; civil engineering historian Edward L. Butts; Tom Northrup of the American Society of Photogrammetry & Remote Sensing; and a special thanks to the author's best friend Steve Tetreault, who accompanied the author of his first tour of the dam in February 1973. Over the last several decades Mr. Tetreault has provided invaluable support and logistical connections in support of the author's numerous visits to the University of Nevada-Las Vegas, Boulder City, and Hoover Dam.

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