Hoover Dam: Operational Milestones, Lessons Learned, and Strategic Import

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ABSTRACT: Hoover Dam was a monumental accomplishment for its era which set new standards for post-construction performance evaluations. Reclamation based many of their decisions on surveys of previous high dams to compare their physical, geologic, and hydrologic features with those proposed at Hoover Dam. Perhaps the greatest triumph was the hydroelectric power generation, which repaid the cost of the project with interest over a term of 50 years, which quickly became the economic model for similar high dam projects, world-wide. In the aftermath of the behemoth project, the project did suffer a number of unexpected failings, principally, the failure of the grout curtain to function as intended (requiring retrofitting between 1936 and 1948) and severe cavitation of the spillway elbows in 1941 and 1983 (requiring installation of air ducts in 1983-84). Along the way Hoover Dam was the first dam to be singled out as a terrorist target (by German agents) and provided electricity for the world's largest magnesium production facility from 1942 onward.

OPERATIONAL MILESTONES

First Hydroelectric Power Generation by Reclamation

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 term of 50 years. It was the first hydropower project undertaken by a federal agency that gained congressional approval, essentially placing the U.S. Department of the Interior in competition with private energy providers (who vociferously opposed the project for this reason). Hydroelectric power plants had been constructed by private interests here and there across the United States since the turn of the 20th Century (the small hydroelectric powerplant at Roosevelt Dam, an early Reclamation project, was never operated by Reclamation). No hydroelectric generation scheme on the scale of what was proposed at Hoover Dam had ever been undertaken by Reclamation.

The Hoover power plant was split into two separate power houses 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 turbulence and spray of bypassed flows (those flows which are not run through the power houses), so the design was altered to move the valve houses, outlet works, and spillway aprons downstream of the power houses (Wilbur and Mead, 1933).

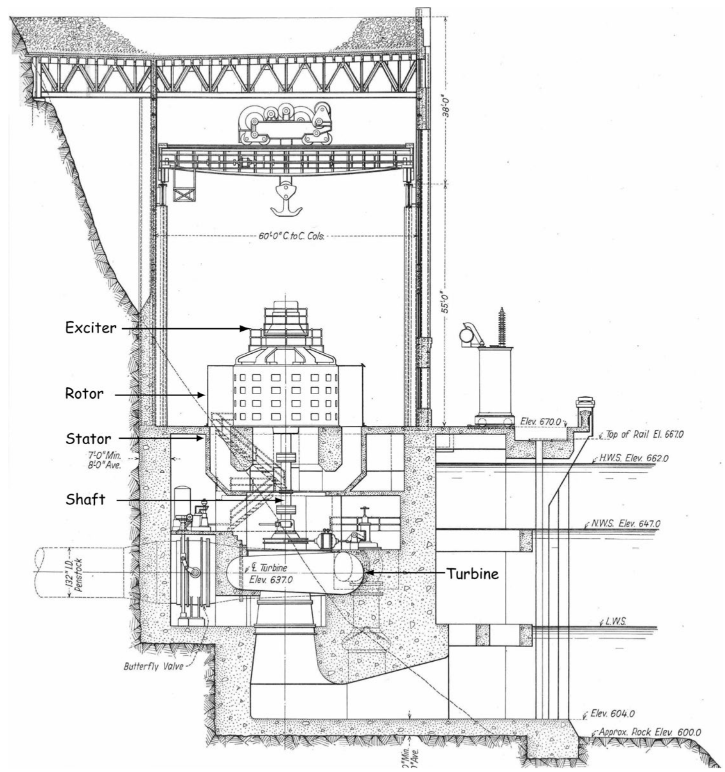

FIG. 1. Elevation views of the Francis turbines originally used at Hoover Dam, with a shaft height of 70 ft, fed by an 11 ft inside diameter penstock (modified from Wilbur and Mead, 1933).

Each power house is 650 feet long with 10 acres of floor space to accommodate eight Francis turbines and two smaller Pelton water wheel turbines, used for internal power production. Reclamation purchased turbines from every manufacturer in the United States as a purposeful economic incentive during the Great Depression. The generating units were comprised of an exciter, rotor, stator, and shaft, as shown in Figure 1.

The exciter is itself a small generator that makes electricity, which is sent to the rotor, charging it with a magnetic field. The rotor is a series of electromagnets, also called poles. The rotor is connected to the shaft, so that the rotor rotates when the shaft rotates. The stator is a coil of copper wire. It 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 (Figure 2). The first generator to go into operation was N-2, shown in Figure 3. It began operating on October 26, 1936. The second generator 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 March 22 and August 16, 1937.

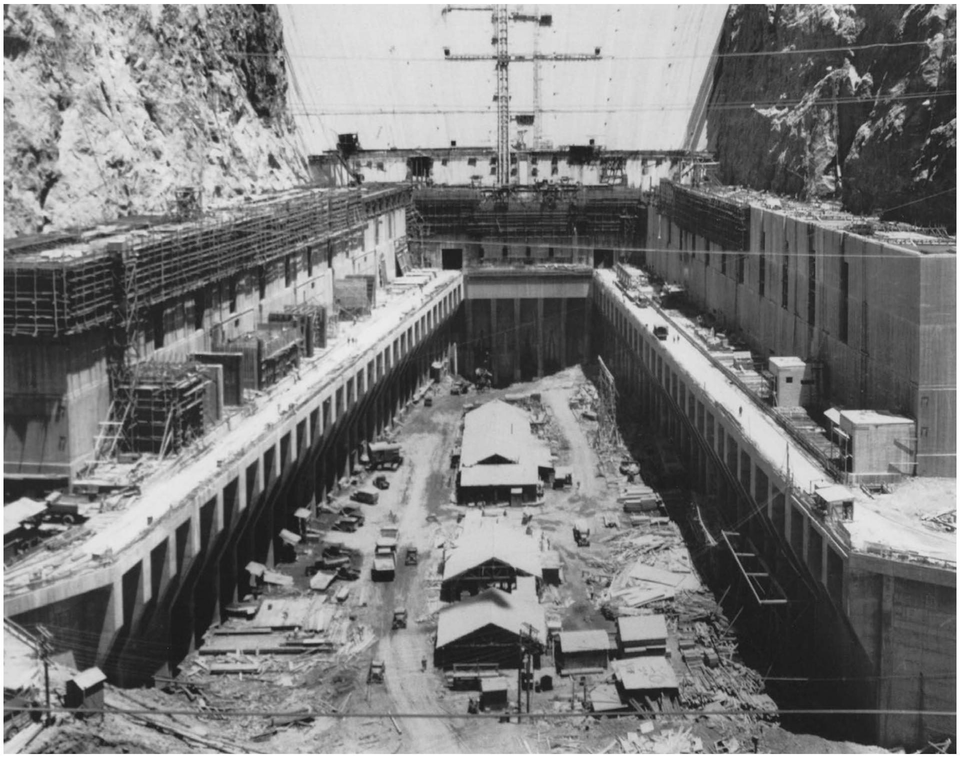

FIG. 2. The last major structures to be constructed at the dam were the two power houses, shown here, looking upstream on June 24, 1935, as the powerhouse neared completion. Note the depth of the forebay (Bechtel Collection, USBR-LCR).

By late summer 1938 storage in Lake Mead reached 24 million acre-feet, and the new reservoir stretched 110 miles upstream, into the lower Grand Canyon. Generators N-5 and N-6 came online on June 26th and August 31st, respectively. By 1939 **s**torage in Lake Mead reached 25 million acre-feet, or more than 8 trillion gallons. Generators A-7 and A-6 began operations June 19th and September 12th, respectively. With an installed capacity of 704,800 kilowatts (kW), Hoover Powerplant was the largest hydroelectric facility in the world, a distinction held until surpassed by the Grand Coulee Dam Powerplant in 1949.

In 1940 Hoover Dam produced 3 billion kilowatt-hours of electricity. On October 9, 1941, generator A-1 was placed into operation, bringing to ten 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 ten 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 of 6,400,000 kilowatt-hours (kW-hr) was generated. The final generating unit was placed into service in 1961, when unit N-8 was placed on-line, bringing the capacity of the powerplant to 1,334,800 kW.

FIG. 3. Gantry crane in the Nevada Powerhouse lowering a 500-ton rotor of Generator N-2, one of the General Electric 82,500 kilovolt-ampere generating turbines, and the first to brought online at Hoover Dam, on October 26, 1936 (USBR).

In the early 1980s, Reclamation began updating the power units at Hoover Dam, and by 1990, ten of the 82,500-kW units had been upgraded to 130,000-kW, and two to 127,000-kW. The remaining 82,500-kW units have been upgraded to 130,000-kW with the 40,000-kW unit upgraded to 61,500-kW and the 50,000-kW unit to 68,500-kW. The upgrade was completed between 1986 and 1993. Today there are thirteen 130,000 kilowatt, two 127,000 kilowatt, one 61,500 kilowatt, and one 68,500 kilowatt generators. All machines are operated at 60 cycles. There are also two 2,400 kilowatt station-service units driven by Pelton water wheels. These provide electrical energy for the powerhouse and dam.

The average annual net generation for Hoover Powerplant for operating years 1947 through 1994 was about 4 billion kilowatt-hours. The maximum annual net generation at Hoover Powerplant was 10,348,020,500 kW-hr in 1984, while the minimum annual net generation since 1940 was 2,648,224,700 kW-hr in 1956.

In the original power contracts negotiated during the dam's construction in 1931-35, the principal consumers negotiating long-term contracts for Hoover Dam's hydroelectric power were: Arizona - 18.9527 %; Nevada - 23.3706 %; Metropolitan Water District of Southern California - 28.5393 %; City of Los Angeles 15.4229 %; and Southern California Edison Co., 5.5377%.

Repayment of Project Cost

The cost of construction completed and in service by 1937 was repaid by the sale of electricity on May 31, 1987. All other costs will 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 of the Colorado River Basin.

Spillway Cavitation in 1941 and 1983

One of the unprecedented challenges at Hoover Dam was the sheer scale of the spillway tunnels. Reclamation recognized that the greatest potential for problems existed at the transition elbows, shown in Figure 4. At these transitions the diversion tunnel was plugged with concrete and a curved transition to the inclined section dropping 500 vertical feet 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-inch misalignment working the spillway's inclined section from top-and-bottom simultaneously (McClellan, 1950). No one was overly concerned and the slight imperfection was gleaned 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 30th and Reclamation Commissioner Elwood Mead 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 1205 feet, flush with the crest of the side channel spillways.

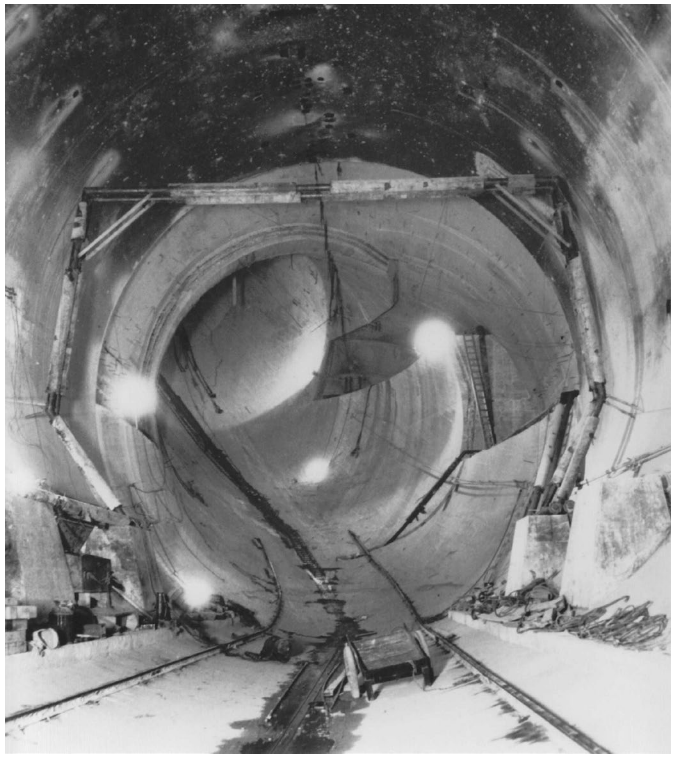

FIG. 4. Elbow transition between the inclined spillway feeder and diversion tunnel No. 3, just after tunnel was plugged with concrete to create a smooth hydraulic transition. Velocities reached 175 fps in this elbow, hastening cavitation (USBR).

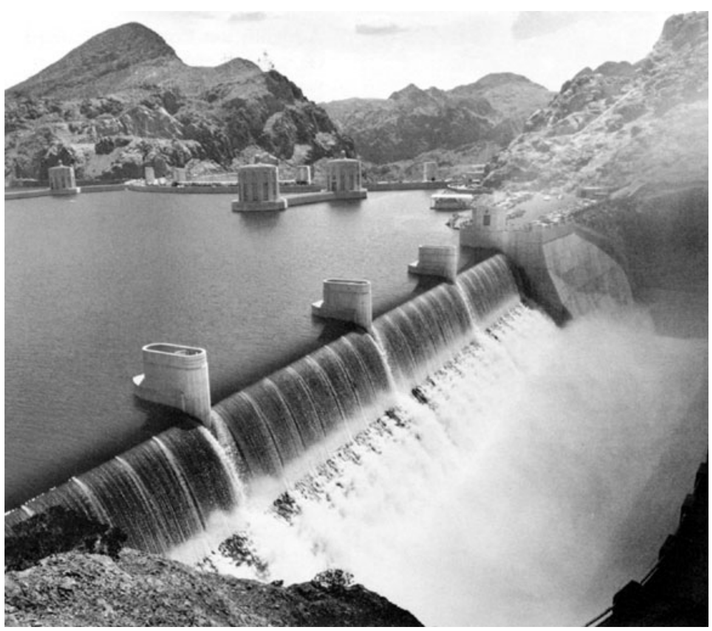

FIG. 5. Water from Lake Mead discharging over the four drum gates of the Nevada spillway during spillway tests in August and October 1941 (USBR).

The drum gates were raised and the reservoir continued to fill, reaching 1220.45 feet by July 30, 1941, within 11.55 feet of the dam crest. On August 6th the drum gates were gradually lowered and several months of spillways testing ensued, which continued through early October (Figure 5). Relatively modest flows, never exceeding 13,000 cfs, were passed through both spillways for four months (Keener, 1943). Even with the modest flows, velocities at the elbows reached 175 fps and cavitation damage ensued on both spillways. 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 was eroded into the high strength reinforced concrete on the Arizona spillway (Figure 6).

Reclamation chose the new Prepakt method to repair the spillway damage during the winter of 1941-42 (Keener, 1943; Chadwick, 1947). Despite this disappointing performance, Reclamation remained unconvinced that it was ascribable to anything but "roughness" and "irregularities" in the concrete lining. Their repair directed the contactor to "remove surface irregularities" (McClellan, 1950). These repairs were not completed until 1943 because of wartime shortages of reinforcing steel.

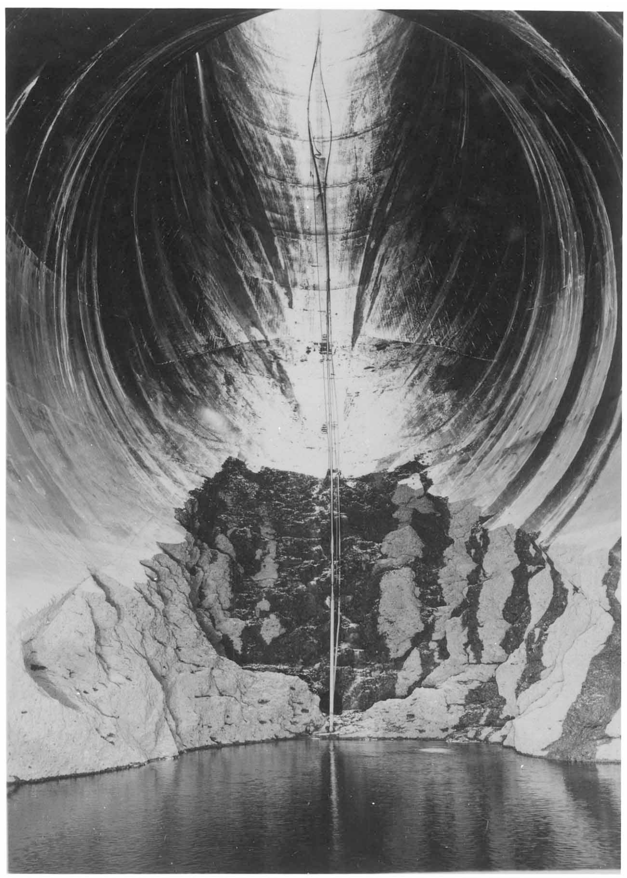

FIG. 6. Cavitation damage observed in December 1941 in the elbow of the Arizona spillway after modest discharges passed through the spillway between August and October 1941. These were a great surprise to the Bureau of Reclamation (from McClellan, 1950).

In the spring of 1945 Reclamation let a contract to correct problems with the outboard spillway-diversion tunnel on the Nevada side and make improvements to the river channel (Arlt, 1954). 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 outlet 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 materials priorities (Figure 7).

That same year (1945) Reclamation began investigating the possibility of installing aeration devices in the spillway tunnels, but concluded that the air introduced into the water dispersed too rapidly to prevent cavitation along the tunnel invert (Frizell and Mefford, 1991). For the next half century Reclamation held a minority view amongst dam engineers that cavitation was ascribable to imperfections in the smoothness of concrete linings, not simply by velocities exceeding 100 to 114 ft/sec, which was advocated by a number of people, but not widely until many years later (Vennard, 1947; Russell and Sheehan, 1974; Cooke, 1979; Chanson, 1989; and Kenn, 1992).

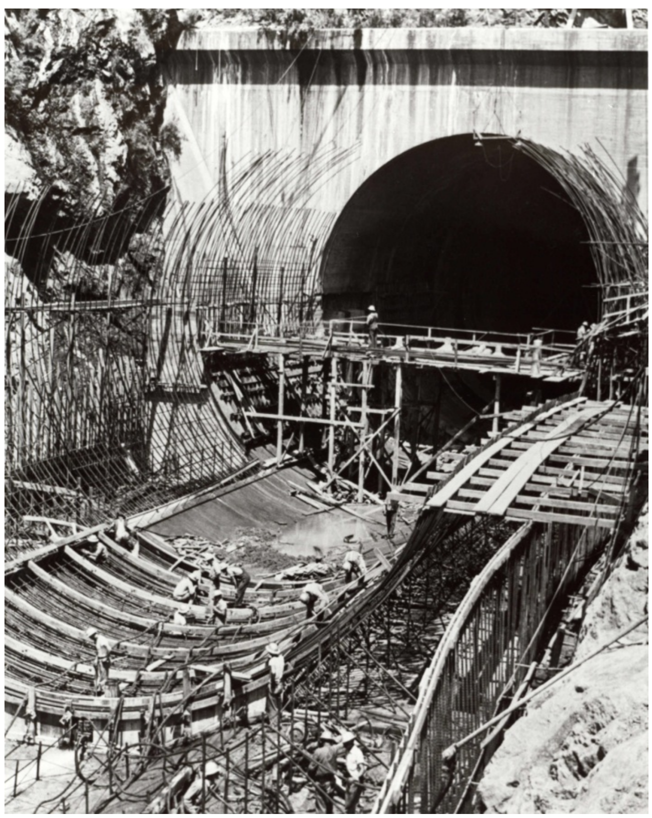

FIG. 7. Crews from Guy F. Atkinson Construction Co. extending the Nevada spillway tunnel outlet on April 26, 1945, as part of a $2 million improvement project that was delayed due to wartime steel shortages. The work shown here improved the hydraulic transition between the outboard Nevada tunnel with the river channel, to correct damage that occurred during the 1941 spillway tests (USBR).

The roughness assumption was finally proven false to everyone's satisfaction during spillage at Glen Canyon and Hoover Dams in the summer of 1983 (Figure 8). That year the Upper Colorado River Basin experienced an abnormally late mountain snow accumulation, followed by an accelerated snowpack ablation, which triggered early seasonal flooding. Many Reclamation reservoirs found themselves without sufficient flood storage to handle the unanticipated inflows (Vandivere and Vorster, 1984).

The tunnel spillways at Glen Canyon and Hoover Dams were run through most of that summer, with Hoover spilling between July 2nd and September 6, 1983. 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 previously afflicted Hoover Dam in 1941.

Reclamation 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 Reclamation undertook a comprehensive program to retrofit their high dams to alleviate cavitation, using aeration slots. These slots were added to the Hoover Dam spillways in 1985-86 (Pugh and Rhone, 1988).

FIG. 8. In July and August 1983 the Nevada and Arizona side channel spillways discharged excess storage for the second time in the dam's history (USBR-LCR).

Problems with a Leaky Grout Curtain and Uplift

During the exploration of Black Canyon prior to 1931, 22 exploratory borings were advanced in the Colorado River channel beneath the proposed dam, along four lines across the channel. 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 feet below low water level, to ascertain whether the andesite breccias continued to great depth. Assessments of the dam abutments were limited to shallow six-inch cores, which were extracted for unconfined compression tests. Reclamation also excavated exploratory adits into both abutments, to explore foundation conditions.

The principal rocks identified during these surveys were latite flow breccias, dam breccia, and basalt dikes which 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 (Ransome, 1923; 1931).

Some hot springs were also noted at the upstream base of the right abutment, at river level (McKay, 1981). Crude percolation tests were employed, using a gravity-feed reservoir that fed to drill holes through sealed pipes. These could not replicate pore pressures induced by 500 to 800 feet of head. The geology of the dam base was mapped after excavation of the channel gravels. Ransome (1931) noted dozens of faults and adjacent zones of intense shearing.

Original Program of Foundation Grouting

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 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 feet deep, about 14 to 21% of the dam height (Figure 9).

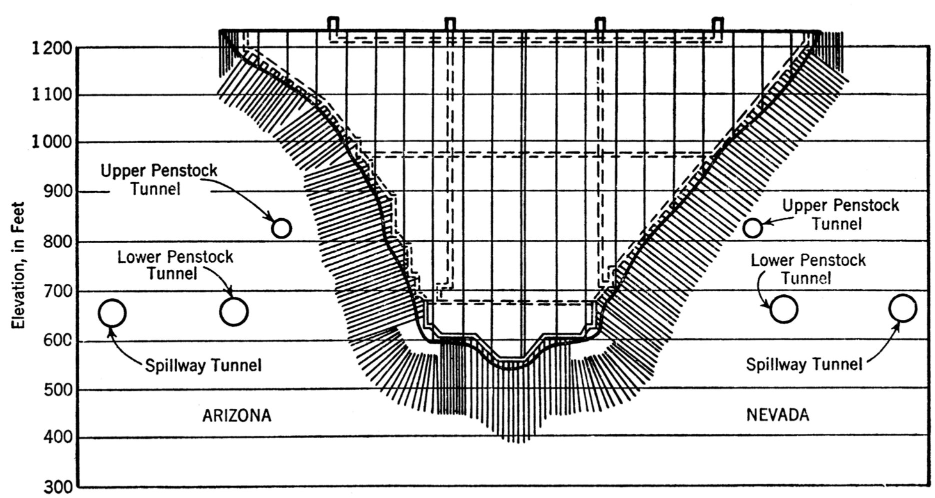

FIG. 9. Elevation view showing the design depths of the original grouting program, performed in 1932-33. These holes extended between 14 to 21% of the dam height (from Simonds, 1953).

These depths were based on a survey of existing dams with grout curtains that Reclamation made prior to construction (Simonds, 1953). Foundation grouting was carried out during construction in 1932-33 along a single line of grout holes. This included grouting of some of the principal faults on both abutments (USBR, 1950). On the Nevada abutment, between elevations 840 and 940 (Figure 10-left), several grout holes penetrated two minor faults, and four holes had to be abandoned, because of excessive grout take and leaks (Simonds, 1953).

When the reservoir reached 1100 ft elevation in 1937, the faults daylighted in the right abutment, and water began entering the fault zone. At this time the abutment drains in 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" (Figure 10-left). It turned out that original grouting of this area was ineffective due to premature set of the cement grout, caused by the elevated water/ground temperatures.

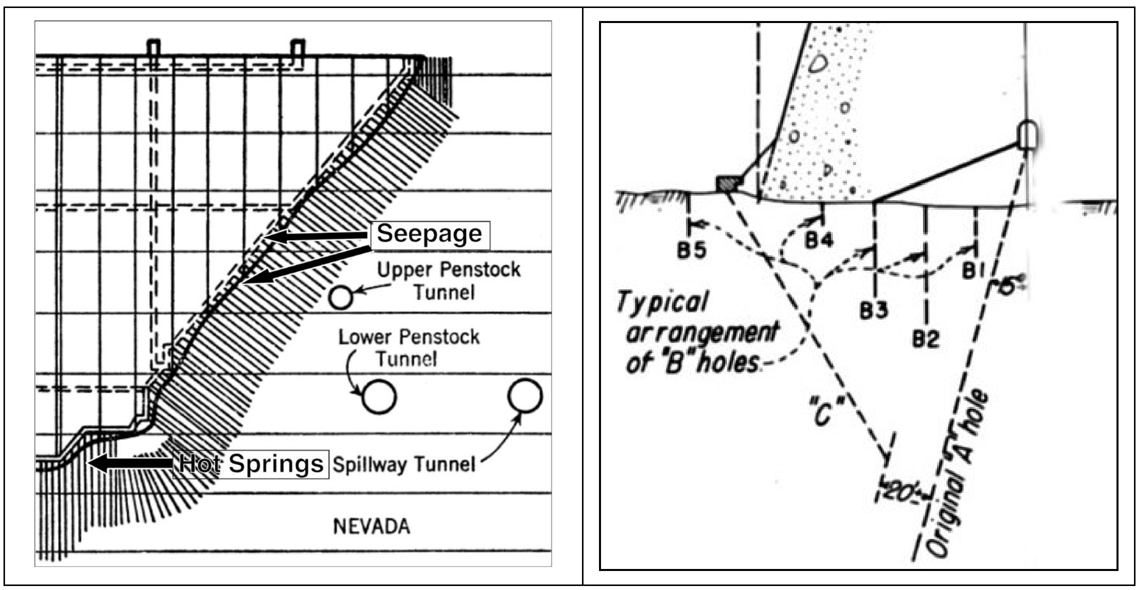

FIG. 10. Left diagram shows the original grout holes on the Nevada abutment, the zone of seepage between elevations 840 and 940 ft, and the hot springs near elevation 555 (annotated from Simonds, 1953). Right figure shows the network of grout holes drilled beneath the dam's upstream heel (McClellan, 1950).

A profile view of the original grout curtain is shown in Figure 10-right. The layout included four rows of shallow B-holes, drilled 30 to 50 ft deep and spaced 20 ft apart. These were considered to be "dental work." The C-holes were drilled on an incline from outside the upstream heel of the dam on 10-foot spacings, to a maximum depth of 100 feet. The C-holes were grouted with pressures of up to 900 psi prior to drilling of the A-holes, which were inclined upstream, from the lower drainage gallery (Figure 10-right). The A-holes forming the curtain were 150 feet deep, on five-foot centers, inclined 15 degrees upstream. 191 A-holes were drilled on the Nevada side, but 33 ended up being abandoned, due to loss of circulation. 202 A-holes were advanced on the Arizona side. Of these, 21 of the holes had to be abandoned.

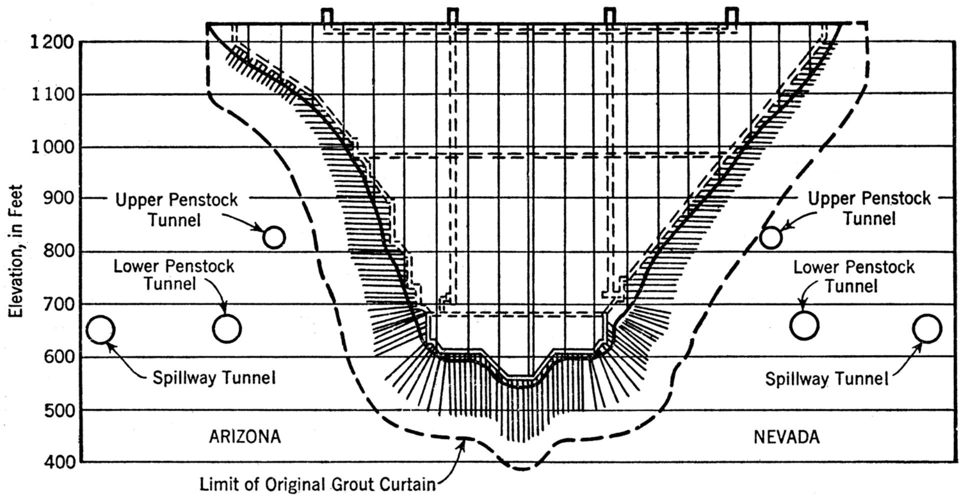

FIG. 11. Elevation view of the uplift relief (drainage) curtain holes, advanced 100 ft from the lower foundation galleries. Dashed line shows limit of the original grout curtain, upstream of the relief wells (Simonds, 1953).

A line of vertical drain holes 100 feet deep was drilled just downstream of the grout curtain. Figure 11 presents the profile of dam centerline showing the pattern of original uplift relief (drainage) holes, which extended a maximum of 100 feet. Note ratio of dam height to depth of the uplift relief holes.

Uplift Problems

By the second year of operation (June 1937), abnormally high uplift pressures began developing beneath the right center of the dam (Figure 12). 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 corrosion of the steel penstock. Hot alkaline water also began seeping through the concrete liner of the inboard 56-foot-diameter Nevada diversion tunnel and spilling onto the 30-foot-diameter steel penstock feeder, causing accelerated corrosion of the steel penstock. These seepage problems were mitigated by additional grouting around the 56-foot-diameter diversion tunnel.

A number of through-going faults were also exposed in the Nevada spillway excavations. The Nevada spillway shaft experienced significant seepage after the reservoir filled, along brecciated zones adjacent to these faults. An extensive program of post-construction 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 (Simonds, 1953). Excessive seepage also manifested itself along two fault strands through the right abutment when the reservoir reached elevation 1100 feet, 132 feet below crest (Figure 13).

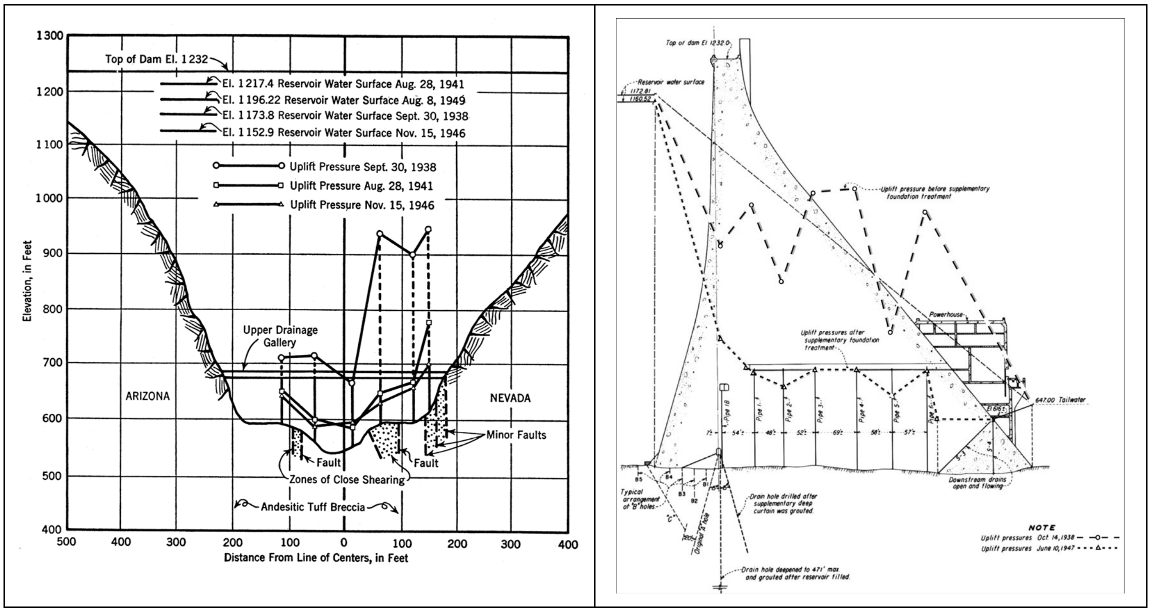

FIG. 12. Left - Uplift pressure gradients along centerline of upper drainage gallery. Note increased pressures on Nevada side, above the fault zones (Simonds, 1953). Right – Profile image of uplift pressures measured before and after the post-construction grouting, between 1939 and 1947 (McClellan, 1950).

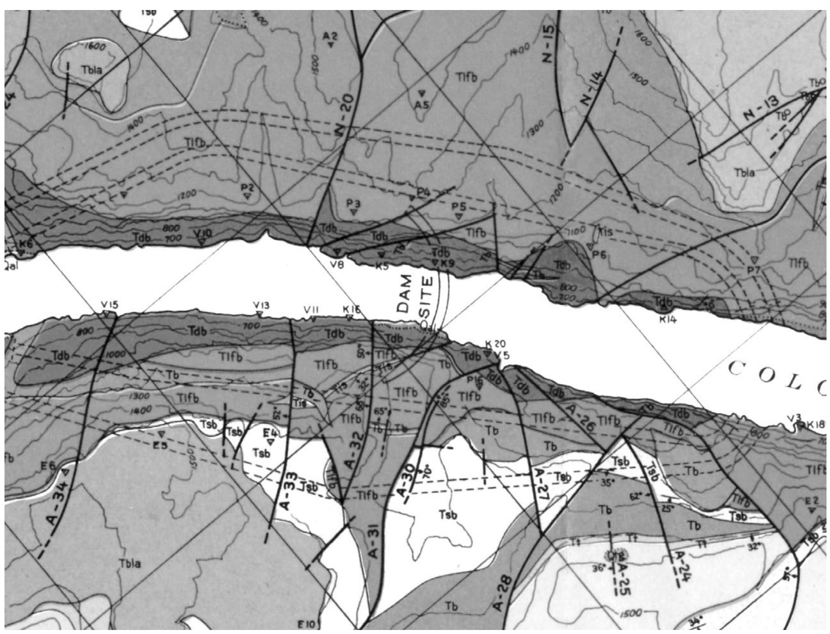

FIG. 13. Portion of the geologic map of the dam site prepared by Ransome in 1931 and reprinted in USBR (1950). The two diagonal faults cutting the dam's right (upper side in this view) abutment (on the Nevada side) preferentially directed seepage through brecciated zones when the reservoir rose to within 130 ft of the dam crest.

Post-construction Foundation Evaluations

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 in the foundation beneath the dam. The drilling revealed that the grout curtain was much too shallow on the faulted abutments, 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 (Figure 14).

The dam's grout curtain was extended deepened extensively between 1938 and 1947 (Figure 15). The grout holes were extended to depths of 300 feet beneath the dam's foundation, then pumped under pressure of full reservoir head. These were drilled from the dam's system of internal inspection galleries, shown in Figure 16. A schematic view of the deepened grout curtain, as it appeared in 1947 is shown in Figure 17.

During the 12-year supplemental drilling program, 410,000 linear feet of grout and drainage holes were drilled, and 422,000 cubic feet of grout were injected under pressure. This remedial program cost an additional $3.86 million (Simonds, 1953). Uplift pressures were significantly reduced, as shown on the right side of Figure 12.

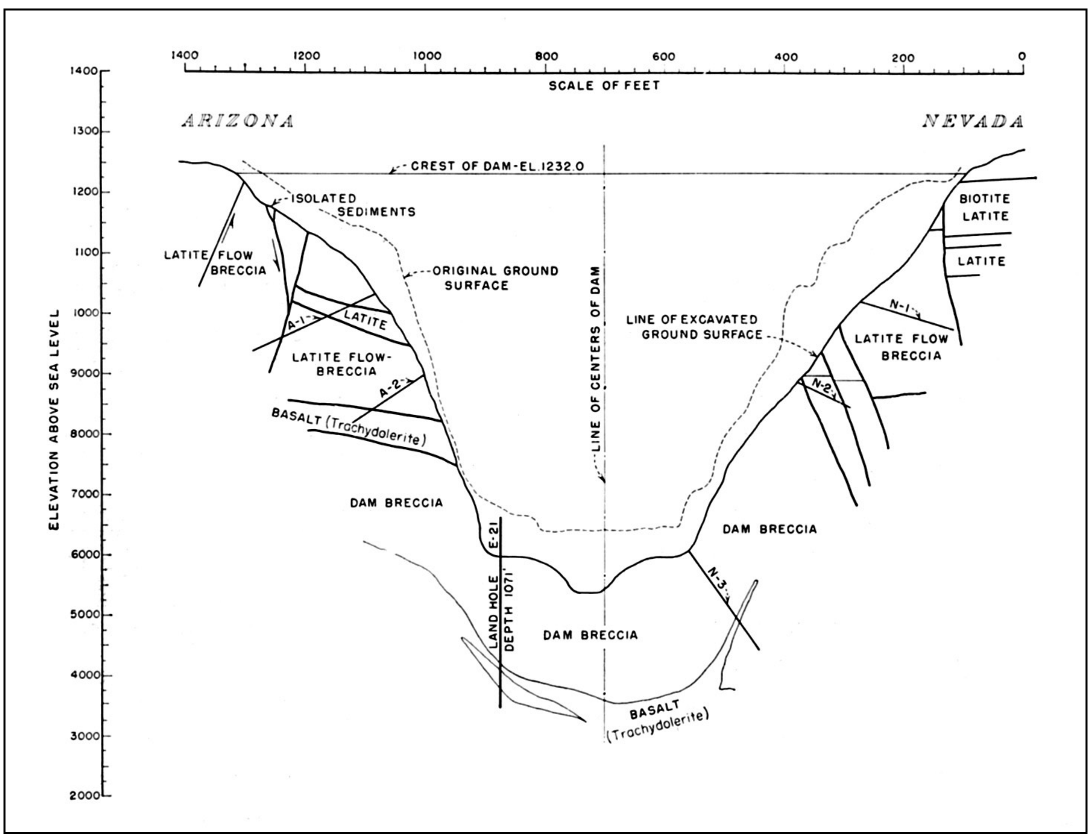

FIG. 14. System of block faults identified during construction. Note absence of data beneath the dam (USBR, 1950).

FIG. 15. Cramped working spaces typified the 9- year program of extending the grout curtain, between 1938 and 1947 (USBR).

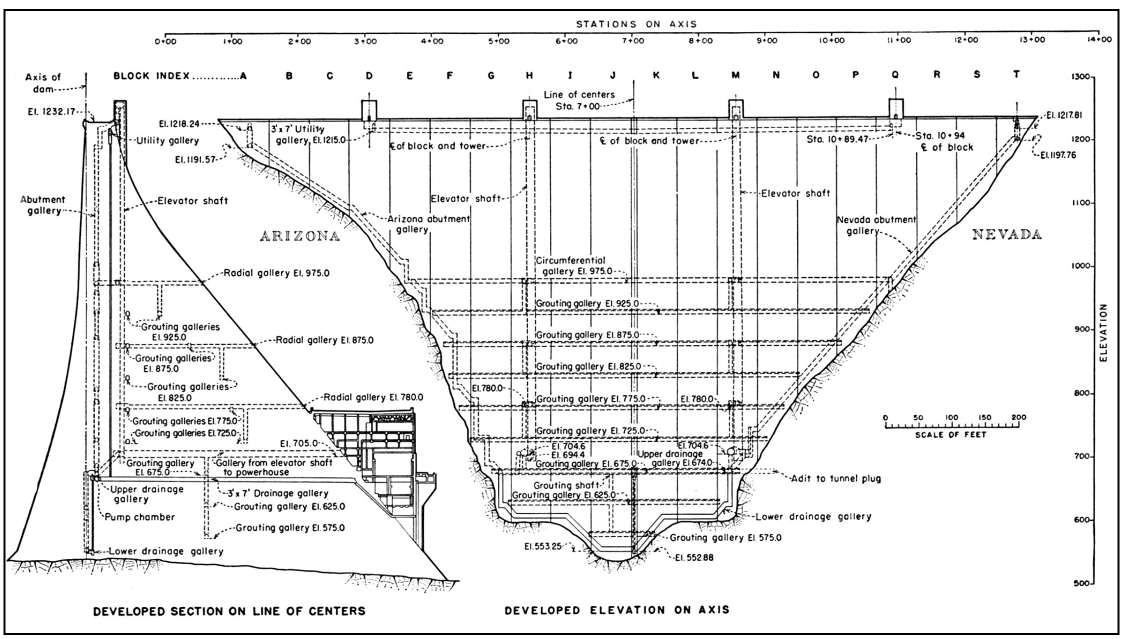

FIG. 16. Distribution of internal galleries in Hoover Dam. Note lower drainage gallery (arrow), from which the new, deeper grout curtain and drainage holes were drilled (USBR).

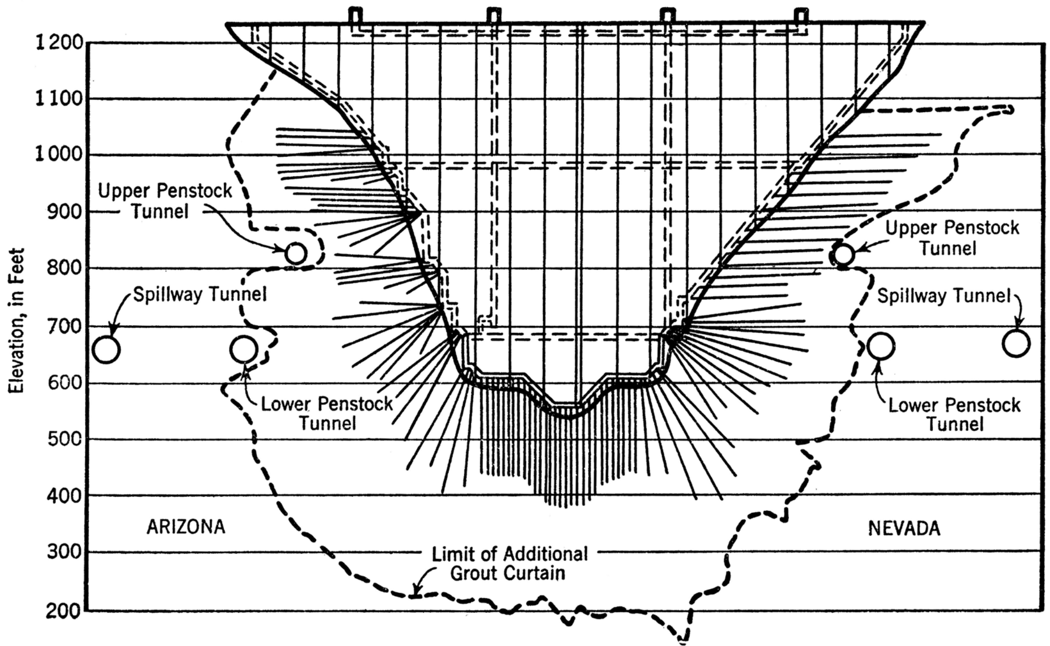

FIG. 17. Profile of dam centerline showing deepened grout curtain, extended between 1938 and 1947 (from Simonds, 1953).

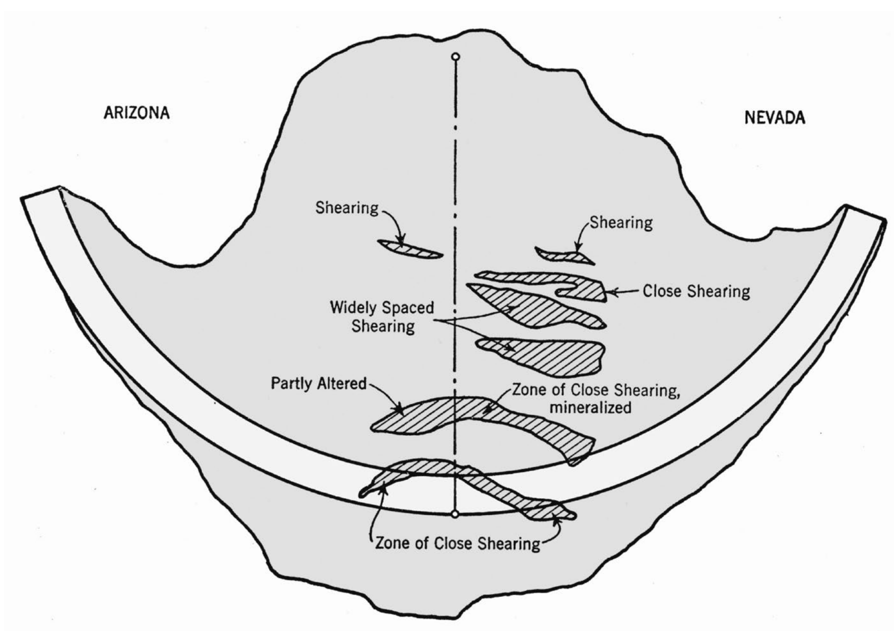

FIG. 18. Manganese-rich gouge zones discovered in the dam foundation, along faults and shear zones (modified from Simonds, 1953).

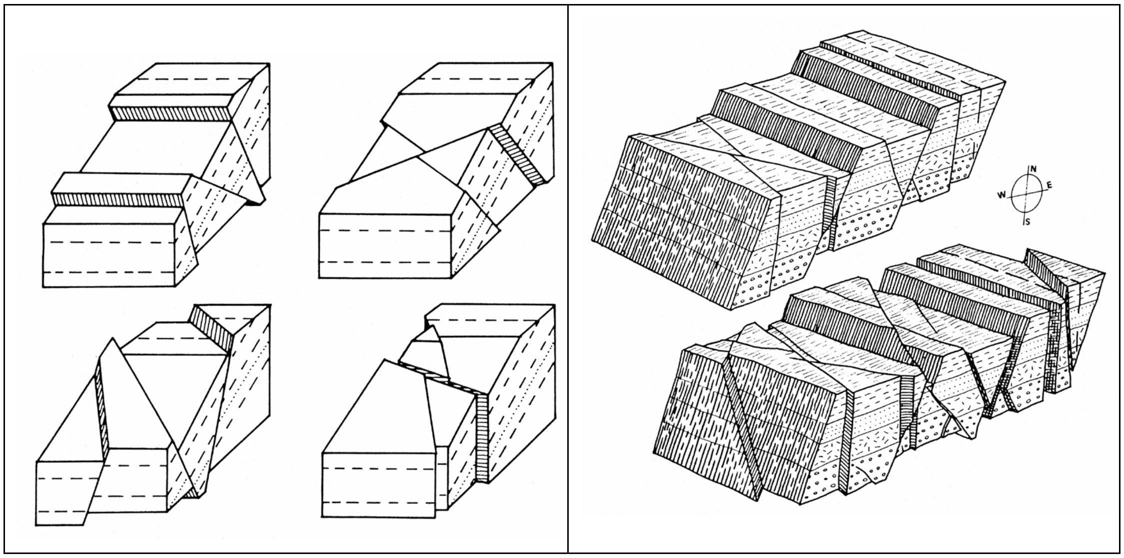

FIG. 19. Left diagram - Four basic types of conjugate fault sets exposed at Hoover Dam, relative to tilt of flow foliation. Upper left shows early normal faults; upper right is early strike-slip faults; lower left late normal faults; and lower right is late strike-slip faults. Right diagram - Block diagrams illustrating tectonic evolution of the dam site. Upper right diagram shows the main tilting stage, typified by NE-SW extension; while the lower diagram shows the principal post-tilt stage, typified by WNW-ESE extension (from Angelier et al., 1985).

Reasons for the Grout Curtain Failure

The failure of the Hoover Dam grout curtain was ascribable to some manganese-rich gouge zones deep in the dam foundation, which developed by chemical weathering along faults and shear zones that perturbed the volcanic strata, as shown in Figure 18. The failure to recognize these features demonstrated that mapping surficial geology in detail doesn't help anyone unless that effort is accompanied by a cogent understanding of how the geologic conditions might impact 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 geological information collected in the field during construction. If the design assumptions about foundation conditions had been shown to be invalid, some sort of action should have been taken.

Black Canyon turned out to be an area that is geologically complex, 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 Angelier et al. (1985). This work revealed that two stages of extensional tectonism occurred at the dam site, summarized in Figure 19. Extensional tectonism can be expected to perturb a brittle ground mass, creating numerous shears, faults and brecciated zones. Hydrothermal activity can cause mineralization and infilling of voids with secondary products not visible from the ground surface.

There was insufficient exploration and characterization of the foundation materials beneath and adjacent to the dam; especially the faults, shears, and breccia zones. The grouting program was not sufficiently deep or redundant to provide an adequate seepage cutoff. The cost of the supplemental grouting program was $1.84 million, about 2.37% of the cost of the dam (Simonds, 1953).

STRATEGIC IMPORT OF THE DAM

Attempted Sabotage and Security Precautions during World War II

On November 30, 1939, just three months after the Second World War began, but two years before America's entry into the conflict, the U.S. Embassy in Mexico City received a tip of a plot by German agents in their 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 (Pfaff, 2003). Two German agents were already living in Las Vegas, one of whom was an "explosives expert." One of these agents allegedly made a dozen visits to the dam to scope the site out, and a "German national" 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 and renting 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 Mead Substation near Boulder City, where the two high-voltage transmission lines bifurcate.

The State Department promptly notified the Bureau of Reclamation in Washington, D.C., but asked that they not reveal any details of the plan, lest the news leak out to the public. Reclamation banned all private boats from Black Canyon, and a few days later placed restrictions upon employees and visitors to the dam (Pfaff, 2003). On December 9^{th} Reclamation requested the aid of the FBI to assess the security of the dam against sabotage. A steel mesh net supported by cross-canyon cables was installed 300 ft upstream of the intake towers to prevent boats from passing and floodlights were set up 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 increase physical security of the dam, including additional security training for the dam's rangers. 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 of yet another alleged plot was passed onto Reclamation, this one involving sabotage of electrical power generation 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 War Department to furnish armed guards to protect and patrol the potentially vital features of Hoover Dam and power plant, as well as the switchyard just outside at Boulder City. The War Department denied the request, but Nevada Senator Patrick McCarran introduced legislation to establish an Army post at Boulder City to protect vital federal property. In July 1940 a Reclamation warehouse at Parker Dam was burned down in a suspicious fire.

In response to these political pressures, in December 1940 the Army announced that it would establish a cantonment with 800 soldiers near Boulder City to train military policemen (Moehring, 1986). This new facility was christened 'Camp Siebert' (Figure 123), named after Corps of Engineers General William L. Siebert, who had chaired the Colorado River Board between 1928-32 (it was later renamed Camp Williston when a larger Camp Siebert was established in the late 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.

Reclamation continued allowing 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 during the duration of World War II. The dam's lights were shut off and roadblocks were established on either side of dam along Hwy 93 that evening. From that point onward the Army agreed to provide convoy escort for vehicles crossing over the dam on U.S. Hwy. 93 between Boulder City and Kingman, Arizona (Figure 20), until these soldiers were transferred to overseas assignments.

FIG. 20. Camp Siebert was constructed on the southern side of Boulder City in the late summer of 1941 to train military policemen. The Army agreed to help patrol transmission switching yards and provide convoy security across the dam until the soldiers were deployed. The camp was later renamed Camp Williston and reconfigured to become Boulder City High School after the war (USBR).

FIG. 21. Army escort for convoy of civilian vehicles cued up along U.S. Highway 93, waiting to cross Hoover Dam during the Second World War (USBR).

The dam did not reopen to the public until August 1945. On December 8th Reclamation formally requested Army assistance in protecting Hoover, Grand Coulee, and Parker Dams, which produced half of all the electrical power used in Pacific Coast wartime production plants (Parker also provided pumping power for the Colorado River Aqueduct, 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 Patton flew over the dam at a height of just 500 ft on July 6th, 1942, while he was commanding desert maneuvers a few hundred miles to the south).

During the summer of 1942 Reclamation and the Army began exploring various means of protecting 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 constructed throughout the war's duration, being completed in 1945). At that time Army Engineer 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 Colorado artist Allen True, as well as outlining additional or alternative measures that might be employed to protect Hoover, Parker, Grand Coulee, and Shasta Dams (Matteson, 1943). True's scheme was classified 'secret' and involved the erection of a cable-supported dummy dam upstream of the actual dam, as shown in Figure 22. 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 high value targets, such as factories, airfields, locks, bridges, highways, etc. (Stanley, 1998).

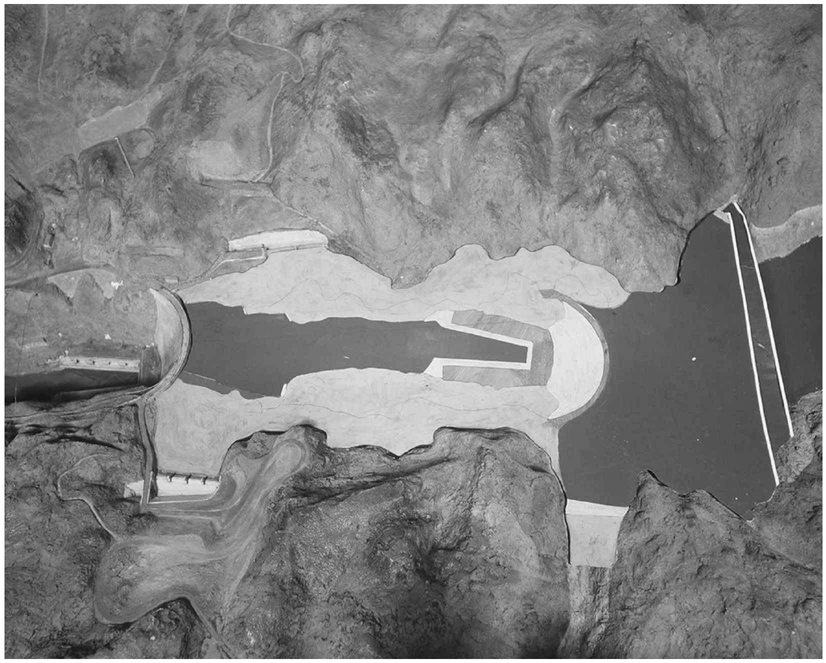

FIG. 22. Painted plaster model of a camouflage scheme believed to have been designed by Allen True, the Colorado artist who had previously designed the western and Native American themes depicted in Hoover Dam's terrazzo floors. His design included a 'dummy dam' and false torpedo nets about a quarter mile upstream of the actual dam, both which would be lit at night. This model was informally preserved as a curiosity at the dam for many years thereafter (USBR).

An alternative plan for a three-quarter scale wire frame 'decoy dam' downstream of the actual dam was also conceived, but never implemented. Matteson felt that it would be far less expensive to employ smoke screens to screen the dam and power house, which "would render precision bombing impossible." He noted that the smoke screens could be deployed in just 15 minutes, provided they were set-up and manned. He also exercised considerable doubt about the difficulty of employing similar camouflage schemes at the other three dams because they were not situated in narrow steep canyons like Hoover Dam. Rumors still abound about a World War II-era 'floating decoy dam' with lights having been deployed, but these are not true.

In September 1943 the Army informed Reclamation that they were re-positioning their military police soldiers in preparation for overseas deployment, and that they would no longer be available to help guard the dam anymore or assist in convoying vehicles. Reclamation appealed to help from the FBI, but was rebuffed (Pfaff, 2003). In January 1944 an Army intelligence officer prepared a report which found some of the allegations about lax security to be without merit, but others to ring true. The report concluded that since no security incidents had occurred, it would be difficult to justify additional military resources being detailed to the dam. In 1946 normal public visitation resumed and the security force dwindled to seven watchmen and the 29 rangers that performed a myriad of collateral duties, in addition to security.

World's Largest Magnesium Production Facility

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 U.S. agreed to supply the British with massive amounts of magnesium, because of its value to aircraft production. Magnesium's low specific weight (about 2/3 that of aluminum) was most advantageous when blended with aluminum and zinc. Magnesium and phosphorus were also requested by the British for munitions.

The Las Vegas Valley quickly emerged as a likely site to construct the world's largest magnesium processing facility because of the vast magnesium deposits in southern Nevada and the proximity to unlimited quantities of fresh water and electrical power that could be drawn from Lake Mead and Hoover Dam, essential to the two-step electrolytic processes to process magnesium ore. The government moved quickly, selecting a site on the alluvial fan between Las Vegas and Boulder City and constructing the Basic Magnesium Industries (BMI) Plant, beginning 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 for materials and draft deferments for working in critical defense industries. These advantages allowed it to begin operations in November 1941, just five months after the first land was purchased. The plant continued expanding throughout 1942-43, triggering feverish building activity to keep up with the housing demand. In 1942 the Defense Housing Corporation met the accelerated demand by constructing their first 300-unit "Victory Village" complex, which included schools, a recreation center, apartments, and dormitories for single workers (Moehring, 1986). Despite these accommodations, there was a chronic shortage of defense workers, in large measure due to 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).

BMI met their manpower shortfall by importing African American workers from Mississippi, who were undaunted by southern Nevada's dry heat. This was during the era of segregation, so the Defense Housing Corporation scrambled to build a separate 324-unit Victory Village which they christened "Carver Village" (for George Washington Carver) on the western side of Las Vegas, which was pretty desolate (Moehring, 1986). By mid-1943 this sprawling complex would include ten separate plants employing 5,000 workers (Figure 23). By war's end BMI would employ almost 10,000 workers.

FIG. 23. The sprawling Basic Magnesium Industries Plant and the community of Henderson were built during the war to supply this strategic metal for the aircraft industry in southern California (Nevada Historical Society).

CONCLUSIONS

Hoover Dam was Reclamations first hydroelectric generating project of any consequence, 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 online until 1961, 26 years after the dam's completion. The most important aspect of Reclamation entering the utility marketplace was the ability of this revenue to repay the cost of increasingly large and ambitious reclamation projects that almost no one envisioned for the American West prior to the construction of Hoover Dam, which was viewed more-or-less as something of a one-time aberration, made possible by the political intrigue of southern California. The Reclamation projects that followed in quick succession, across the American West, bear testimony to an era of massive reclamation and public works construction undertaken by the federal government which proved to be of inestimable value during the Second World War (such as the Basic Magnesium Inc plant) and in the post-war southwestern expansion, which continues to present.

A much-less publicized aspect of Hoover Dam were the operational failings that occurred, from which much valuable engineering information was gleaned, which impacted dam engineering world-wide. 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 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 which presaged 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. That the site was complexly faulted there was no question, and it would be difficult to envision the siting of a mass concrete dam at the same site today, given the state-of-the-practice in dam safety considerations (there are 26 faults less than 4 Ma age cutting 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, after the failure mode triggering the 1959 Malpasset Dam failure became more understood and appreciated (Londe, 1973; 1987).

The cavitation damage experienced in the spillway elbows at Hoover Dam in 1941 and again in 1983 were perhaps Reclamation's greatest failing. In the 1930s there were very few high dams (> 200 ft) with any appreciable record of operation where velocities > 150 ft/sec were reached. At that time many engineers noted that smooth finished concrete tended to exhibit less tendency towards cavitation than rougher surfaces (Vennard, 1947). Reclamation 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 mis-alignment of ½ inch (Kenner, 1943). Their 1942-43 repairs focused exclusively on replacing the damaged elbows with a thoroughly smooth transition, bereft of any "alignment bumps" (Warnock, 1947). This same approach was used on all subsequent Reclamation high dams built in the 1960s, including Glen Canyon and Yellowtail.

During this same interim (1945-83) many dam engineers took exception with Reclamation's views, assuaging that cavitation was most ascribable to implosion of entrained air at velocities between 114 and 150 ft/sec (Raphael, 1977; Cooke, 1979; Vanoni, 1990). This view was being born out in the massive post-war projects being built elsewhere around the globe, which had suffered grievous cavitation damage until air ducts were installed (Russell and Sheehan, 1974). Reclamation studied these largely foreign projects (Many of the consultants on those projects were former Reclamation engineers) and developed contingency plans for retrofitting their highest dams with air ducts, but the funds were not forthcoming (Pugh and Rhone, 1988).

When the 1983 spring flows necessitated modest levels of spillage at Glen Canyon and Hoover Dam, all of the spillway elbows suffered cavitation damage that required emergency repairs. Reclamation's repairs included the insertion of air ducts, bringing Reclamation in line with general practice, world-wide (Frizzell and Medford, 1991; Kenn, 1992).

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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.

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Between 1976 and 1988 the author conducted interviews with Professor Jerome M. Raphael (1912-1989) in the civil engineering program at U.C. Berkeley and Professors Vito Vanoni (1904-99) and George Housner (1910-2008) at Caltech, regarding the historical aspects of hydraulic uplift that developed beneath Hoover Dam and the various controversies surrounding cavitation, which was the one technical area Recalamtion engineers found themselves most at-odds with consulting engineers throughout the post-war era (after 1945). Other key interviews included J. Barry Cooke (1915-2005) in 1979, 1983, and 1984 regarding the evolution of understanding what causes cavitation on high dams and methods to mitigate it. Cooke had been a vociferous critic of Reclamation's long-held views about surface roughness preventing cavitation.

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