In Appreciation of A Civil Engineering ICON

LAST MONTH, ASCE's History and Heritage Committee celebrated the 75th anniversary of Hoover Dam in conjunction with the 140th Annual Civil Engineering Conference, which was held in Las Vegas. During the two-day-long Hoover Dam 75th Anniversary History Symposium—conducted October 21–22—presenters discussed the dam's construction and operation as well as the many lessons learned from this engineering feat lauded around the globe. (See "Hoover Dam Symposium Celebrates Engineering Icon," *ASCE News,* November 2010, page 1.)

The preface of the symposium proceedings notes that "the dedication of Hoover Dam 75 years ago, on September 30, 1935, culminated what many regard as the world's greatest dam design and construction project of the 20th century. Hoover Dam has remained highly regarded within the national and international civil engineering profession, which led ASCE to designate Hoover Dam as its Monument of the Millennium dam in 2000 after a vote by ASCE members. Also, Hoover Dam has been designated an ASCE National Civil Engineering Landmark in 1984, a National Historic Landmark in 1985, and was listed [in] the National Register of Historic Places in 1981."

In recognition of this extraordinary accomplishment on the part of American civil engineers, we are publishing this special section—"Celebrating Hoover Dam"—which includes the contemporary article "The Majesty of Hoover Dam" by J. David Rogers, Ph.D., P.E., R.G., C.E.G., C.HG, M.ASCE, who authored five papers for the symposium proceedings, as well as two articles reprinted from issues of *Civil Engineering* printed in 1935, both authored by Walker R. Young, M.ASCE, who was a construction engineer for the Bureau of Reclamation on the Hoover Dam project. The first, entitled "Significance of Boulder Canyon Project," was published in the May 1935 issue; the second, "Mission of Boulder Dam Fulfilled," appeared in the June 1935 issue. We believe you will find the counterpoint of perspectives from a contemporary engineer and an engineer who worked on the Hoover Dam project extremely enlightening.

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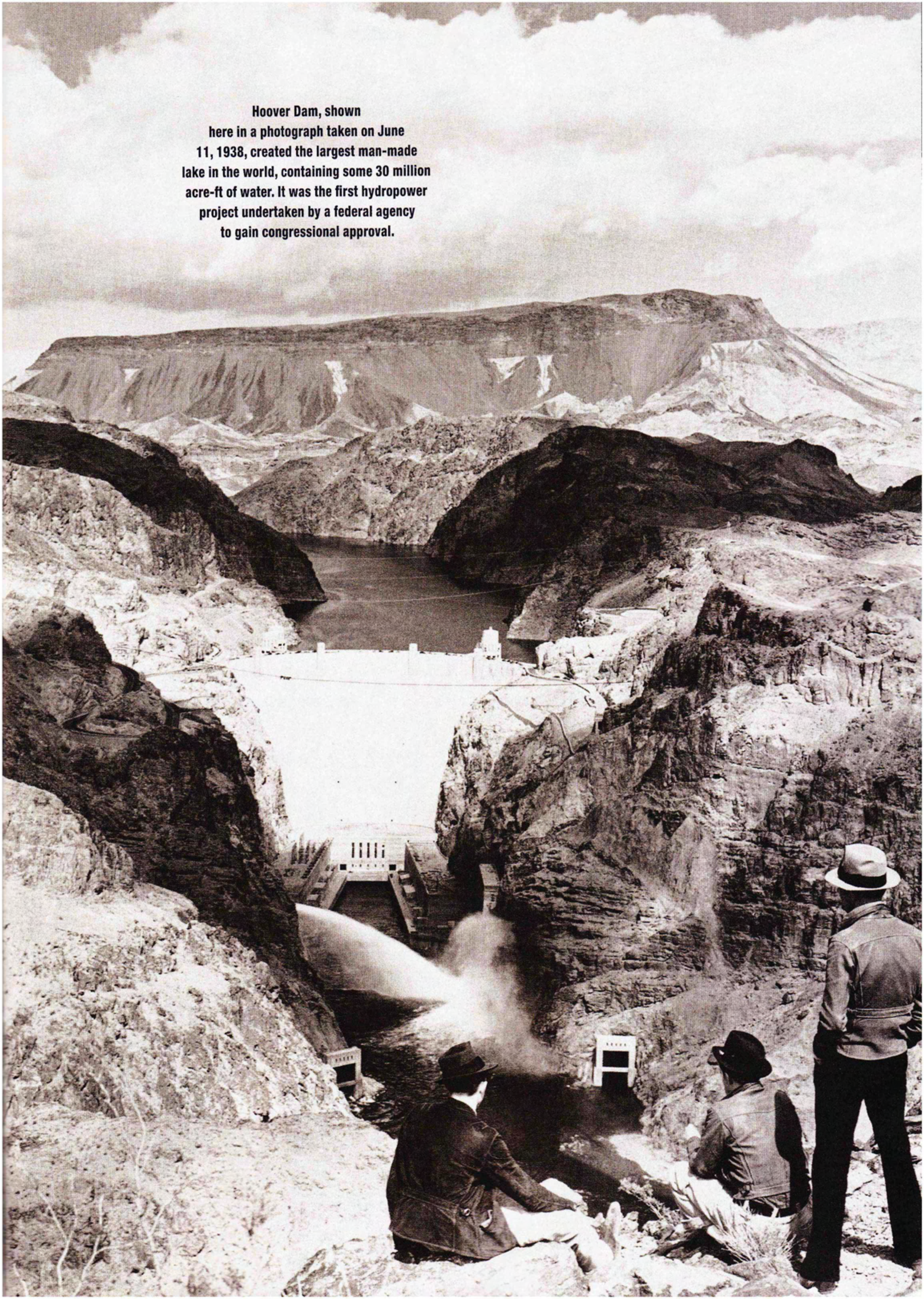
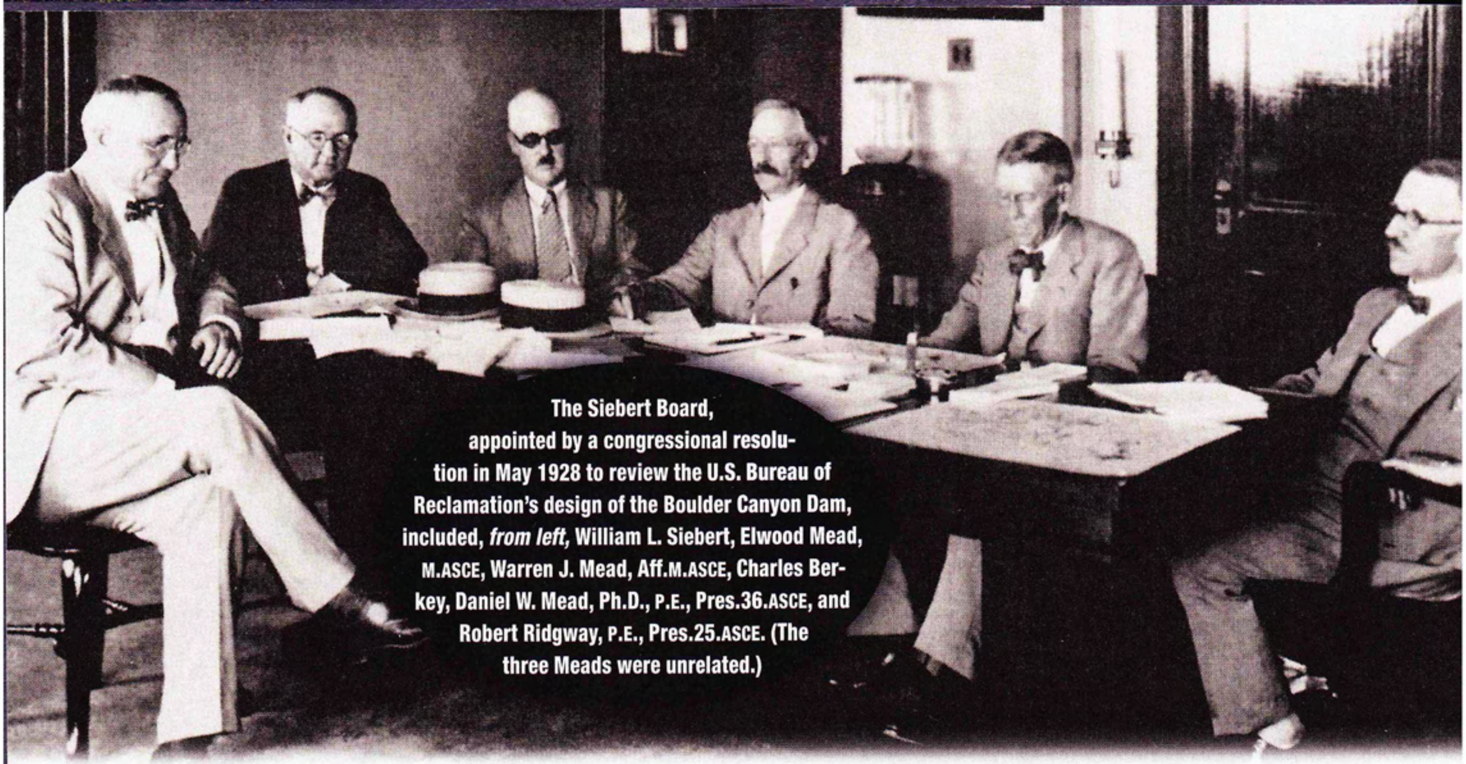


Hoover Dam, shown here in a photograph taken on June 11, 1938, created the largest man-made lake in the world, containing some 30 million acre-ft of water. It was the first hydropower project undertaken by a federal agency to gain congressional approval.



The Siebert Board, appointed by a congressional resolution in May 1928 to review the U.S. Bureau of Reclamation's design of the Boulder Canyon Dam, included, *from left,* William L. Siebert, Elwood Mead, M.ASCE, Warren J. Mead, Aff.M.ASCE, Charles Berkey, Daniel W. Mead, Ph.D., P.E., Pres.36.ASCE, and Robert Ridgway, P.E., Pres.25.ASCE. (The three Meads were unrelated.)

AP PHOTO

The Majesty of Hoover Dam

The design and construction of Hoover Dam constituted a feat unlike any that had been previously accomplished; in its sheer size, scope, and level of technical difficulty, the structure surpassed expectations and set world records. And the history of its creation is replete with fascinating stories about the men, the machines—and the engineering—that made it possible.

By J. David Rogers, Ph.D., P.E., R.G., C.E.G., C.HG, M.ASCE

WHEN IT WAS COMPLETED, in late 1935, Hoover Dam was a monumental accomplishment, breaking all records in dam design and construction and setting new standards for feasibility studies, structural analysis and behavior, rock excavation, mass concrete production, quality control, instrumentation, and postconstruction performance evaluations. The Colorado was America's most fickle river, varying from a high of 384,000 cfs in 1884 to a minimum of just 500 cfs in 1913, and it possessed the fifth-largest silt load of any river in the world. Harnessing its enormous potential would be an engineering feat of unparalleled ambition, especially given the paucity of reliable flow data. The project evolved from a complex interplay of factors coming together with fortuitous timing, as the government found itself searching for high-visibility public works projects to fund in the midst of a staggering economic depression in the early 1930s.

The U.S. Reclamation Service, the forerunner of the U.S. Department of the Interior's Bureau of Reclamation, had been established in 1902, and within two years it began examining potential dam sites along the lower Colorado River to provide flood control and to irrigate up to 2 million acres of farmland in Arizona and California. From 1920 onward the studies zeroed in on six potential sites: three in the granite of upper Boulder Canyon (about 50 mi east of Las Vegas) and three in the volcanic andesite of upper Black Canyon (about 26 mi southeast of Las Vegas).

The California congressional delegation began introducing the Boulder Canyon Project Act during each session beginning in the fall of 1922. However, they failed to garner sufficient national support until they helped their colleagues from the Midwest and the South pass the Flood Control Act of 1928, which was prompted by the Mississippi River flood of 1927. By the spring term in 1928 it appeared that California finally had the votes to pass the Boulder Canyon Project Act.

Fate intervened on the night of March 12, 1928, when the

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St. Francis Dam, near Los Angeles, failed, killing more than 432 people in the worst American civil engineering failure of the 20th century. The catastrophe couldn't have come at a worse time for the proponents of the Boulder Canyon project, among them William Mulholland, the chief of the Los Angeles Bureau of Water Works and Supply, who took responsibility for the dam's untimely collapse. Mulholland had been vociferous in lobbying Congress to develop the lower Colorado River. He had also been the principal figure in forming the Metropolitan Water District of Southern California, which established a goal of constructing the 242 mi long Colorado River Aqueduct and using the electric power generated by the Boulder Canyon project to power its pumps.

The similarities between the St. Francis Dam and the proposed behemoth structure in either Boulder Canyon or Black Canyon were, in the public's perception, too great to ignore, both being curved concrete arch-gravity structures. The proposed Boulder Canyon Dam would store 843 times as much water as had been unleashed in the St. Francis flood, which could permanently alter the course of the lower Colorado River and could inundate the Imperial Valley, which had no natural drainage outlet.

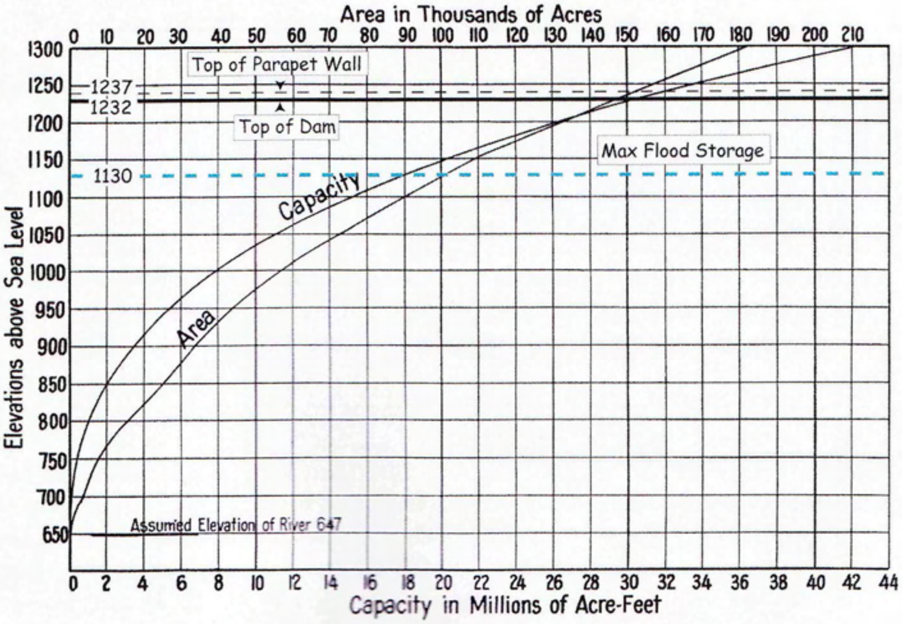
The compromise Congress settled on was appointing an independent board of experts to examine the Bureau of Reclamation's design and report back to Congress within six months. Major General William L. Siebert, who had retired from the U.S. Army Corps of Engineers, was named the board's chairman. Siebert was respected as one of the principal figures in the construction of the Panama Canal and was the first chief of the chemical warfare branch established by the army during World War I. The other members were Robert W. Ridgway, P.E., Pres.25.ASCE, who had worked on the New Croton and Catskill aqueducts, in New York State; Daniel W. Mead, Ph.D., P.E., Pres.36.ASCE, a professor at the University of Wisconsin and the nation's most respected figure in hydraulics; and the geology professors Charles Berkey from Columbia University's School of Mines and Warren J. Mead, Aff.M.ASCE, from the University of Wisconsin at Madison (who spent most of his subsequent career at the Massachusetts Institute of Technology). Elwood Mead, M.ASCE, the commissioner of what was now the Bureau of Reclamation, rounded out the team, serving as the liaison between the bureau in Denver and the panel, which convened in Washington, D.C. Officially christened the Colorado River Board (CRB), it was referred to by the media as the Siebert Board.

On December 3, 1928, the CRB issued a 15-page report that was brief and succinct, its members agreeing that although the Bureau of Reclamation's scheme was feasible from an engineering standpoint, the proposed dam, should it fail, would create a national tragedy of immense and unprecedented proportions. To avert such a possibility, the CRB felt that the proposed dam should be constructed along "ultra-conservative lines" and should be situated in Black Canyon rather than in Boulder Canyon because of the former's superior geology and topography, as well as its better access to existing railroad lines and highways at Las Vegas. The CRB also believed that a dam in this location would cost less and store a greater volume of water than would one in Boulder Canyon, that the rock was less intensely jointed, and that the volcanic andesite would be more easily drilled and excavated than the granite in Boulder Canyon (which turned out not to be true).

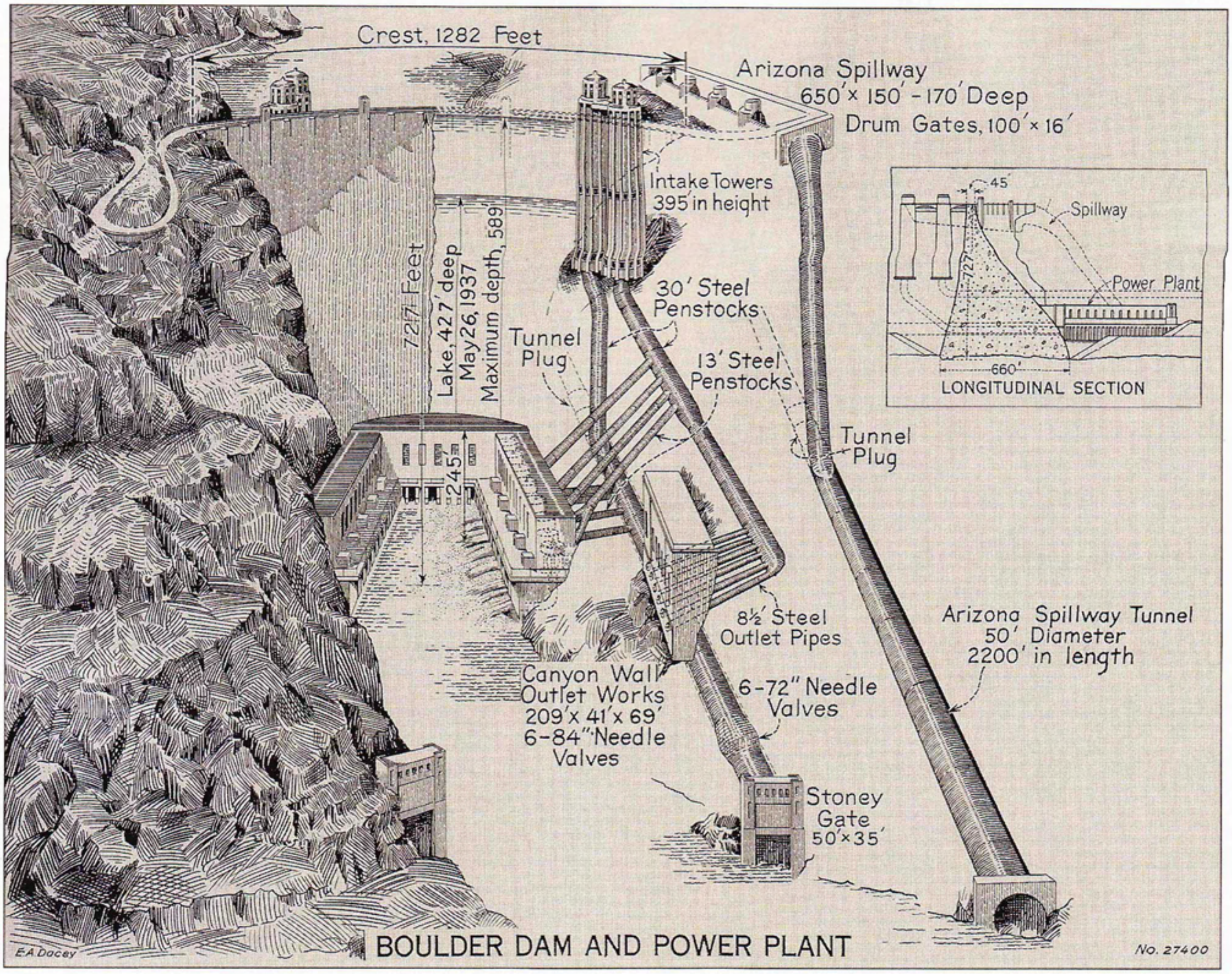
The board also proposed a series of important changes to the dam's design and construction, recommending that the Bureau of Reclamation reduce the foundation contact pressure from 40 to 30 tons per square foot; double the capacity of the bypass diversion tunnels from 100,000 cfs to 200,000 cfs (to handle a 25-year flood); increase the spillway capacity from 110,000 cfs to 160,000 cfs; and expand the reservoir storage from 26 million acre-ft to 30.5 million acre-ft. The proposed changes increased the estimated cost of the project by 32 percent, from $125 million to $165 million.

The CRB's favorable report resulted in rapid congressional approval of the fourth version of the Boulder Canyon Project Act by a vote of 63–11 in the Senate on December 14, 1928. The House approved a similar version but it included amendments requested by Utah on December 18 to secure future water rights for the state, and President Calvin Coolidge approved the act with those amendments on December 21. At the time it was the largest single appropriation bill ever enacted by Congress, and its successful realization

RESERVOIR AREA AND CAPACITY CURVES FOR PROPOSED DAM (CURVES) AND HOOVER DAM (LINES)



BUREAU OF RECLAMATION, *BOTH*



The layout of the main side-channel spillway, the canyon outlet works, the needle valve outlets in the inboard diversion tunnel, and the penstocks leading to the powerhouse, all on the Arizona abutment, was drawn by hand. A similar array exists on the Nevada side.

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.

CONSTRUCTION OF THE DAM officially began on September 17, 1930, when President Herbert Hoover's secretary of the interior, Ray Lyman Wilbur, presided over the project's initial construction at the "Silver Spike" ceremony at Boulder Junction, where the Union Pacific Railroad spur veered off the line from Los Angeles to Salt Lake and headed to the future site of Boulder City, 26 mi distant. In his dedication speech, Wilbur announced that the dam would be named Hoover Dam, in honor of the president, just as dams constructed during the administrations of Theodore Roosevelt and Calvin Coolidge had been named in their honor.

Hoover Dam was the first project that forced the federal government to assume the broad spectrum of risks that had previously been the burden of contractors—contingencies that often drove bid prices up or down. Responding to concerns about the likely estimates associated with a project of such unprecedented size and duration, the federal government proposed a number of innovative measures designed to limit the uncertainties and mitigate the risks:

- The bid bond and construction surety to be advanced by the winning bidder were fixed at the moderate amounts of respectively $2 million and $5 million. This was an incredible bargain on a $50-million project (the assumed cost of the dam and powerhouse alone).
- Once the Bureau of Reclamation accepted the cofferdams, it accepted responsibility for flood damage to all property, with the exception of the contractor's facilities.
- Military veterans and U.S. citizens would be given preferential employment on the project, and the federal government would supply all of the materials except the concrete aggregate.
- The federal government contracted directly for construction of a rail spur between Las Vegas and Boulder City, as well as another rail line to the rim of Black Canyon, overlooking the Nevada powerhouse.
- Contracts specified that electricity be delivered to the dam site no later than June 25, 1931, via a 222 mi long power line from San Bernardino, California.
- A contract was awarded for the construction of a paved highway to the dam site from Boulder City.
- Separate contracts were awarded for the construction of Boulder City, discussed below, which was to be administered by the Department of the Interior.

It was initially envisioned that Six Companies, Inc., the joint venture of construction companies that was formed to build the dam, would house 2,000 workers and their families in a temporary work camp located 9 mi from the dam site that the government named Boulder City. 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. The town that became Boulder City was built in just 15 months to house 5,000 government employees and contract workers and their families.

The CRB continued to review the various design amendments made by the Bureau of Reclamation prior to construction. In April 1930 the CRB recommended that the bureau increase the height of the dam by 25 ft, from 1,207 ft to 1,232 ft. The purpose of the increase was to provide 4.5 million acre-ft of additional flood storage with a minimum freeboard of 3 ft, thereby increasing the maximum seasonal flood storage to 9.5 million acre-ft, a startling 31 percent of the total storage.

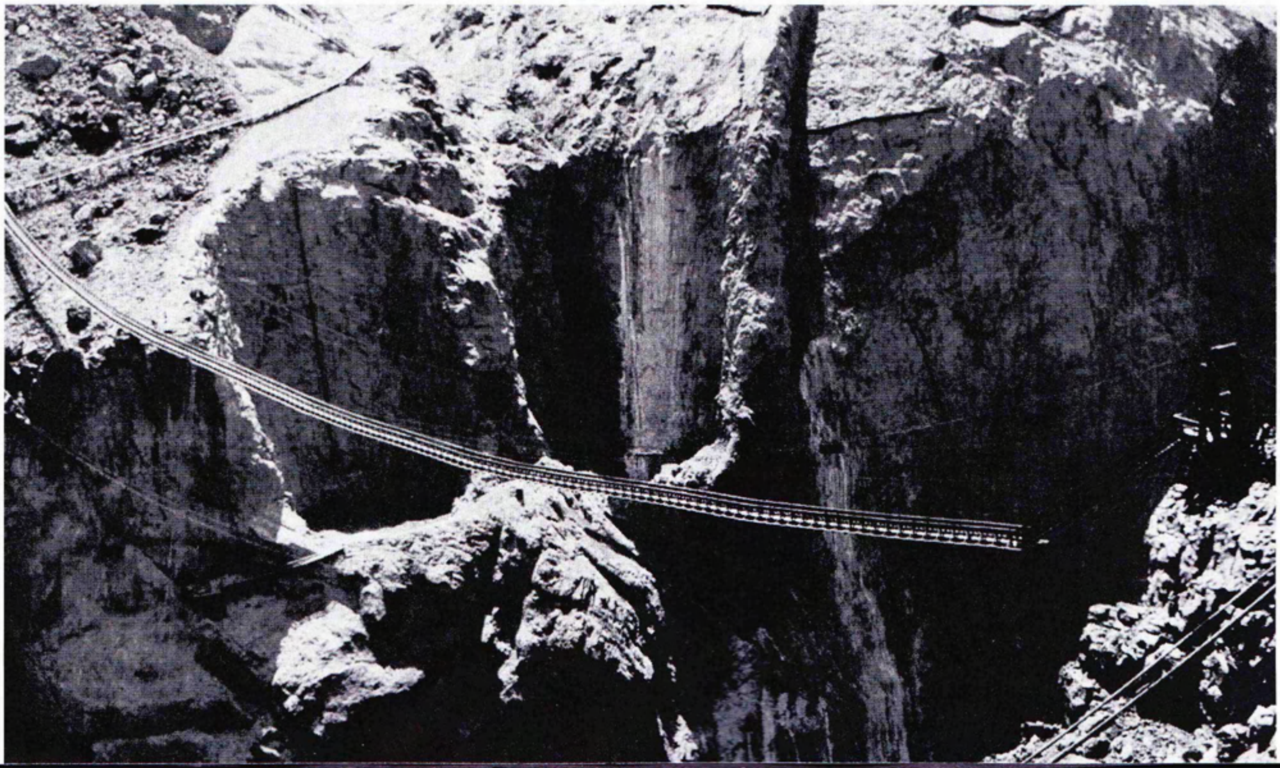
In April 1930 the dam's height was increased as the CRB recommended, providing 30,500,000 acre-ft of total reservoir storage, equal to two years' cumulative flow of the Colorado River. The reservoir area and capacity curves estimated by the Bureau of Reclamation in 1928 are presented in the figure on page 53. Of that total, 9.5 million acre-ft of seasonal flood storage between April 1 and September 1 of each year was intended to accommodate spring runoff from the mountainous interior.

In mid-1931 the Bureau of Reclamation changed the design of the spillways to accommodate full gate control by employing the largest floating steel drum gates in the world, with four 100 by 16 ft hollow drum gates on each spillway (each drum weighing 250 tons). These allow spillage of between 63,000 and 400,000 cfs. The two side-channel spillway troughs are 650 ft long, 150 ft wide, and 170 ft deep on each canyon wall. More than 600,000 cu yd of rock was excavated for the spillways. The troughs led into inclined shafts 50 ft in diameter and 600 ft long.

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. The maximum discharge velocity in the voluminous spillway shafts is about 175 ft/s, or 120 mph. 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 is shown in the figure on page 54. Construction access to the higher elevations on the dam's left abutment—as viewed by one looking downstream—was provided by constructing high catwalks. The equipment used by the workmen had to be transported 237 mi.

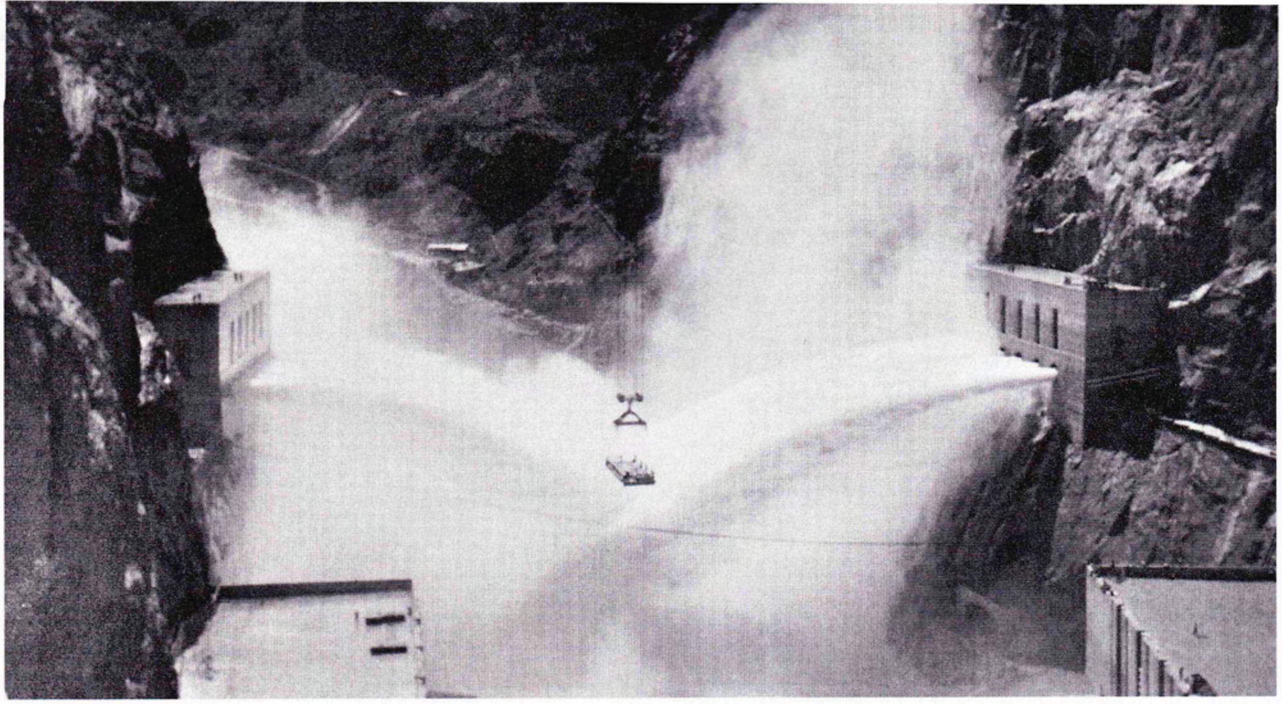
At the dam's completion, in 1935, the total spillage capacity was roughly 491,200 cfs. This was broken down as 400,000 cfs in the main side-channel spillways, another 48,000 cfs through the canyon wall outlet works, and 43,200 cfs through the diversion tunnel plug outlet works. An additional 28,800 cfs capacity was gradually absorbed as the powerhouse turbines were added between 1938 and 1961. At present up to 50,000 cfs can be passed through the powerhouses, and the aggregate spillage capacity is assumed to be 493,000 cfs. In 1941 tests were run on the valve houses, which are situated 180 ft above the river on either abutment downstream of the powerhouses.

IN NOVEMBER 1930 the Bureau of Reclamation established a body called the Concrete Research Board, which comprised P.H. Bates, W.K. Hatt, M.ASCE, H.J. Gilkey, M.ASCE, F.R. McMillan, M.ASCE, and R.E. Davis, M.ASCE. Its members met from 1931 through 1934 and provided advice on the many challenging issues encountered during construction, and their work involved considerable research and innovation. The bureau's chief design engineer, John L. "Jack" Savage, M.ASCE, specified four



A daring catwalk suspension bridge was situated 650 ft above the river to enable workers to cross from the Nevada side to work on the Arizona spillway.

BUREAU OF RECLAMATION, *BOTH*



During the spillway tests in the late summer of 1941, water was discharged downstream of the Nevada and Arizona valve houses.

BUREAU OF RECLAMATION, *BOTH*

sacks of cement per cubic yard for the mass concrete in all of his dams. Each sack weighed 96 lb, so 376 lb of cement was used in each cubic yard, precisely the weight of one barrel of cement. Low-heat cement was used for the main dam after a small portion of the base was placed (low-heat cement not yet being available in large quantities). During the winter months workers used a blend of 60 percent low-heat and 40 percent standard portland cement.

The mass concrete allowed rock aggregate up to 9 in. in diameter, which was unusual for mass concrete at that time (this would be equivalent to a size of 8 in. using modern aggregate screens). A fairly "dry mix" was specified, allowing for a 3 in. slump, and standard 6 by 12 in. test cylinders were used. The resulting mix averaged 155.5 lb/cu ft.

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

The dam being of unprecedented height and volume, Bureau of Reclamation engineers soon determined that the cement's intense heat of hydration would cause a major design problem. Even with the low-heat cement, the internal temperature still reached 150°F. The calculated heat of hydration for the final design was 40°F, with 125 years to cure and cool in the absence of artificial cooling. The Concrete Research Board felt that this volume of concrete would set off thermal stresses that would certainly crack the dam. In addition to using low-heat cement, the workers were able to control the internal heating of the mass concrete during hydration by casting the concrete in blocks small enough so that they would shrink monolithically, thereby preventing the development of uncontrolled shrinkage cracks. Dry mixes were specified to reduce shrinkage from moisture changes.

The dam was built in blocks, or vertical columns, varying in size from about 60 ft square at the upstream face of the dam to about 25 ft 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 (see the figure opposite). Lift heights in each block were limited to 5 ft in 72 hours and to 35 ft within 30 days. After the concrete cooled, grout was forced into the spaces created between the columns by the contraction of the cooled concrete to form a monolithic structure. Shrinkage was about 0.5 percent.

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

IN A PROGRAM SUPERVISED by a young physicist from the University of California at Berkeley by the name of Roy Carlson, A.M.ASCE, who was working with Raymond E. Davis, a professor at the university, Hoover Dam was fitted with every sort of measuring instrument then available. By the time Six Companies began placing concrete in June 1933, Carlson had developed and tested electrical instruments that could be embedded in the dam's concrete to measure strain, joint openings, and temperature. These included 450 of his electrical-resistance joint meters, which provided crucial instrumentation of the dam's expansion joints (although some of the meters were rendered inoperative by being carried beyond their design range).

Carlson's resistance strain meters were used to measure the strains engendered by the cement heat of hydration and the dead weight accumulation (as the dam rose higher) and, through inference, to validate the design assumptions about cantilever and arch stress distributions in the trial load method of analysis employed in the dam's design.

These measurements were continued on a regular basis until the end of 1941, when the reservoir had filled and the spillways were tested. Instrument readout banks were established inside the dam's galleries.

One of the most controversial aspects of the Boulder Canyon project was the eventual proposal for the dam to generate electricity and thereby pay for itself over a period of 50 years. It was the first hydropower project undertaken by a federal agency to gain congressional approval, essentially placing the Department of the Interior in competition with private energy providers. Hydroelectric power plants had been constructed by private interests here and there across the United States since the beginning of the 20th century. (The small hydroelectric power plant at Roosevelt Dam, an early Bureau of Reclamation project, was never operated by the bureau.) No hydroelectric generation scheme on the scale of what was proposed at Hoover Dam had ever been undertaken by the bureau or, for that matter, by anyone else.

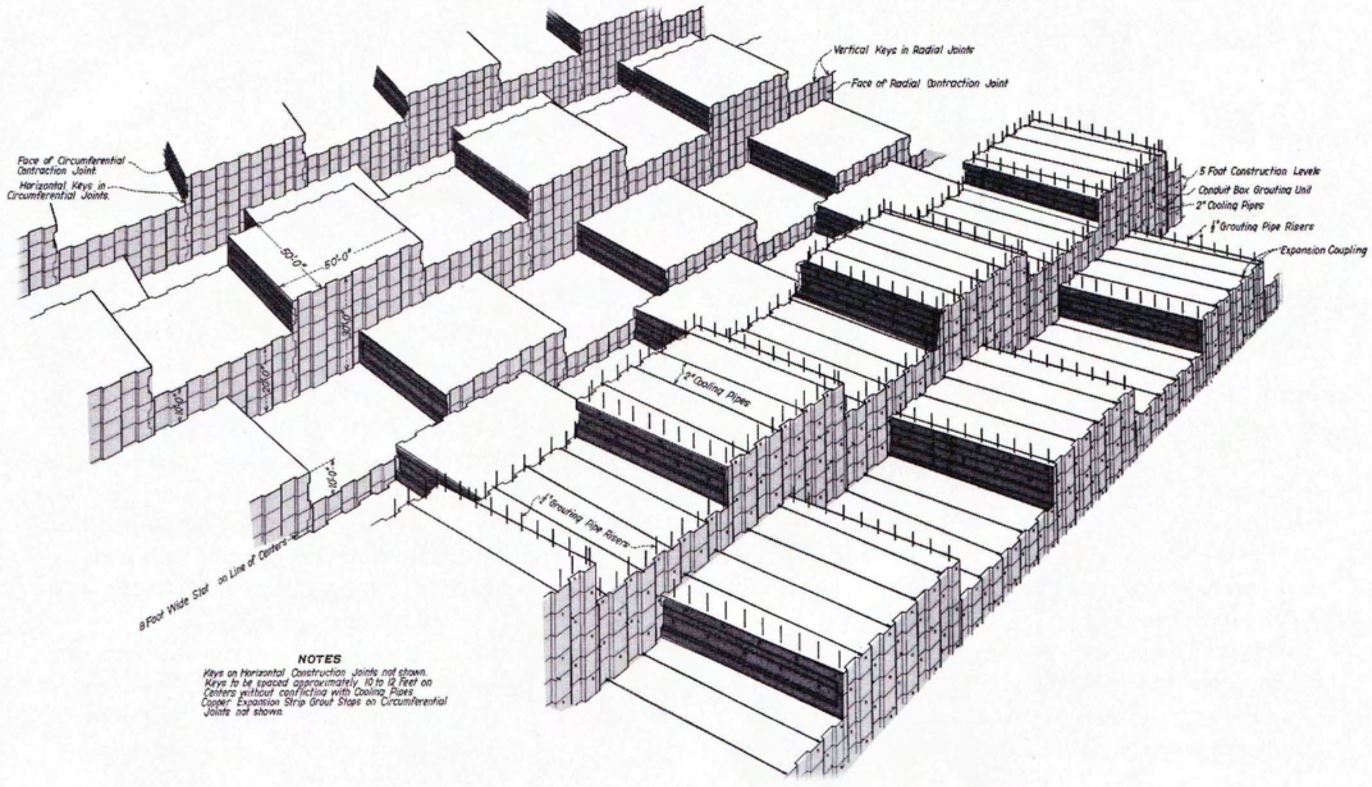
The Hoover power plant was split into two separate powerhouses on the Arizona and Nevada banks of the Colorado River just downstream of the dam. Many critics felt there would be undue transmission loss caused by the turbulence and spray of bypassed flows (the flows not run through the powerhouses), so the design was altered to move the valve houses, outlet works, and spillway aprons downstream of the powerhouses.

Each powerhouse is 650 ft long with 10 acres of floor space to accommodate eight Francis turbines (originally developed by the engineer James Bicheno Francis, who was born in Britain and immigrated to this country as a young man) and two smaller Pelton waterwheel turbines (invented by Lester Allan Pelton in the 1870s), the latter for internal power production. As an economic incentive during the Great Depression, the Bureau of Reclamation purchased turbines from every manufacturer in the United States. The generating units comprised an exciter, a rotor, a stator, and a shaft, as shown in the figure on page 58.

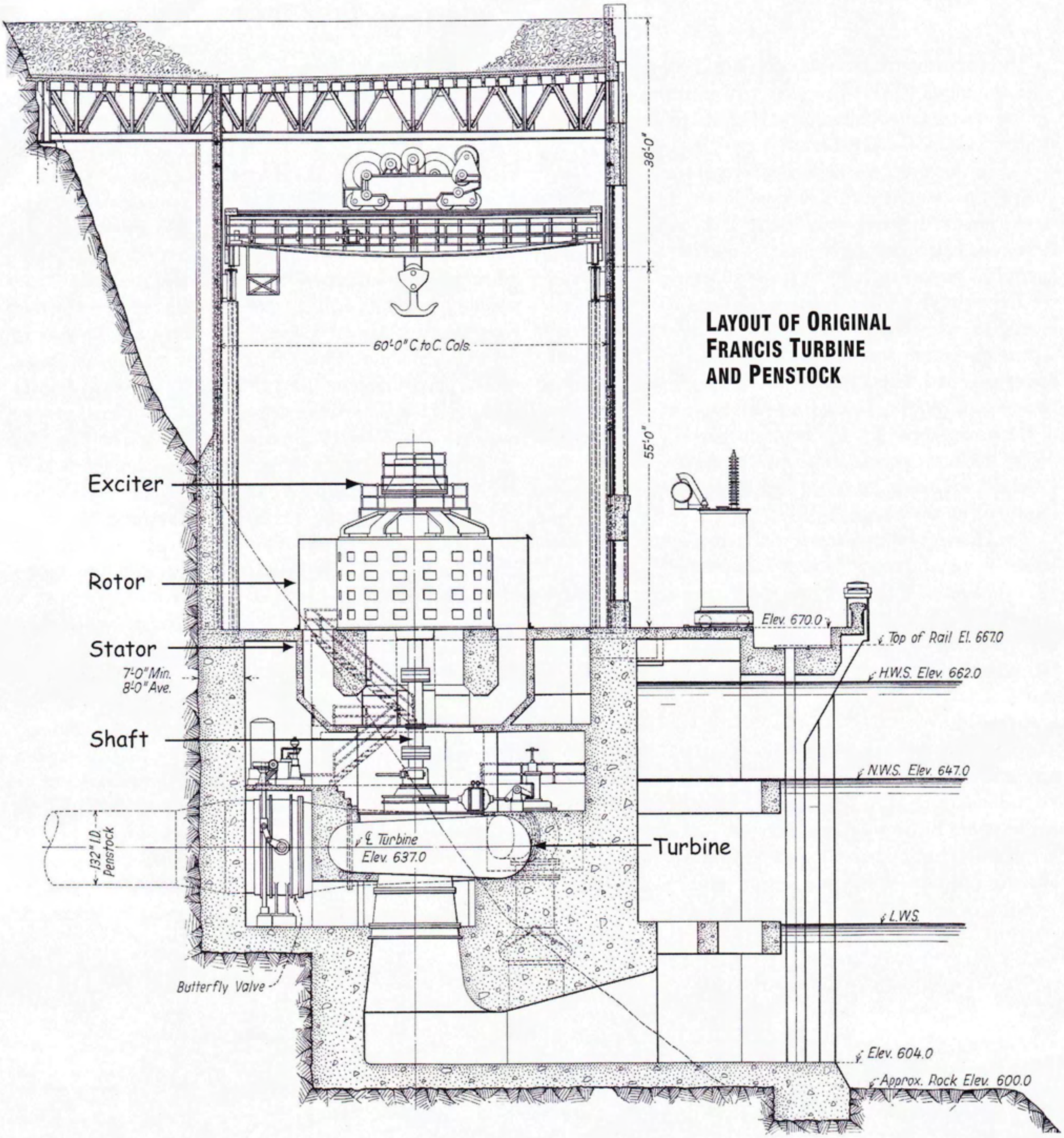
The exciter is itself a small generator that produces electricity, which is sent to the rotor, charging it with a magnetic field. The rotor comprises a series of electromagnets—also called poles—connected to the shaft so that the rotor rotates when the shaft rotates. The stator is a coil of copper wire that is stationary. The shaft connects the exciter and the rotor to the turbine. Water strikes the turbine, causing it to spin.

The government installed all of the generators at Hoover Dam after Six Companies delivered the completed powerhouses in November 1935 (see the photograph on page 59). The first generator to go into operation was known as N-2, and it began providing power on October 26, 1936. The second to go into operation was N-4, on November 14, 1936, and generator N-1 began producing electricity on December 28, 1936. Generators N-3 and A-8 begin operating on respectively March 22, 1937, and August 16, 1937.

By the late summer of 1938 storage in Lake Mead, the reservoir formed by the dam, had reached 24 million acre-ft, and the new reservoir stretched 110 mi upstream, into the lower Grand Canyon. Generators N-5 and N-6 came onstream on respectively June 26 and August 31 of that year. By 1939 storage in Lake Mead had reached 25 million acre-ft, or more than 8 trillion gal. Generators A-7 and A-6 began operations on respectively June 19 and September 12 of that year. With an installed capacity of 704,800 kW, the Hoover power plant was the largest hydroelectric



The offsets of the monolithic blocks comprising the dam were intended to avoid the formation of random shrinkage cracks within the structure. Beveled shear keys between the blocks and the cooling pipes were laid parallel to the dam's radius.



LAYOUT OF ORIGINAL FRANCIS TURBINE AND PENSTOCK

facility in the world, a distinction held until surpassed by the Grand Coulee Dam's power plant in 1949.

In 1940 Hoover Dam produced 3 billion kWh of electricity. On October 9, 1941, generator A-1 was placed in operation, bringing to 10 the number of units in service. Generator A-2 began operations in July 1942, followed by unit A-5 in January 1943 and unit N-7 in November 1944. In October 1946 a ceremony was held at the dam commemorating 10 years of commercial power production. In 1952 units A-3, A-4, and A-9 were placed into service, and during 1952 and 1953 a record amount of 6.4 million kWh was generated. The final generating unit, N-8, was placed in service in 1961, bringing the capacity of the power plant to 1,334,800 kW.

In the early 1980s the Bureau of Reclamation began updating the power units at Hoover Dam, and by 1990 10 of the 82,500 kW units had been upgraded to 130,000 kW and 2 of them had been upgraded to 127,000 kW. The remaining 82,500 kW units have been upgraded to 130,000 kW. Moreover, the 40,000 kW unit was upgraded to 61,500 kW and the 50,000 kW unit to 68,500 kW. The upgrades were completed between 1986 and 1993. Today there are 13 generators with a capacity of 130,000 kW, 2 of 127,000 kW, 1 of 61,500 kW, and 1 of 68,500 kW. All machines are operated at 60 cycles per second. There are also two 2,400 kW units for station service driven by Pelton waterwheels. These provide electric energy for the powerhouse and dam.

The average annual net generation of the Hoover power plant for the operating years 1947 through 1994 was about 4 billion kWh. The maximum annual net generation at the plant was 10,348,020,500 kWh, which was in 1984, while the minimum annual net generation since 1940 was 2,648,224,700 kWh, which was in 1956.

In the original power contracts negotiated during the dam's construction (from 1931 to 1935), the principal consumers that negotiated long-term contracts for Hoover Dam's hydroelectric power were Arizona (18.9527 percent), Nevada (23.3706 percent), the Metropolitan Water District of Southern California (28.5393 percent), the City of Los Angeles (15.4229 percent), and Southern California Edison (5.5377 percent).

THE COSTS that had been incurred in constructing the dam and placing it in service by 1937 were repaid by the sale of electricity on May 31, 1987. All other costs were to be repaid within 50 years of the date of installation or as established by Congress. Repayment of the $25-million construction cost allocated to flood control was subsequently deferred beyond 1987, and further action will be subject to congressional direction. Arizona and Nevada each receive $300,000 annually, paid from revenues, and $500,000 annually is set aside from revenues for further irrigation and power development in the Colorado River basin.

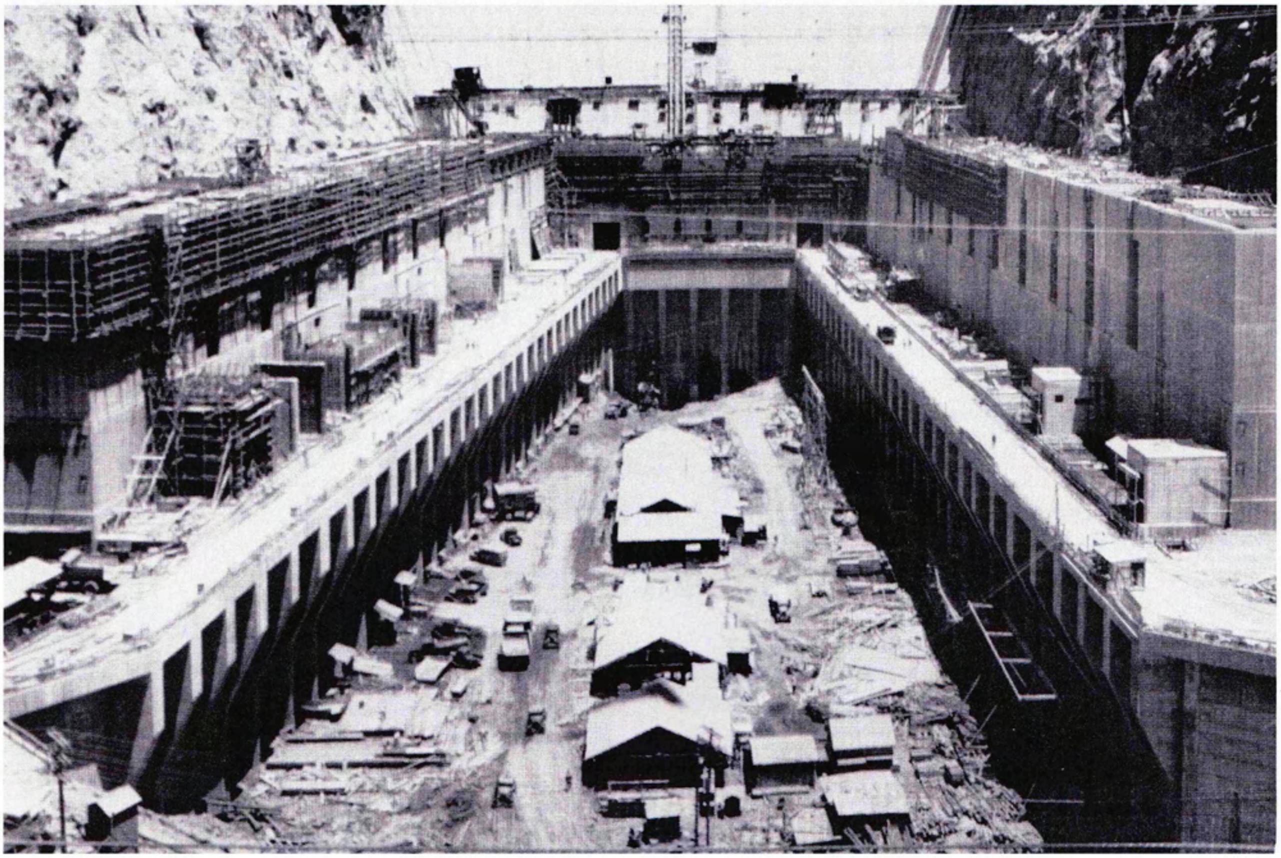
One of the unprecedented challenges at Hoover Dam was the sheer scale of the spillway tunnels. The Bureau of Reclamation recognized that the greatest potential for problems existed at the transition elbows. At these transitions the diversion tunnel was plugged with concrete, and a curved transition to the inclined section dropping 500 ft vertically from the side-channel spillway troughs had to be formed with smooth, high-strength concrete. When the lining of these transitions was completed, in March 1934, it was discovered that there was a 3 in. misalignment between the segment that had been excavated from the top down and the segment constructed from the diversion tunnels upward. No one was overly concerned, and the slight imperfection was glossed over with an application of neat grout.

Water impoundment behind Hoover Dam began on February 1, 1935, four months before the last concrete was placed on the dam. The dam was dedicated on September 30, and Elwood Mead, who, as mentioned above, had served as commissioner of the Bureau of Reclamation, died a few months later, on January 28, 1936. The new reservoir was christened Lake Mead in his honor shortly thereafter, in April 1936. The reservoir continued to fill and by early June 1941 had reached an elevation of 1,205 ft, flush with the crest of the side-channel spillways.

The drum gates were raised, and the reservoir continued to fill, reaching 1,220.45 ft by July 30, 1941, within 11.55 ft of the dam crest. On August 6 the drum gates were gradually lowered, and spillway tests were carried out until early October. Relatively modest flows, never exceeding 13,000 cfs, were passed through both spillways for four months. Even with the modest flows, velocities at the elbows reached 175 ft/s, and cavitation damage ensued on both spillways (see the photograph on page 63). The cavitation was most severe on the Arizona spillway elbow, where a hole 112 ft long, 35 ft wide, and up to 36 ft deep formed in the high-strength reinforced concrete on the Arizona spillway.

The Bureau of Reclamation chose a method that was new at the time to repair the spillway damage—a method developed by the Prepakt Concrete Company, now defunct. The process was implemented during the winter of 1941–42. Despite the evidence revealed by the cavitation, the bureau remained unconvinced that it could be attributed to anything but "roughness" and "irregularities" in the concrete lining. The bureau directed the contractor to "remove surface irregularities." These repairs were not completed until 1943 because of wartime shortages of reinforcing steel.

The last major structures to be constructed at the dam, on June 24, 1935, were the two powerhouses.



BUREAU OF RECLAMATION, *BOTH*

In the spring of 1945 the bureau let a contract to correct problems with the outboard spillway diversion tunnel on the Nevada side and to effect improvements to the river channel. These problems had been revealed during the four months of spillage in the fall of 1941, when the outflow swept considerable debris downstream, clogging the outlet area downstream of the inboard tunnel. The river channel was also deepened immediately downstream of the dam to increase the net energy head on the turbines by lowering the tailwater. This work was deferred until 1945 because of wartime material priorities.

That same year, the bureau began investigating the possibility of installing aeration devices in the spillway tunnels, but it concluded that the air introduced into the water dispersed too rapidly to prevent cavitation along the tunnel invert. For the next half-century the bureau held a minority view among dam engineers, contending that cavitation was ascribable to imperfections in the smoothness of concrete linings, not simply to velocities exceeding 100 to 114 ft/s, a view held by a number of people many years later.

The roughness assumption was finally proven false to everyone's satisfaction during spillage at Glen Canyon Dam and Hoover Dam in the summer of 1983. That year the upper part of the Colorado River basin experienced an abnormally late mountain snow accumulation, followed by an accelerated snowpack ablation, which triggered early seasonal flooding. Many Bureau of Reclamation reservoirs found themselves without sufficient flood storage to handle the unanticipated inflows.

The tunnel spillways at Glen Canyon Dam and Hoover Dam were operated through most of that summer, Hoover spilling between July 2 and September 6. The left spillway at Glen Canyon Dam passed up to 32,000 cfs, but neither of those at Hoover Dam ever exceeded 14,000 cfs (about 4.5 ft above the raised drum gates). Despite these relatively low flows, both dams experienced the same style of cavitation damage that had afflicted Hoover Dam in 1941.

The bureau had been studying aeration ducts for the previous 15 years because of concerns about cavitation damage at Yellowtail Dam in 1967. After the 1983 floods the bureau undertook a comprehensive program using aeration slots to retrofit its high dams to alleviate cavitation. These slots were added to the Hoover Dam spillways in 1985 and 1986.

DURING THE EXPLORATION of Black Canyon prior to 1931, 22 exploratory borings along four lines were advanced across the Colorado River channel beneath the proposed dam. The primary focus of the exploratory borings was to ascertain the depth and character of the channel fill and the profile of the bedrock. One deep boring was drilled to a depth of 545 ft below the low-water level to ascertain whether the andesite breccia continued to great depth. Assessments of the dam abutments were limited to shallow 6 in. cores, which were extracted for unconfined compression tests. To explore foundation conditions, the Bureau of Reclamation also excavated exploratory adits into both abutments.

The principal rocks found during these surveys were latite flow breccias, dam breccia, and basalt dikes that perturbed both abutments. The latite breccia was characterized by locally intense fractures, especially along faults and shear zones. These inclined faults also crisscrossed one another.

Some hot springs also were noted at the upstream base of the right abutment at river level. Crude percolation tests were employed using a gravity feed reservoir that fed to drill holes through sealed pipes. These could not replicate the pore pressures induced by 500 to 800 ft of head. The geology of the dam base was mapped after excavation of the channel gravels. The Bureau of Reclamation's geologic consultant. Frederick Leslie Ransome, Ph.D., who earlier had worked for the U.S. Geological Survey, noted dozens of faults and adjacent zones of intense shearing.

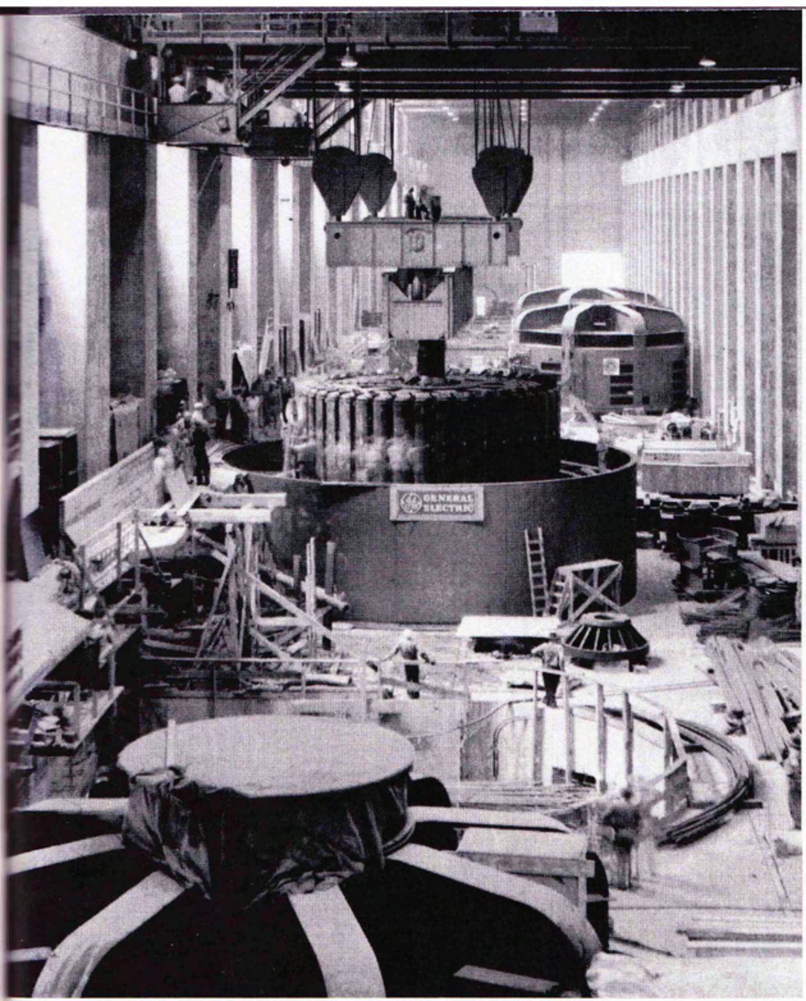
A specially designed joint was employed between the dam concrete and the rock abutments. These joints were not grouted prior to the reservoir filling because the designers believed the dam would deflect downstream under a full reservoir load. A conventional grout curtain was installed beneath the dam's upstream axis. This included a single line of holes 100 to 125 ft deep, or about 14 to 21 percent of the dam height.

These depths were based on a survey of existing dams with grout curtains that the Bureau of Reclamation had conducted prior to construction. Foundation grouting was carried out during construction in 1932 and 1933 along a single line of grout holes. This included grouting of some of the principal faults on both abutments. On the Nevada abutment, between elevations 840 and 940, several grout holes penetrated two minor faults, and four holes had to be abandoned because of excessive grout intake and leaks.

When the reservoir reached 1,100 ft in elevation, in 1937, the faults could be seen from the surface in the right abutment, and water began entering the fault zone. At this time the abutment drains on the Nevada side began discharging cool water. Warm water from the natural hot springs was collected along the right abutment drainage gallery near elevation 555, emanating from several "shattered" zones. It turned out that the original grouting of this area was ineffective because of the premature setting of the cement grout brought about by the elevated water and ground temperatures.

The layout of the original grout curtain included four rows of shallow holes (labeled with the letter *B* in the figure at the bottom of page 65) drilled 30 to 50 ft deep and spaced 20 ft apart. These were referred to as dental work. The holes labeled with a *C* were drilled on an incline from outside the upstream heel of the dam at 10 ft spacings to a maximum depth of 100 ft. The *C* holes were grouted with pressures of up to 900 psi prior to the drilling of another set of holes from the lower drainage gallery. Labeled *A* (not shown in the figure), these holes were inclined upstream. Forming the curtain, they were 150 ft deep, spaced 5 ft apart on center, and inclined 15 degrees in the upstream direction. Some 191 of these *A* holes were drilled on the Nevada side, but 33 ended up being abandoned because of loss of circulation. Some 202 *A* holes were advanced on the Arizona side, 21 of which had to be abandoned.

A line of vertical drain holes 100 ft deep was drilled just downstream of the grout curtain. These uplift relief holes along the dam's upstream centerline extended a maximum



A gantry crane in the Nevada powerhouse lowered a 500-ton rotor for generator N-2, one of the 82,500 kW generating turbines, on October 26, 1936. N-2 was the first generator to be brought onstream at Hoover Dam.

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of 100 ft. It turned out that the ratio of the dam height to the depth of the uplift relief holes was far too low.

BY THE SECOND YEAR OF OPERATION (June 1937), abnormally high uplift pressures began developing beneath the right center of the dam. The inflowing abutment seepage began overwhelming the lower galleries, pouring out of the canyon wall above the Nevada powerhouse. In addition to these unforeseen levels of seepage, alkaline water seeping into the lower penstock header tunnel began accelerating the corrosion of the steel penstock. Hot alkaline water also began seeping through the concrete liner of the inboard 56 ft diameter Nevada diversion tunnel and spilling onto the 30 ft diameter steel penstock feeder, again accelerating the corrosion of the steel penstock. These seepage problems were mitigated by additional grouting around the 56 ft diameter diversion tunnel.

A number of through-going faults, those extending through an entire formation, also were exposed in the Nevada spillway excavations. After the reservoir filled, the Nevada spillway shaft experienced significant seepage along brecciated zones adjacent to these faults. An extensive program of postconstruction grouting was carried out during the 1940s to extend a grout curtain beneath the Nevada spillway and intake towers. This program succeeded in mitigating the seepage problems that arose in 1937. Excessive seepage also manifested itself along two fault strands through the right abutment when the reservoir reached an elevation of 1,100 ft, 132 ft below crest.

The reservoir uplift reached its maximum levels in September 1938. At that juncture the decision was made to drill a series of BX size cores—that is, those with a 3 in. outer diameter—in the foundation beneath the dam. The drilling revealed that the grout curtain was much too shallow on the faulted abutments. This was because six zones of intensely sheared rock were feeding water into the foundation, and a series of crisscrossing manganese gouge seams were perching the underseepage, causing abnormally high pore pressures to develop.

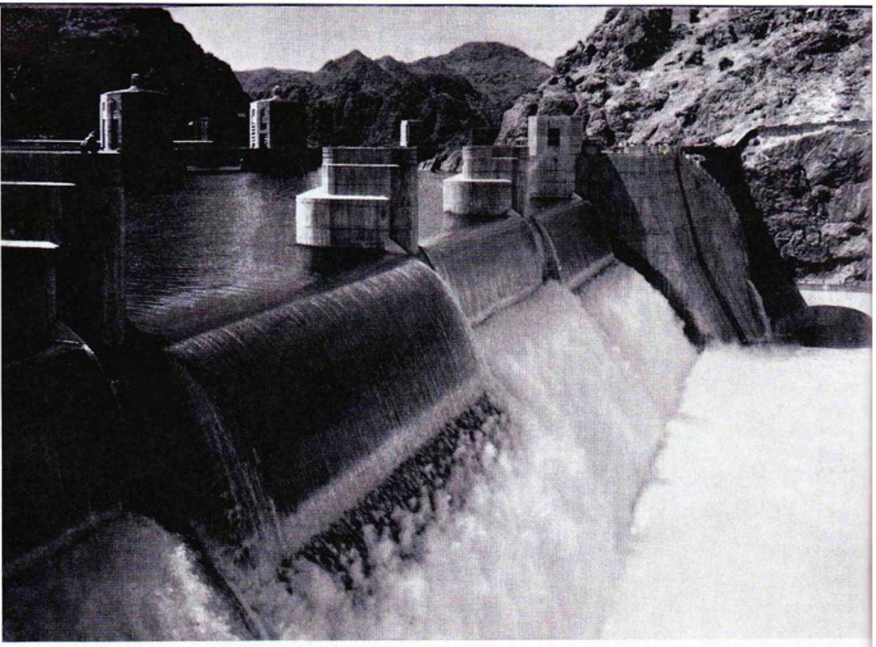
The dam's grout curtain was extended extensively between 1938 and 1947. The grout holes were extended to depths of 300 ft beneath the dam's foundation, then injected with cement grout under very high pressure to counteract the 350 to 1,026 ft of vertical pressure exerted by the reservoir on the dam's foundations. The holes were drilled from the dam's system of internal inspection galleries; a schematic view of the deepened grout curtain as it appeared in 1947 is shown in the figure at the top of page 65.

During the 12-year supplemental drilling program, 410,000 linear ft of grout and drainage holes were drilled, and 422,000 cu ft of grout was injected under pressure. This remedial program, which included other remedial protective measures and considerable work on the Nevada spillway, cost an additional $3.86 million. This significantly reduced uplift, which was corroborated by measurements.

The failure of the Hoover Dam grout curtain was ascribable to some manganese-rich gouge zones deep in the dam foundation that developed by chemical weathering along faults and shear zones that perturbed the volcanic strata. The failure to recognize these features demonstrated that mapping surficial geology in detail is not useful unless that effort is accompanied by a thorough understanding of how the geologic conditions might affect the proposed structure. The Bureau of Reclamation's Board of Consulting Engineers did not include an engineering geologist, so there was no technical oversight of the geologic information collected in the field during construction. If the design assumptions about the foundation conditions had been shown to be invalid, some sort of action should have been taken.

Black Canyon turned out to be an area of considerable geologic complexity, as it is pervasively sheared by more than 500 mapped faults. Detailed structural geologic assessments were carried out in the vicinity of Hoover Dam and Black Canyon in the early 1980s by French geologists working with the U.S. Geological Survey. This work revealed that two stages of extensional tectonism occurred at the dam site. Extensional tectonism can be expected to perturb a brittle ground mass, creating numerous shears, faults, and breccia zones. Hydrothermal activity can cause mineralization and infilling of voids with secondary products—sodium, calcium, potassium, phosphorus, and sulfurous salts—not visible from the ground surface.

The exploration and characterization of the foundation



Water from Lake Mead was discharged over the four drum gates of the Nevada spillway during a test conducted in August and October 1941.

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materials beneath and adjacent to the dam were insufficient, especially with regard to the faults, shears, and breccia zones. The grouting program was insufficiently deep and insufficiently redundant to provide an adequate seepage cutoff.

ON NOVEMBER 30, 1939, just three months after World War II began but two years before America's entry into the conflict, the U.S. embassy in Mexico City received a tip concerning a plot by agents in Germany's Mexico City embassy to bomb the intake towers at Hoover Dam. The attack was intended to paralyze the American aviation industry, which was showing signs of aiding Great Britain. Two German agents were already living in Las Vegas, one of whom was an explosives expert. One of these agents was believed to have made a dozen visits to the dam for reconnaissance purposes, and a person overheard to be speaking with a German accent and presumed to be a German citizen was observed by a National Park Service ranger taking dozens of detailed photos of Hoover Dam in early October.

The German plan envisioned the pair posing as fishermen, renting a boat at Boulder Bay Marina, making their way to the intake towers after dusk, and planting the explosives inside the towers. (No details were ever revealed about how they would pierce the stainless steel screens on the gates of the towers.) A second prong of this attack was to have included setting similar charges off at the substation near Boulder City, where the two high-voltage transmission lines bifurcate.

The U.S. Department of State promptly notified the Bureau of Reclamation in Washington, D.C., but asked that it not reveal any details of the plan, lest the news leak to the public. The bureau banned all private boats from Black Canyon and a few days later placed restrictions on employees at the dam and visitors. On December 9 the bureau requested the aid of the Federal Bureau of Investigation (FBI) to assess the vulnerability of the dam to sabotage. A steel mesh net supported by cables extending across the canyon was installed 300 ft upstream of the intake towers to prevent boats from passing, and floodlights were installed to illuminate the lake upstream of the dam.

In January 1940 the FBI issued a report listing 38 security precautions that could be implemented to protect the dam, including additional training for the dam's rangers. Some 149 men subsequently received this specialized training from the FBI. Rumors of plots to sabotage the dam spread quickly because of all the precautionary measures being taken. In February 1940 information on yet another plot was passed on to the Bureau of Reclamation, this one involving sabotage of power-generating stations in Southern California. The German agents slated to carry out these attacks were supposedly coming from Havana, Cuba.

In June 1940 the Department of the Interior asked the Department of War to furnish armed guards to protect and patrol the potentially vital features of Hoover Dam and its power plant as well as the switchyard just outside at Boulder City. The Department of War denied the request, but Senator Patrick McCarran of Nevada introduced legislation to establish an army post at Boulder City to protect vital federal property. In July 1940 a Bureau of Reclamation warehouse at Parker Dam burned down under suspicious circumstances.

In response to these political pressures, the army announced in December 1940 that it would establish a cantonment of 800 soldiers near Boulder City to train military policemen. This new facility was christened Camp Siebert for Major General William L. Siebert, who, as mentioned above, had chaired the CRB. (It was subsequently renamed Camp Williston when a larger Camp Siebert was established in the general's home state of Alabama.) In July 1941 the army agreed to allow some of these military police soldiers to patrol the transmission switchyards.

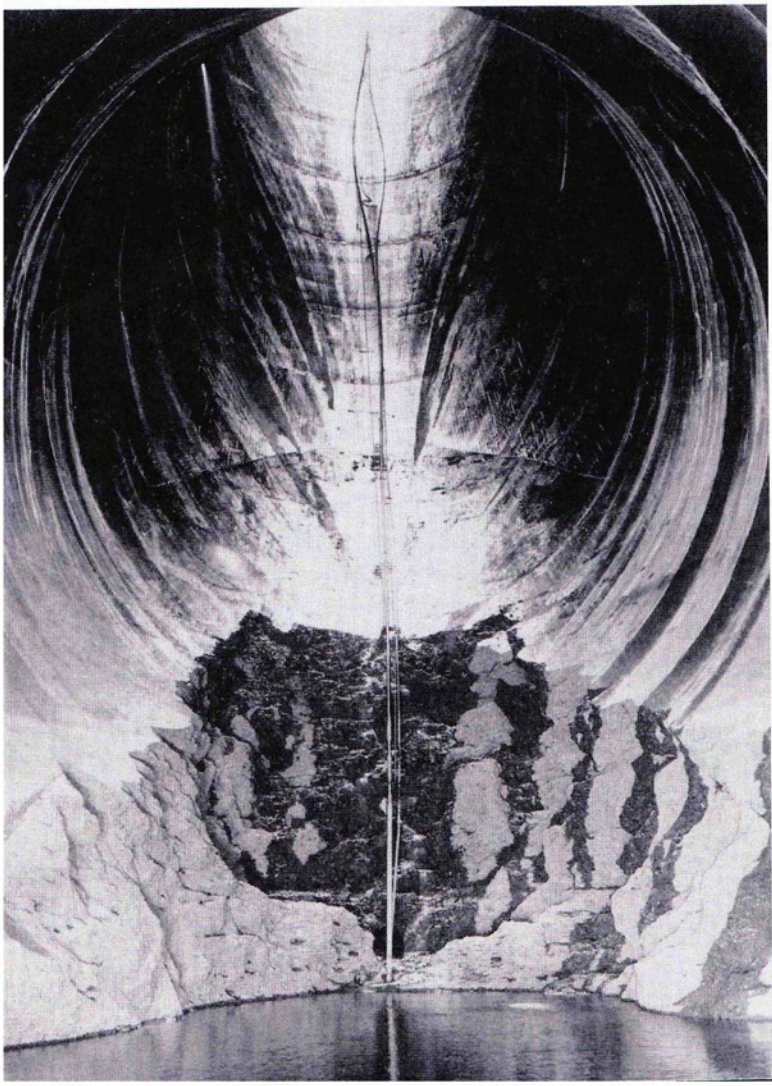
The Bureau of Reclamation continued to allow tours of the dam until Pearl Harbor was attacked, on December 7, 1941. That day the dam was closed to the public at 5:30 PM and remained closed for the duration of World War II. The dam's lights were turned off, and roadblocks were established on either side of the dam along U.S. Highway 93 that evening. From that point onward the army agreed to provide a convoy escort for vehicles crossing the dam on Highway 93 between Boulder City and Kingman, Arizona, until these soldiers were transferred to overseas assignments.

On December 8 of that year the Bureau of Reclamation formally requested army assistance in protecting the Hoover, Grand Coulee, and Parker dams, which were producing half of all the electric power used in the West Coast wartime production plants. (Parker Dam also provided pumping power for the Colorado River Aqueduct, which was vital to Southern California.) Security precautions then shifted to defense against aerial attack, and a no-fly zone was established around the dam, although there was no means to enforce the restriction. (General George S. Patton flew over the dam at a height of just 500 ft on

July 6, 1942, while he was commanding desert maneuvers a few hundred miles to the south.)

During the summer of 1942 the Bureau of Reclamation and the army began exploring various means of protecting the Hoover, Parker, Grand Coulee, and Shasta dams from aerial attack, including smoke generators and a number of elaborate camouflage schemes. (Shasta Dam was actually under construction throughout the war and was completed in 1945.) At that time Corps of Engineers battalions included dedicated "camouflage companies" trained and equipped solely for that purpose.

In an April 1943 letter to the chief of engineers, Colonel W.J. Matteson provided a review of the plan to camouflage Hoover Dam by the Colorado artist Allen True and outlined additional or alternative measures that might be employed to protect the Hoover, Parker, Grand Coulee, and Shasta dams. Classified "secret," True's scheme involved the erection of a cable-supported dummy dam upstream of the actual dam. The ruse would have employed a network of highly reflective features attached to welded wire mesh draped over heavy supporting cables attached to the steep walls of Black Canyon. This scheme was designed to look like concrete and rock. Similar techniques were employed by the Germans and the British to camouflage such valuable targets as factories, airfields, locks, bridges, and highways.



Cavitation damage was observed in December 1941 in the elbow of the Arizona spillway after modest discharges passed through the spillway between August and October 1941. The damage came as a great surprise to the U.S. Bureau of Reclamation.

AUTHOR'S COLLECTION

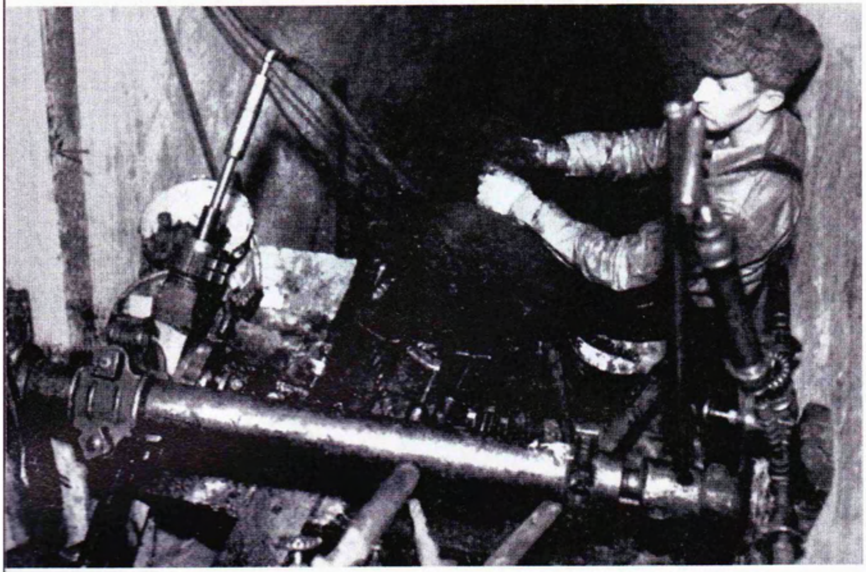
An alternative plan for a three-quarter scale wire frame "decoy dam" downstream of the actual structure also was conceived but never implemented. Matteson felt that it would be far less expensive to employ smoke screens to protect the dam and powerhouse, which "would render precision bombing impossible." He noted that the smoke screens could be deployed in just 15 minutes, provided they were ready and manned. He also expressed considerable doubt about the difficulty of employing similar camouflage schemes at the other three dams because, in contrast to Hoover Dam, they were not situated in narrow, steep canyons. Rumors still abound concerning a World War II–era "floating decoy dam," its lights having been seen, but these rumors are entirely without foundation.

In September 1943 the army informed the Bureau of Reclamation that it was repositioning its military police soldiers in preparation for overseas deployment and that it would no longer be available to help guard the dam or assist with convoys of vehicles. The bureau appealed for help from the FBI but was rebuffed. In January 1944 an army intelligence officer prepared a report on allegations of lax security at the dam, finding some to be without merit but others having foundation. The report concluded that since no security breaches had occurred, it would be difficult to justify assigning additional military resources to the dam. In 1946 public visitation resumed, and the security force dwindled to 7 watchmen and the 29 rangers who performed myriad collateral duties in addition to security. The dam did not reopen to the public until August 1945.

IN THE LATE SUMMER OF 1940 the German Luftwaffe began hammering the British Isles, initially focusing their efforts on bombing airfields, aircraft factories, and munitions plants. In January 1941 the United States entered into a massive lend-lease agreement with Great Britain. The United States agreed to supply the British with massive amounts of magnesium because of its value in aircraft production. Magnesium's low specific weight (about two-thirds that of aluminum) was most advantageous when blended with aluminum and zinc. Magnesium and phosphorus also were requested by the British for munitions.

The Las Vegas area quickly emerged as a likely site for constructing the world's largest magnesium-processing facility because of the vast magnesium deposits in southern Nevada and the proximity to unlimited quantities of freshwater and electric power that could be drawn from respectively Lake Mead and Hoover Dam. These resources are essential to the two-step electrolytic processes used to process magnesium ore. The government moved quickly, selecting a site on the alluvial fan between Las Vegas and Boulder City and beginning construction of the Basic Magnesium Industries (BMI) plant in June 1941 (six months before the attack on Pearl Harbor). The government's plans included the initial construction of 1,000 homes for workers and their families in what was christened the Basic Townsite. (It was renamed Henderson, Nevada, after the war.)

The BMI plant received top government priority with respect to materials and draft deferments offered to those working in critical defense industries. These advantages enabled it to begin operations in November 1941, just five months after the first land was purchased. The plant continued expanding throughout 1942 and 1943, triggering feverish construction activity to keep up with the housing demand. In 1942 the Defense Housing Corporation met the accelerated demand by constructing the first 300-unit Victory Village complex, which included schools, a recreation center, apartments, and dormitories for single workers. Despite these accommodations, there was a chronic shortage of defense workers, in large measure because of competition from aircraft plants, steel mills, and shipyards in nearby Southern California, where the weather was more favorable and the environment more family friendly (no casinos).



Cramped working spaces typified the nine-year program of extending the grout curtain, which ran from 1938 to 1947.

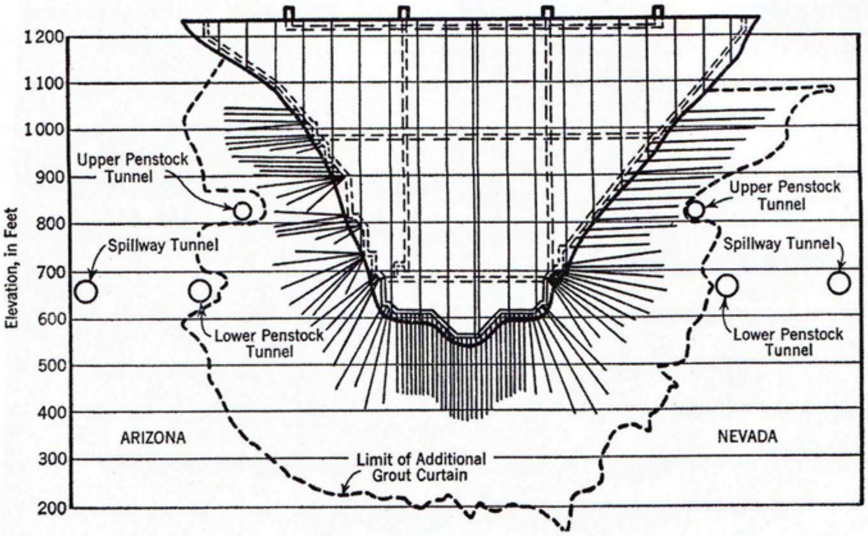
BUREAU OF RECLAMATION

BMI overcame its manpower shortfall primarily with African-American workers from Mississippi, who were undaunted by southern Nevada's intense heat. This was during the era of segregation, so the Defense Housing Corporation scrambled to build a separate 324-unit Victory Village on the desolate western side of Las Vegas, which it named Carver Village (for George Washington Carver). By mid-1943 this sprawling complex would include 10 separate plants employing 5,000 workers. By war's end BMI would employ almost 10,000 workers.

HOOVER DAM was the Bureau of Reclamation's first hydroelectric generating project of any consequence and one of the world's largest hydroelectric power plants. Its detractors did not envision a need for so much electricity in the sparsely populated American Southwest. The last generating unit was not brought onstream until 1961, 26 years after the dam's completion. The most important aspect of the bureau entering the utility marketplace was the ability it gave the bureau to recover the cost of increasingly large and ambitious projects that almost no one had envisioned for the American West prior to the construction of Hoover Dam. Indeed, the dam was viewed as something of an aberration made possible by the political intrigue of Southern California. The bureau projects that followed in quick succession across the American West bear testimony to an era of massive public works construction undertaken by the federal government that proved to be of inestimable value during World War II (such as the BSI plant) and in the postwar expansion in the Southwest, which continues to this day.

Much less publicized aspects of Hoover Dam included the operational failings that occurred, but from these much valuable engineering information that affected dam engineering worldwide was gleaned. The failure of the dam's grout curtain led to excessive uplift pressures beneath the right side of the dam, which were of unprecedented scale. These were ascribable to the complex faulting and geologic structure associated with Tertiary age volcanic units located in a tectonically active portion of the Basin and Range Province. The geologic reconnaissance that preceded the dam's construction was of a fundamental nature, with very little energy expended to drill into the abutments and ascertain the nature of the volcanostratigraphy or block faulting. It was clear to the investigators that the site was complexly faulted, and it would be difficult to envision the siting of a massive concrete dam at the same site today given the state of the practice in dam safety considerations. (There are 26 faults that are less than 4 million years old beneath the dam's foundation.) Engineering geology was in its embryonic years when Hoover Dam was designed and constructed, and very little attention was paid to evaluating stratigraphy and structure at any significant depth beneath or adjacent to the dam's foundation. Considerations of block kinematics were altogether nonexistent until the 1970s, when the failure mode that triggered the collapse of France's Malpasset Dam, in 1959, became better understood and appreciated.

The cavitation damage experienced in the spillway elbows at Hoover Dam in 1941 and again in 1983 was perhaps the Bureau of Reclamation's greatest failing. In the 1930s there were very few high dams (more than 200 ft) with any appreciable record of operation at which velocities of more than 150 ft/s were reached. At that time many engineers noted that concrete with a smooth finish tended to exhibit less of a tendency toward cavitation than did rougher surfaces. Bureau engineers attributed the 1941 cavitation damage at Hoover Dam to surveying imprecision between the diversion tunnels and the inclined shafts coming from the abutment spillways, which caused a misalignment of $^{1}/_{2}$ in. Their repairs in 1942 and 1943 focused exclusively on replacing the damaged elbows with a thoroughly smooth transition, one bereft of any "alignment bumps." This same approach was used on all subsequent high dams built by the bureau in the 1960s, including Glen Canyon Dam and Yellowtail Dam.

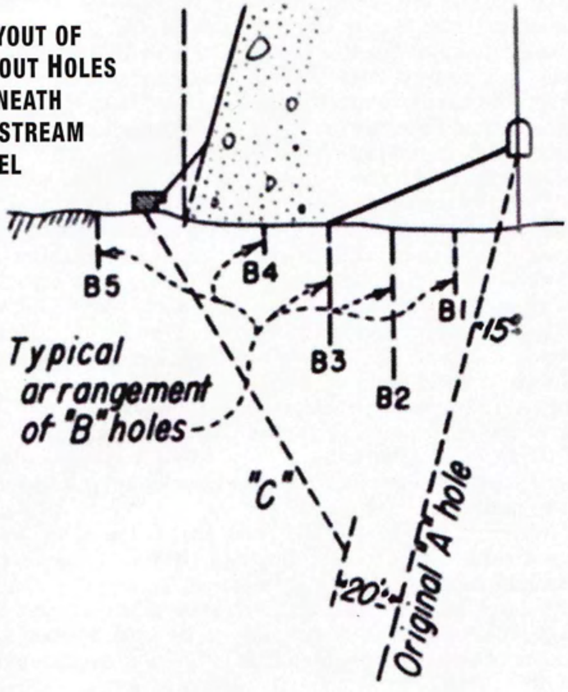


PROFILE OF DAM CENTERLINE SHOWING DEEPENED GROUT CURTAIN

During this same period (1945–83) many dam engineers took exception to the bureau's views, arguing that cavitation was most ascribable to the implosion of entrained air at velocities of between 114 and 150 ft/s. This view was being borne out in the massive postwar projects being built elsewhere around the globe, which had suffered grievous cavitation damage until air ducts were installed. The bureau studied these largely foreign projects (many of the consultants on those projects being former bureau engineers) and developed contingency plans for retrofitting their highest dams with air ducts, but the funds were not forthcoming.

When the 1983 spring flows necessitated modest levels of spillage at Glen Canyon Dam and Hoover Dam, all of the spillway elbows suffered cavitation damage, requiring emergency repairs. The Bureau of Reclamation's repairs included the insertion of air ducts, bringing the bureau in line with general practice worldwide.

LAYOUT OF GROUT HOLES BENEATH UPSTREAM HEEL



BUREAU OF RECLAMATION, TOP; AUTHOR'S COLLECTION, BOTTOM

IN 1955 ASCE selected Hoover Dam as one of its Seven Wonders of the Modern World, and in 1985 it included the structure in its Historic Civil Engineering Landmark Program. Also in 1985, in recognition if the dam's contribution to the history of the Southwest, the U.S. Department of the Interior designated it a national historic landmark. In 2000 ASCE again recognized the dam, this time as part of its Monuments of the Millennium program. For years engineers and politicians have touted the benefits of Hoover Dam to society. These benefits include the following:

- The dam can store a two-year supply of the average flow of the Colorado River, the water to be released as needed.
- More than 15 million people use water taken from the Colorado River, including the Arizona cities of Phoenix and Tucson and cities in California's Los Angeles, Orange, and San Diego counties.
- Water from the Colorado River is diverted to irrigate 750,000 acres in California and Arizona, as well as 470,000 acres in Mexico.
- The Imperial and Coachella valleys have become the "salad bowls" of the Southwest, providing the entire United States with lettuce, carrots, and other crops during cool winter months. These cash crops are valued at more than $1 billion annually.
- Hoover Dam's power plant produces 4 billion kWh of clean, nonpolluting electric energy each year, providing power to 1.3 million people in Nevada, Arizona, and California.
- Hoover Dam generates $1 billion in economic benefits to the American Southwest each year.
- More than 700,000 people visit the dam each year. **CE**


Rogers

J. David Rogers, Ph.D., P.E., R.G., C.E.G., C.HG, M.ASCE, holds the Karl F. Hasselmann Chair in Geological Engineering at the Missouri University of Science and Technology. Rogers has 25 years of experience in evaluating the stability of natural slopes, embankments, stream channels, highways, and hydraulic structures. Between 1979 and 2001 he managed more than 500 projects in the western United States, Hawaii, Taiwan, the Philippines, and the Middle East, and he has served as a principal investigator for scientific research funded by the National Science Foundation, the U.S. Geological Survey, the Federal Highway Administration, the Department of Defense, and the California and Missouri departments of transportation. He authored five papers for the Hoover Dam 75th Anniversary History Symposium, a gathering sponsored by ASCE's History and Heritage Committee and held last month in Las Vegas in conjunction with the Society's annual conference.