Hoover Dam: Construction Milestones in Concrete Delivery and Placement, Steel Fabrication, and Job Site Safety

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ABSTRACT: The size of the Boulder Canyon Project necessitated a broad array of innovations in construction engineering and management which had enormous impacts on all of the large scale projects that followed it. Major milestones were achieved in mass concrete handling and placement across a large and sometimes treacherous job site; equally challenging problems with forming and pouring structural concrete elements for the project, such as the intake towers, penstocks, spillways, and outlet works; steel penstock fabrication and placement; and establishment of basic job site safety precautions that became increasingly common thereafter, including on-site medical care the provision of hard hats to all workers.

MILESTONES IN CONCRETE HANDLING AND PLACEMENT

Overlapping System of Cableways and Derricks

Six Companies General Superintendent for Hoover Dam was Frank Crowe. Crowe was renown in the dam construction industry for his ability to innovate, devising clever site-specific schemes for delivering critical components in a regular, timely manner, without creating undue delays. One of the innovations he was most remembered for was his novel employment of traveling cable hoists covering a dam site, which could be adjusted on any given day to cover expansive portions of the work under construction (Yates, 1933), shown in Figures 1 through 3.

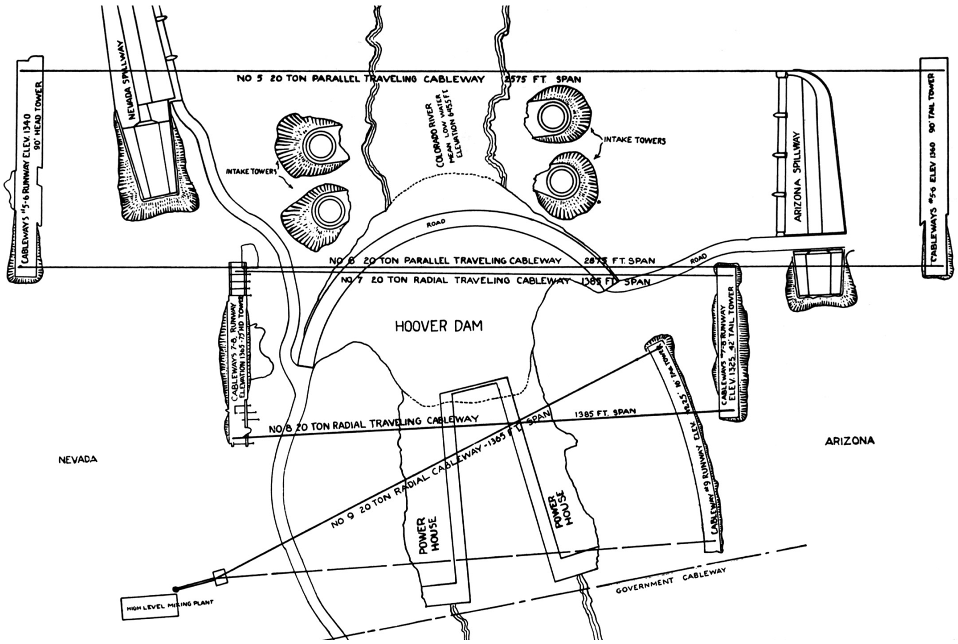

FIG. 1. Plan view of cross-canyon cableways designed for maximum flexibility to move buckets of concrete and construction materials to any spot on the dam, inlet towers, most of the spillways, outlet works, and powerhouses. Aerial delivery was not used on any of the diversion tunnels (Six Companies Collection, USBR-LCR).

This method of "overhead delivery" had been widely employed on steep mountains sides during the late 19th and early 20th Centuries using cableways to haul mining ore and timber, as well as grading earthen levees (Gillette, 1916; 1920). Overhead cableways were initially used in dam construction on some of Reclamation's earliest projects, such as Pathfinder Dam in Wyoming, built between 1905 and 1909, which Frank Crowe had observed early in his professional career with Reclamation. Cableways were also being used with great success by General Construction Company at Owyhee Dam (ENR, 1930a).

The system had innumerable advantages insofar that it avoided cumbersome transport across rough or uneven ground and avoided all manner of obstructions, provided the various cableways were aerially separated. Figures 1 through 5 show some of the essential components of the aerial cableway systems employed by Six Companies during construction of Hoover Dam. All but the 150-ton Government Cableway were dismantled after the powerhouse was completed in 1936.

FIG. 2. One of the 20-ton cableway towers mounted on rails, which allowed it and another similarly configured unit on the opposite canyon wall, to be moved 500 ft up or down the canyon, to facilitate precise placement of the 8-cubic-yard concrete buckets (USBR).

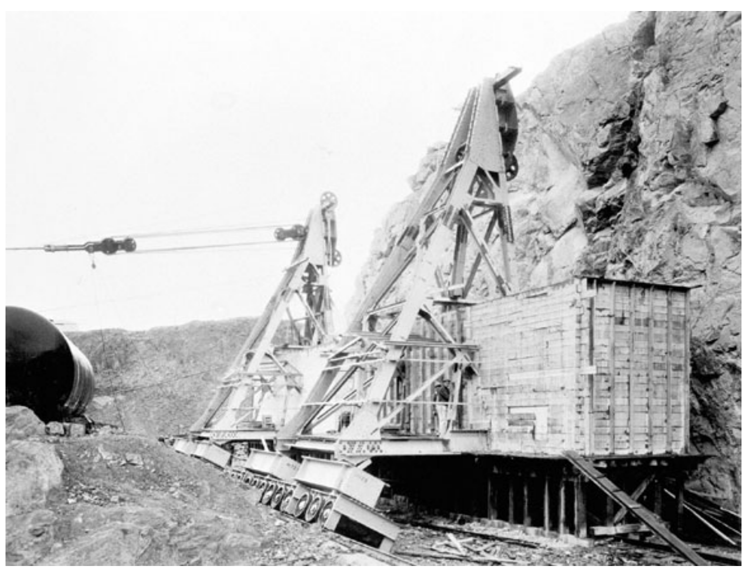

FIG. 3. Cableways 7 and 8 being set up on November 29, 1932 to carry 8-cubic-yard buckets of concrete from the high mix plant to the dam. These were equipped with electric drive cable hoists that allowed pinpoint precision in dropping the buckets on the downstream 2/3 of the dam (USBR).

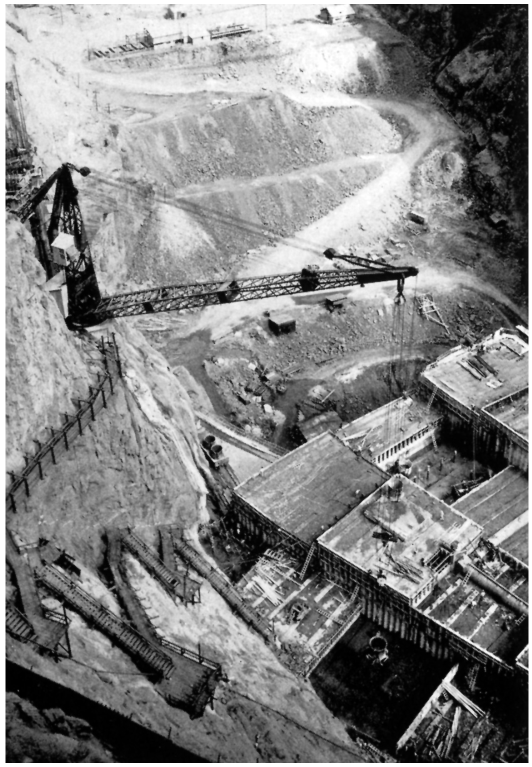

FIG. 4. After the dam rose above the level of the rail line leading from the Low Level Mixing Plant this stiff-leg derrick positioned at elevation 930 ft to lift the concrete buckets from the rail cars to the blocks closest to the dam's upstream right abutment until the Low-Level Mixing Plant was shut down. (USBR)

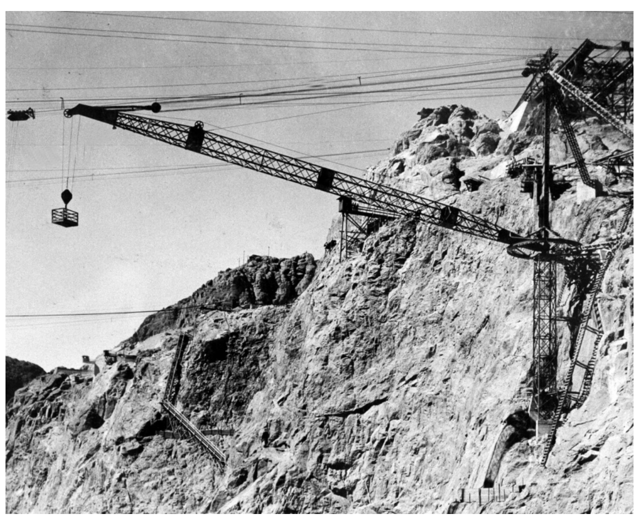

FIG. 5. Another 20-ton capacity stiff-leg derrick in its precarious perch on the dam's right abutment to continue handling of concrete buckets coming from the Low-Level Mixing Plant after the dam rose 150 ft above the river bed. (USBR)

Innovations in Concrete Placement

The main dam contained 3.25 million yd^3 and Six Companies poured 4.36 million yd^3 of concrete in the entire project (including the diversion tunnels, spillways, intake towers, valve houses, and power plant). Most of the concrete placed using 8-cubic-yard cylindrical hopper buckets, each weighing approximately 20 tons loaded (16.2 tons of concrete and 3.6 tons for the buckets). The first concrete for the dam was placed on June 6, 1933 at approximately 135 feet below river level (Figure 6). As shown in Figure 7, by August 1932 concrete production zoomed up to 149,000 yd^3 per month, a record for that time (the previous record had been 50,000 yd^3/month at Owyhee Dam in June 1931). By October concrete placement exceeded 200,000 yd^3/month. In March 1934 concrete production reached a peak rate 262,000 yd^3, or about 1,100 buckets per day, basically one bucket every 78 seconds. The record one-day pour was 10,350 yd^3 on June 1, 1934. The last bucket of concrete for the main dam was poured on May 29, 1935.

Some of the essential elements of the concrete placement for the main dam structure are profiled in Figures 7 through 12, below. The most important aspects were the coordination that had to be maintained between adjacent blocks of the dam, and the working space that became increasingly congested as the dam rose and narrowed. The C-2 and C-5 cableways covered most of the two spillways, the intake towers, and the upstream portion of the dam, while the C-6 to C-7 cableways covered the abutments, which curled downstream. The pivoting C-8 cableway handled demands in the power plants, where a much lower volume of concrete was required for the reinforced concrete framework.

FIG. 6. Placing the first 8-cubic-yard bucket of concrete on the scrubbed bedrock surface of the inner channel on June 6, 1933. Note batter boards supporting forms. (USBR)

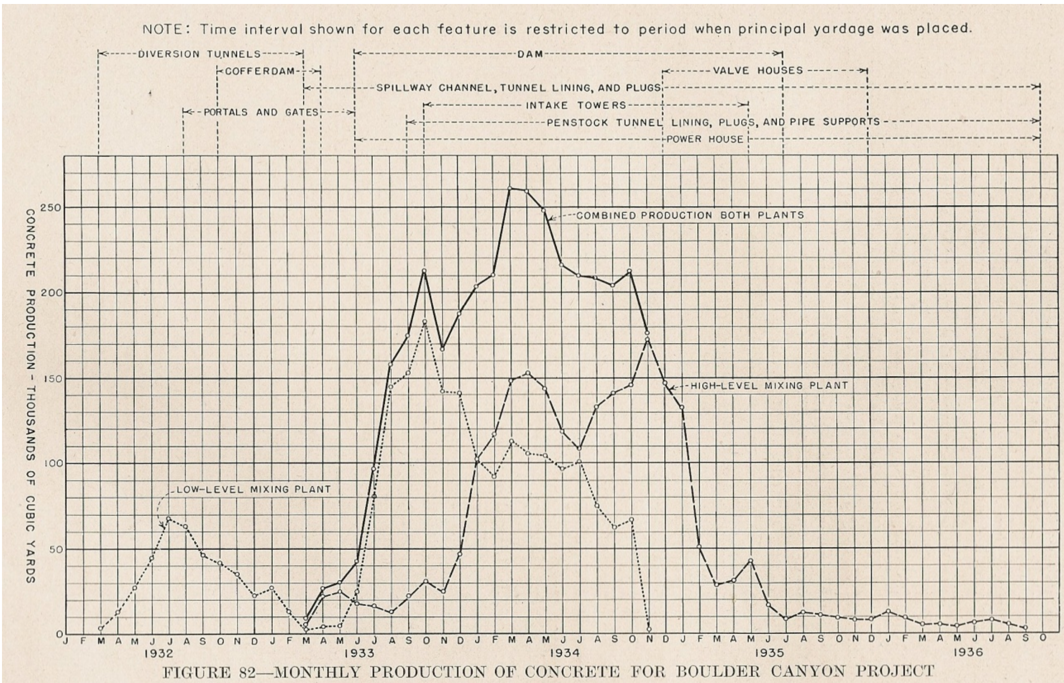

FIG. 7. Monthly production of concrete by the Low-Level and High-Level Mixing Plants at Hoover Dam (in thousands of cubic yards) versus the various project elements that were constructed (USBR, 1947).

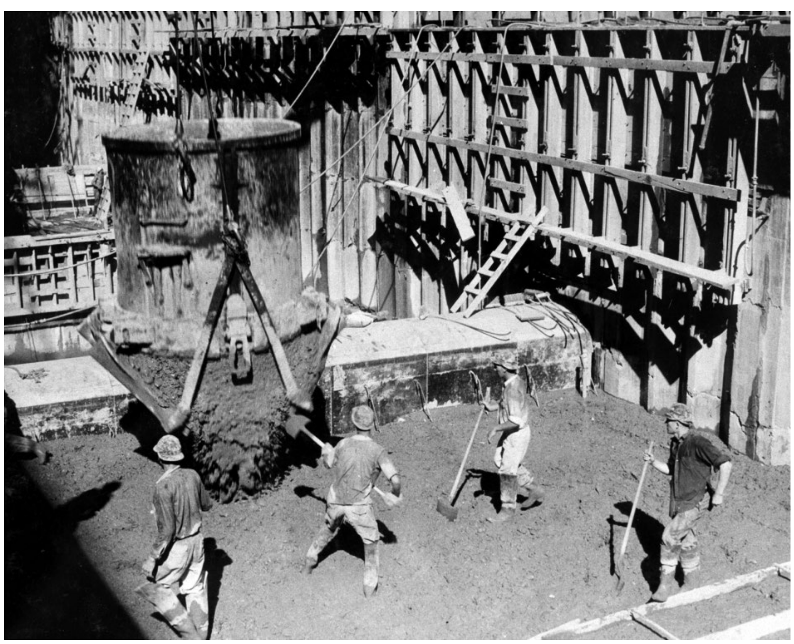

FIG. 8. Concrete tampers flipping the release on the bucket containing 8 cubic yards of concrete. Stories about workmen being entombed in the dam's concrete were completely fallacious. When the bucket's contents were spread over a typical 50 x 50 ft pour block, it only amounted to one inch of concrete! (USBR)

FIG. 9. Workman using pneumatically powered concrete vibrator to remove some of the entrained air from wet concrete in one of the dam's blocks (USBR).

FIG. 10. Looking downstream on July 17, 1933, as the inner gorge was being filled with concrete. Note the 8 ft gap at center, to access the cooling pipes. Also note the excavation of the right abutment and temporary trestle which brought concrete buckets by rail from the Low-Level Mixing Plant to the dam site (USBR).

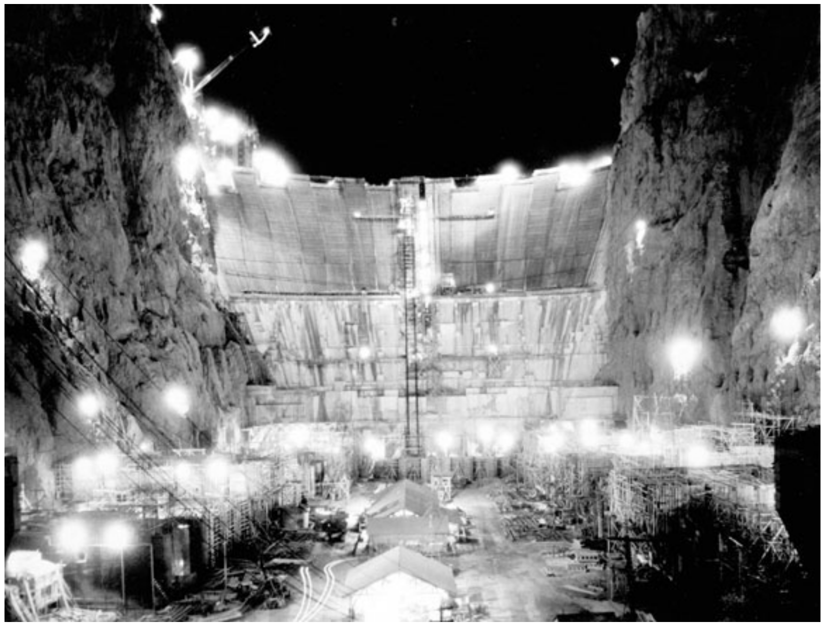

FIG. 11. Concrete placement was carried out around-the-clock, and the night shifts were a welcome respite during the summer. This time exposure shows the formwork for the powerhouses in the foreground with the dam in the background (USBR).

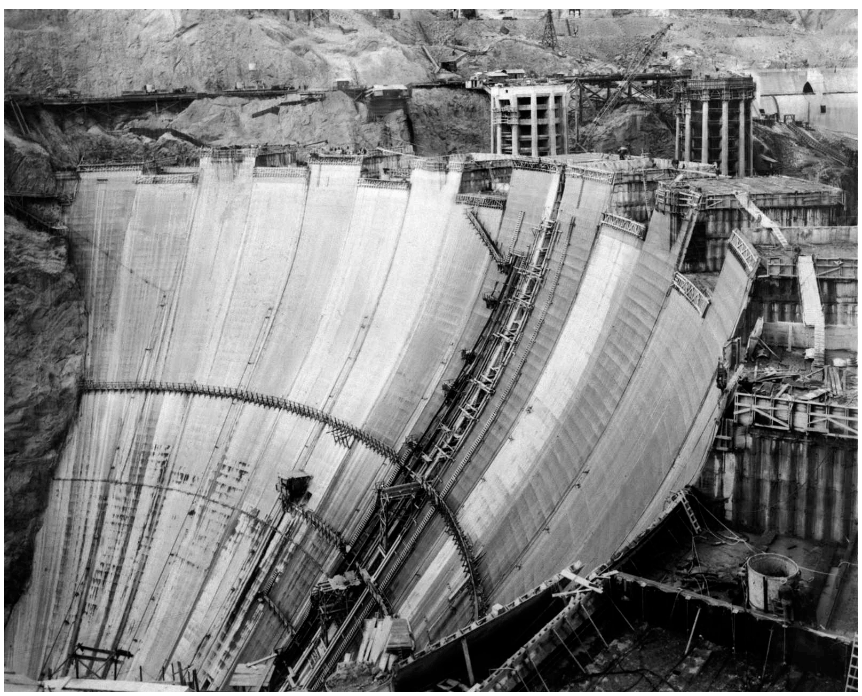

FIG. 12. Hoover Dam nearing completion, as seen along the downstream face, around New Years 1935. Note the vertical slot at midstream, which was not filled until after cooling water circulation was completed in mid-March 1935 (USBR).

Design Standards for Contraction Joints

One of the most foreboding aspects of the St. Francis Dam failure near Los Angeles in March 1928 was the existence of large shrinkage cracks that developed transverse to the dam's axis (Rogers, 1995). These cracks had been caulked with oakum across the dam's upstream face, which promoted the development of excessively high pore water pressures between the dam's blocks separated by these fractures. A significant technical debate erupted shortly thereafter wherein dam engineers argued about what values of hydraulic uplift beneath dams and inter-block pressures between adjacent blocks of the dam would be appropriate for design (Henny, 1928; Floris, 1928; Pearce, 1928a, 1928b; Jakobsen, 1928; and Hinds, 1929).

One aspect of mass concrete dam design everyone seemed to agree upon was to do everything in their power to avoid the development of uncontrolled transverse shrinkage cracks, and to seal all open fissures with cement grout to allay development of debilitating pore water pressure within the body of the dam (ENR, 1930b; Noetzli, 1930; Wiley, 1931; Henny, 1931; Houk, 1932; Weaver, 1932; and Terzaghi, 1934).

As a consequence, every conceivable measure was taken to control concrete shrinkage and employ an intricate system of criss-crossing expansion joints between pour blocks. The joints between adjacent blocks were equipped with interlocking shear keys, patented state-of-the-art water stops (Figure 13, and then grouted after sufficient curing (Figure 14) with an intricate system of grout pipes (Figure 15). A system of internal galleries with seepage collection gutters and measurement weirs was also built into the dam, with a much greater density of openings than had been originally envisioned when the project was approved in December 1928.

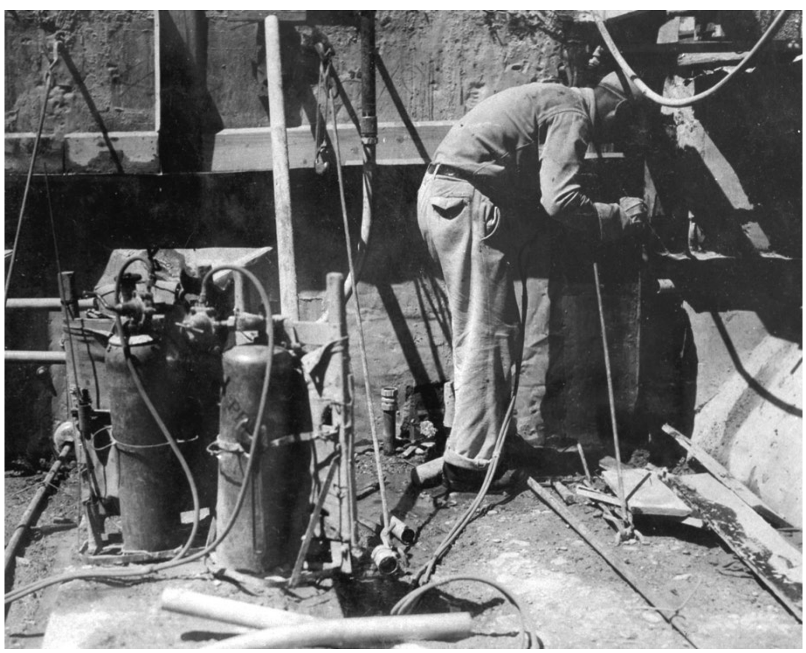

FIG. 13. Welder carefully brazing joints on a copper water stop placed in one of the dam's contraction joints. (USBR)

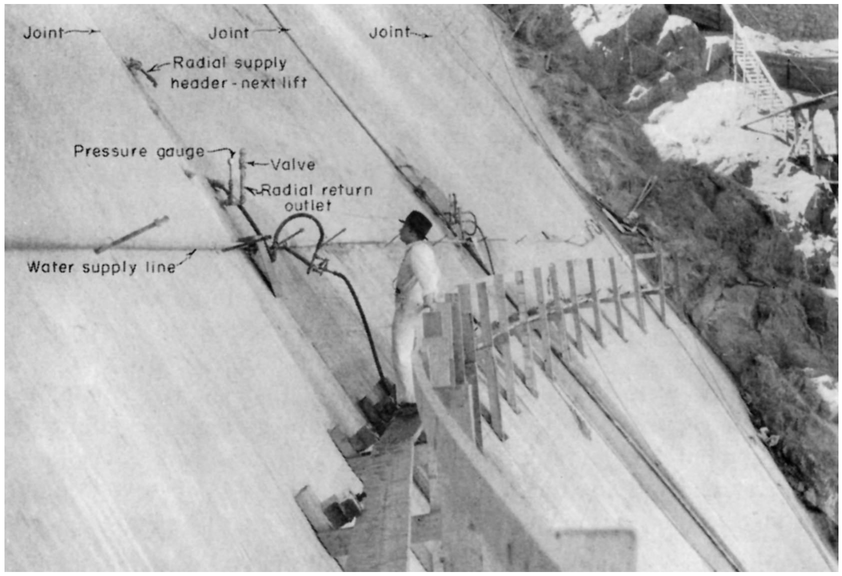

FIG. 14. Workman grouting one of the dam's radial joints from a scaffold walkway on the dam's downstream face (from USBR, 1941).

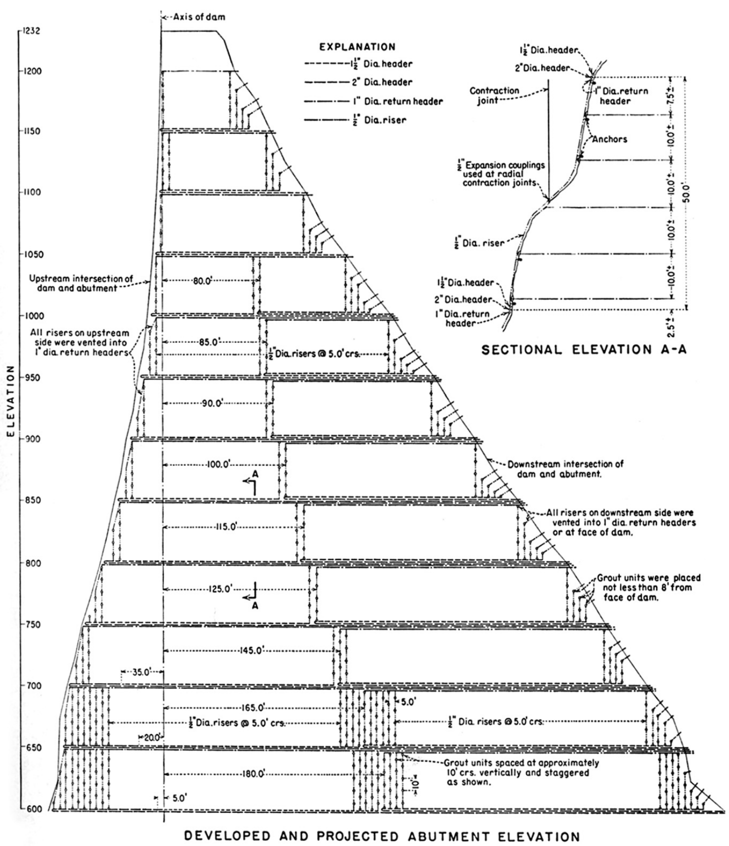

FIG. 15. Layout of grout pipes leading to contraction joints between the dam's monolithic blocks. Grout injection pipes were placed for every 30 to 50 ft^2 of joint surface area, using injection pressures between 100 and 300 psi (USBR, 1947).

MILESTONES IN PLACEMENT OF STRUCTURAL CONCRETE

Intake Towers

The four intake towers were constructed on cut benches upstream of the dam. The diameter of these towers is 82 ft at the base, 63.25 ft at the top, and 29.67 ft inside. Each tower is 395 ft high and extends above the crest of the dam (to accommodate periodic removal and cleaning of steel inlet screens). Each intake tower controls one-fourth of the water supply for the powerplant turbines. The water taken into each tower is funneled through two cylindrical gates, each 32 ft in diameter and 11 feet high. One gate is near the bottom and the other near the middle of each tower. The gates are protected by trash racks.

Their positions upstream of the main dam created some access problems that had to be overcome, as shown in Figures 16 and 17. The towers were constructed of high-strength reinforced concrete, using a 5-sack mix, traveling steel forms, and considerable timber falsework (Figure 18), because the towers taper upward.

FIG. 50. Intricate network of overhead cableways and suspended catwalks just upstream of the dam. These were used to carry workers and convey buckets of concrete to the spillways and intake towers. High strength structural concrete was used on the intake towers (Preston Collection Boulder City Library).

FIG. 17. Stiff-leg derricks were also erected on the Arizona abutment to place concrete to the Arizona intake towers. Taken on December 27, 1933 (USBR).

FIG. 18. Overview of the four intake towers approaching completion, as seen on March 26, 1935. The towers rise above the dam crest and are just under 400 ft high (USBR).

Penstocks and Outlet Works

Reservoir water is taken from the lake through 30-foot-diameter steel penstocks installed within 37- and 50-foot-diameter concrete-lined tunnels, shown in Figure 19. The upstream intake towers are connected to the inner diversion tunnels by 37-foot-diameter inclined tunnels. 37-foot-diameter tunnels also connect the downstream towers to the penstocks and outlet works.

The powerplant turbines are fed through four main penstocks, two on each side of the river (Figure 19). Wicket gates control water delivery to each turbine. The maximum pressure head is 590 ft and the minimum operating head is 420 ft. The average operating head assumed in design was between 510 and 530 ft. Water is fed to the Francis turbines by sixteen 13-foot-diameter steel penstocks (eight on each abutment) installed in 18-foot-diameter concrete-lined tunnels (Figures 20-23). The total length of these penstocks is about 5,800 feet. All of these figures were world records at the time of the dam's construction (USBR, 1938).

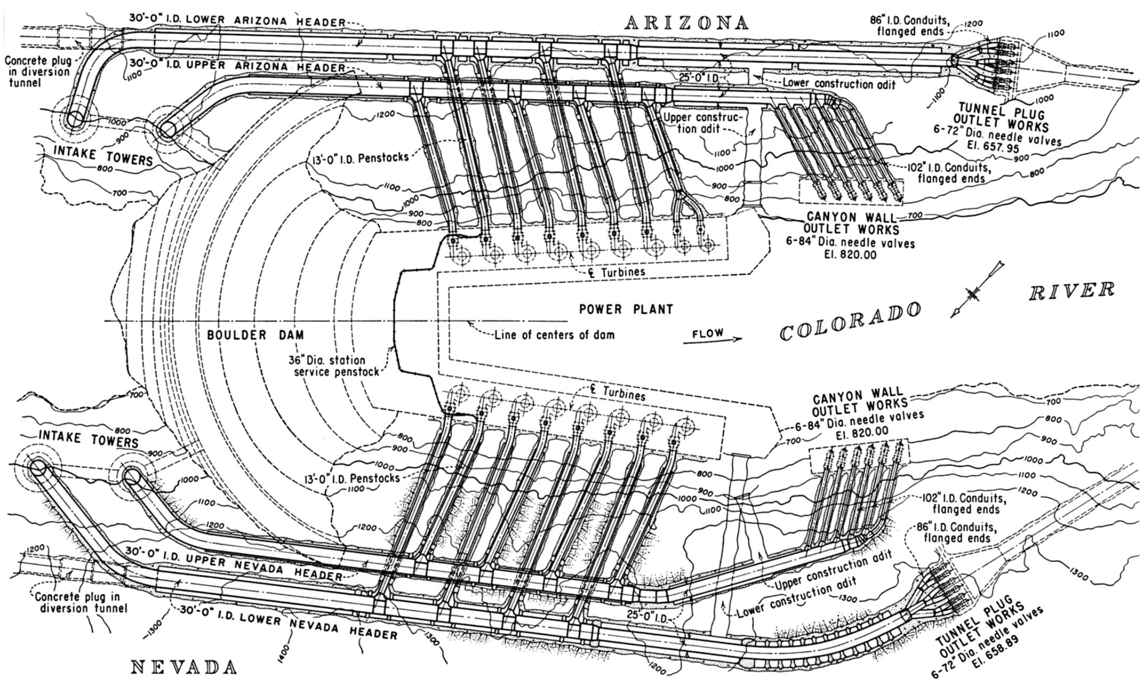

FIG. 19. Plan showing the network of tunnels and penstocks feeding into the dam's two power houses, canyon wall outlet works, and bypass tunnel outlet works. The intake tunnels lead to penstocks constructed within the four diversion tunnels. The headers leading into the powerhouses were 30 feet in diameter. These fed off the inboard and outboard 50-foot-diameter diversion tunnels (USBR).

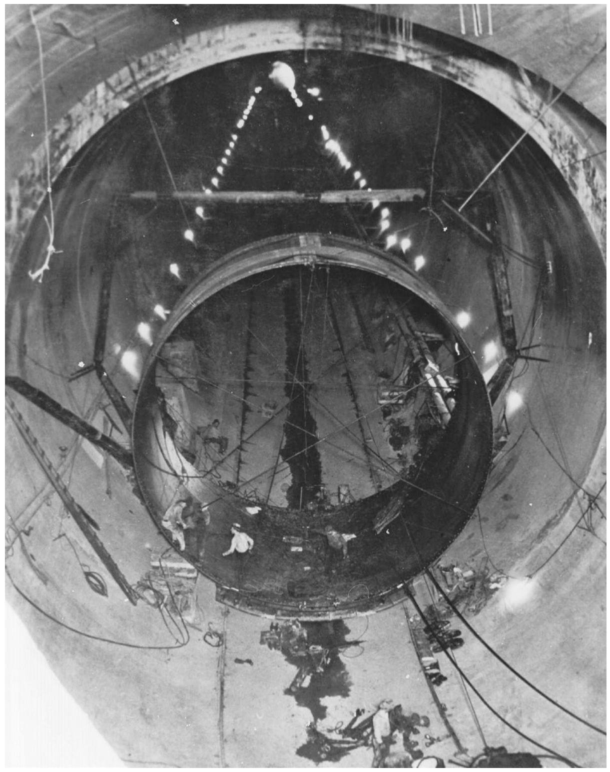

FIG. 20. Single section of 30-foot-diameter lining for one of the steel penstock headers being dropped into one of the outboard 50-foot-diameter diversion tunnels, as viewed on Nov 16, 1934 (USBR).

FIG 21. Lining of one of the 14-foot finished diameter feeder tunnel leading to one of the Francis turbines in the power house, taken on Nov 16, 1934 (USBR).

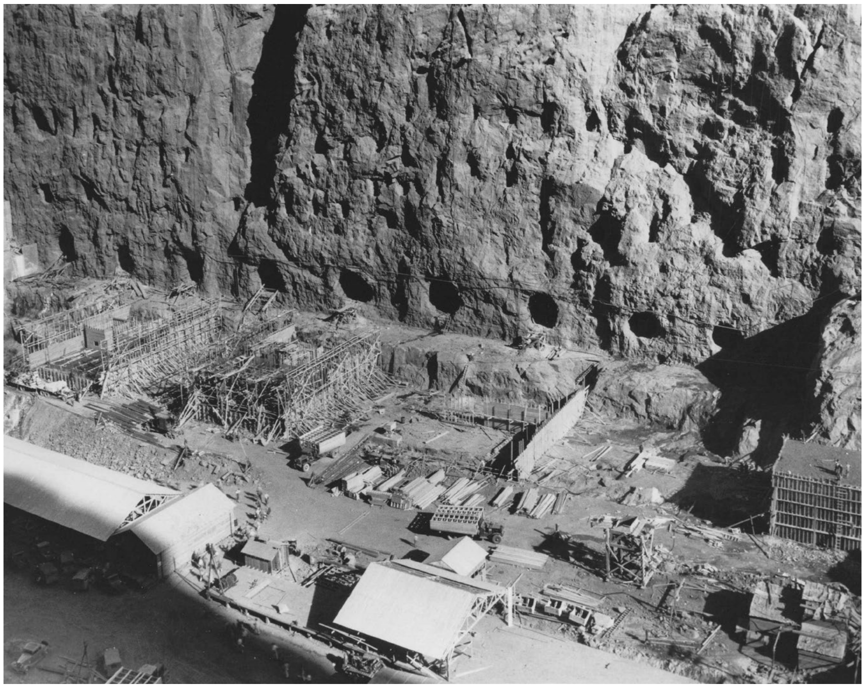

FIG. 22. Oblique view of the eight 21-foot finished diameter penstock feeder tunnels connecting to the Arizona power house, under construction. The steel penstocks are 11 feet in diameter (USBR).

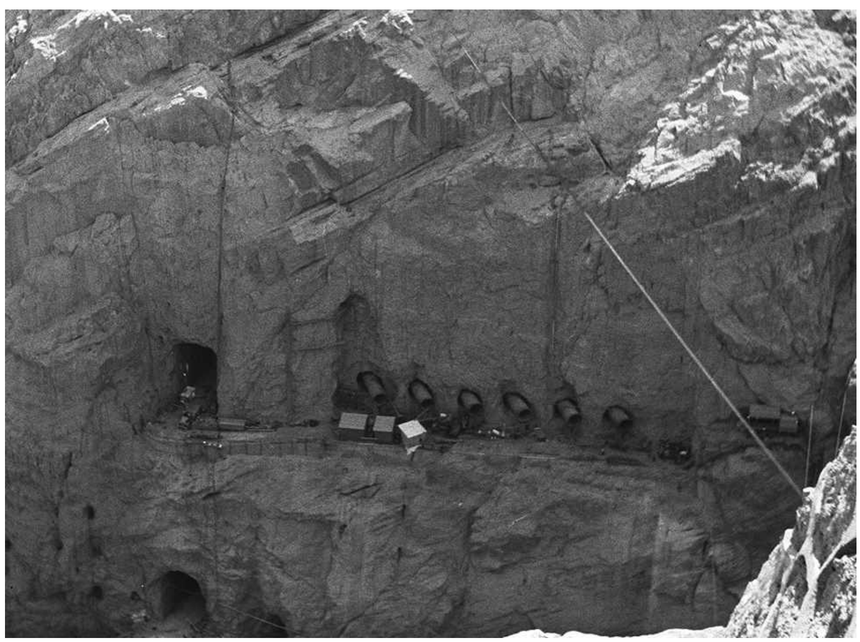

FIG. 23. Oblique view of the canyon wall valve house outlet works tunnels. The conduits were 7 ft in diameter and the tunnels 11 ft in diameter with a horseshoe shape. These tunnels were lined after the 102-inch-diameter outlet pipes were placed (Preston Collection-Boulder City Library).

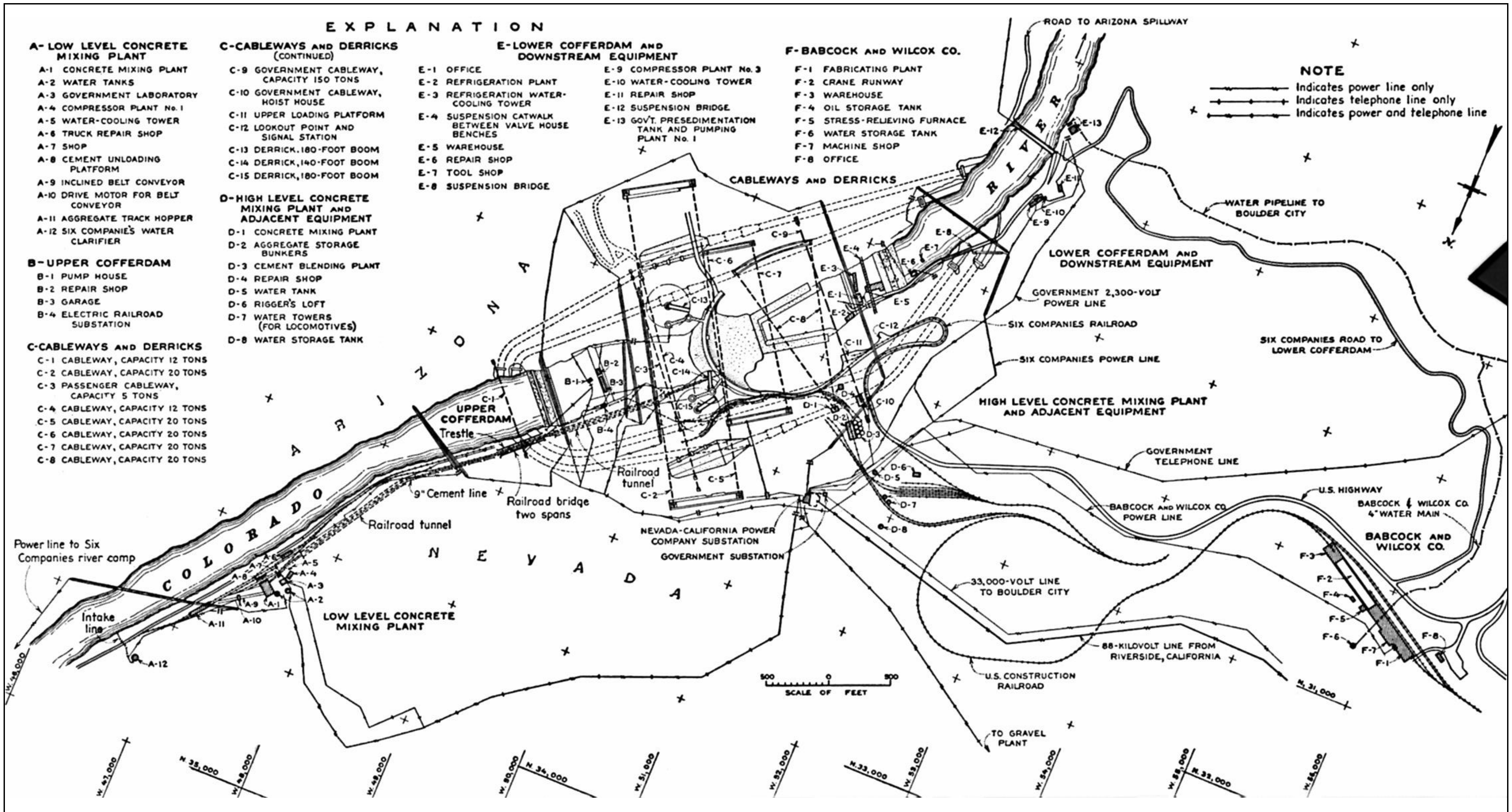

FIG. 24. Construction plan showing the network of temporary roads, bridges, cableways, rail spurs, concrete batch plants, and transmission lines. The Babcock & Wilcox Steel Fabrication Plant was located 1.6 miles by road from the dam, at lower right. (USBR)

Steel Fabrication Plant

Steel penstocks and the pressure feed lines serving the outlet works were fabricated at a specially constructed Steel Fabrication Plant constructed by Babcock & Wilcox approximately 1.6 miles southwest of the dam's right abutment, accessible by road (Figure 24). The fabrication plant cost $600,000 and was essential to the project

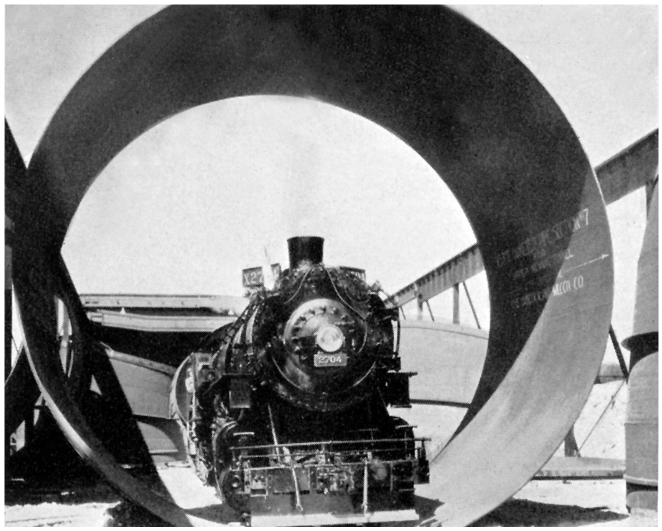

FIG. 25. Publicity still showing the scale of the 37-foot-diameter steel liners for the power house headers, in comparison to one of Six Companies steam locomotives (USBR).

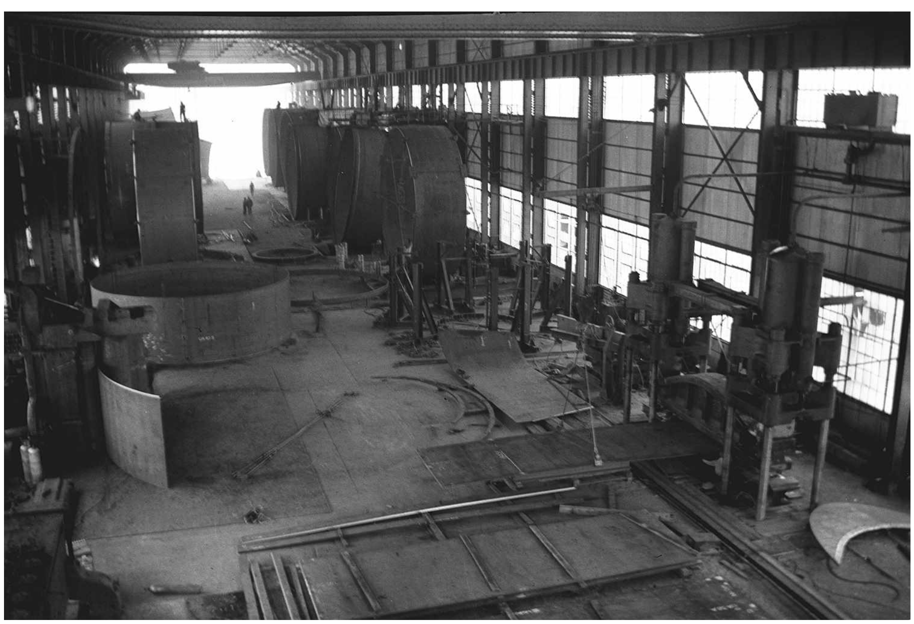

FIG. 26. 11-foot-long sections of the 37-foot-diameter penstocks being bent and conjoined by arc-welding inside the Babcock & Wilcox Steel Fabrication Plant (Preston Collection-Boulder City Library).

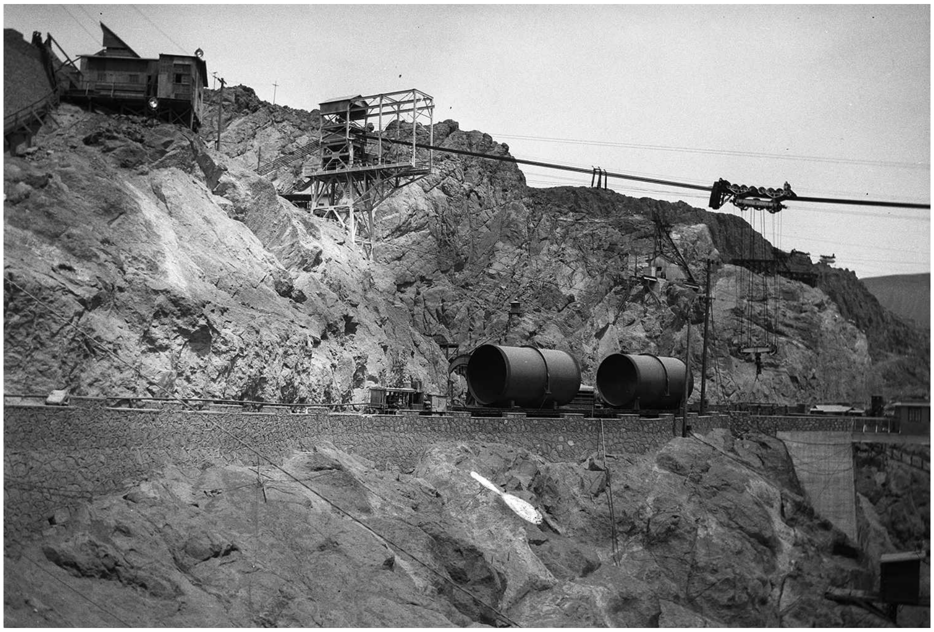

FIG. 27. Caterpillar tractor pulling two 22-foot-long sections of the 13-foot-diameter steel penstocks to the dam site. All of the steel liners were conveyed to the dam site in this manner (USBR).

because the components were too large to transport by truck or by rail (Figures 25 and 26). The plant fabricated the required shapes from steel plate that varied between 5/8 inch and 2-3/4 inches in thickness. Penstock sections were fabricated in 11-foot-long sections, and adjoining sections were then attached to create 22-foot-long assemblies that could be transported the 1.6 miles to the dam site, as shown in Figure 27. 16,000 lineal feet of steel penstocks were be fabricated at this plant, more than had ever been fabricated for any other dam up to that time (USBR, 1938).

MILESTONES IN JOB SITE SAFETY

Ventilation Problems and Heat Prostration

The unprecedented scale of the Boulder Canyon Project and the hostile summer environment of Black Canyon led to a number of safety measures that were not anticipated prior to construction. During the first year of construction, housing, drinking water, and sanitation facilities were either lacking for many of the workers or were still under construction. In the summer of 1931 average daytime temperatures reached 120 degrees F at the dam site and heat exhaustion killed 14 of Six Companies workers.

In August 1931 the Industrial Workers of the World (IWW) trade union succeeded in convincing Six Companies' workers to strike. Six Companies' lawyers and local and federal law enforcement fought vigorously to break this and succeeding strikes, or threats thereof, without making formal concessions to the worker's demands (summarized in Stevens, 1988 and Hiltzik, 2010).

In total, 21,000 men worked on the dam over a four year period, with the workforce averaging 3,500 employees. At its zenith 5,218 men were on Six Companies payroll during June 1934. The labor troubles always stemmed from a job site safety problem of one kind or another, and Six Companies General Superintendent Frank Crowe was obliged to make whatever adjustments he could to keep the job moving and thereby appear concerned about the worker's safety (Hiltzik, 2010). These concessions included provision of potable water for the worker's dormitories, the hiring orderlies to carry ice water to workers on the job (Figure 28), transporting and feeding the workers using three shifts per day (Figures 29 and 30), establishing first aid stations with doctors and nurses closer on the job site instead of nine miles away at the Boulder City dispensary (Figure 31), and encouraging job site safety and security (Figure 32).

At the completion of the job the official death toll was 96 men, but this did not include any of the men who were fired or quit prior to dying. A common myth perpetuated for years thereafter was that the massive dam contained an unknown number of entombed bodies, which was wholly without merit (as shown in Figure 8). The only 'body' allegedly entombed in the dam resulted from a practical joke carried out during one of the graveyard shifts while one of the crews were pouring the concrete lining of one of the penstock feeder tunnels. They thought it would be humorous to embed a worker's hard hat, gloves, and boots within the tunnel lining, which were revealed when the forms were pulled off. Frank Crowe was not amused. He hunted down the perpetrators and promptly discharged them, to set an example that such nonsense would not be tolerated by the management (Stevens, 1988).

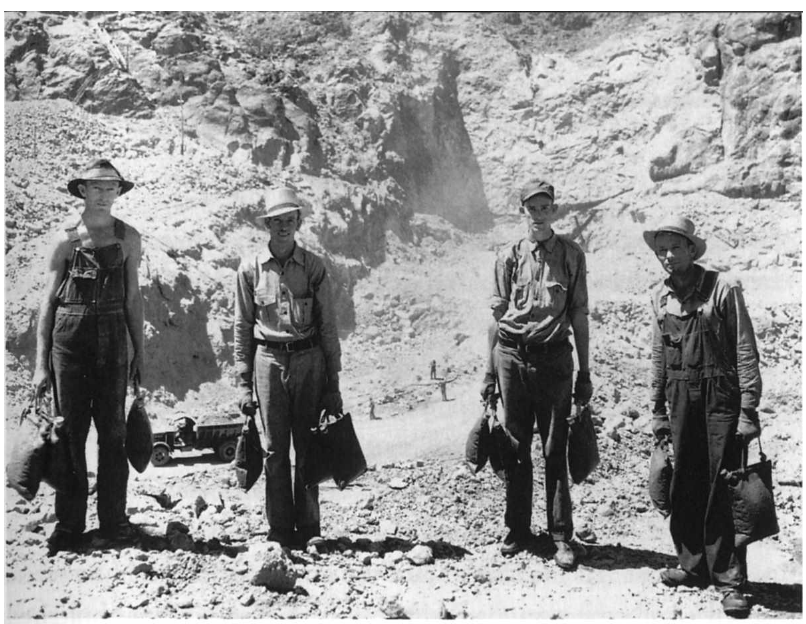

FIG. 28. Orderlies hired by Six Companies to carry ice water to its workers after the strike by IWW in August 1931 (USBR).

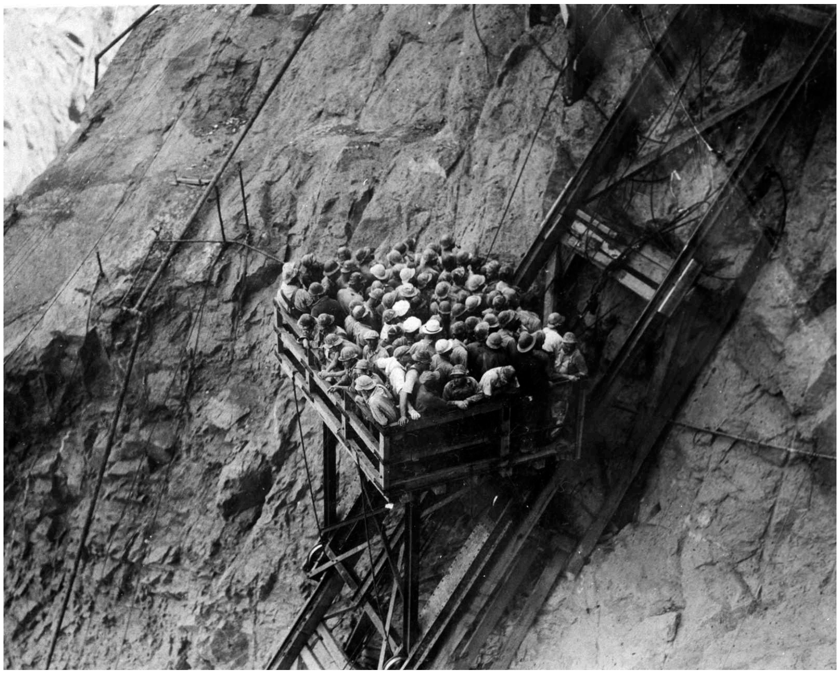

FIG. 29. 80 men being taken down the 10 by 12 ft skiff on the Nevada Abutment, heading to work on the 4 PM to Midnight swing shift. The skiff made the 565 ft trip in just over a minute (USBR).

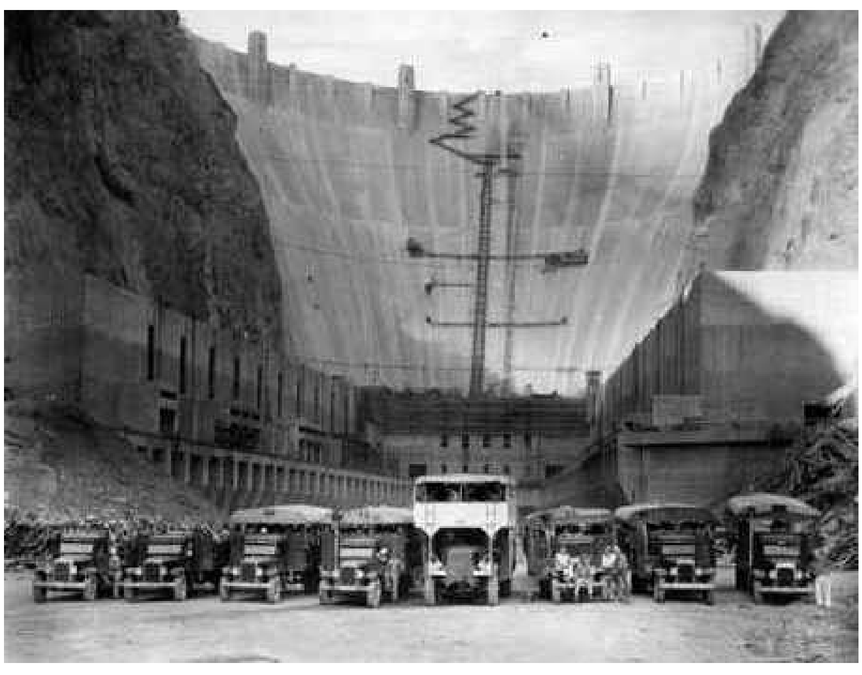

FIG. 30. Some of the buses used to shuttle workers the nine miles between Boulder City and the dam site pose in front of the dam and power houses towards the end of the job, in July 1935 (Six Companies Collection, USBR-LCR).

FIG. 31. One of the medical dispensaries positioned on the job site after the deaths of more than a dozen men working in the diversion tunnels without forced-air ventilation. These were equipped with a doctor, nurse, ambulance, and driver (USBR).

FIG. 32. As the job progressed, increasing attention was paid to safety and security after accidents or carelessness had taken the lives of workers. These signs appeared after an accident involving a driver who failed to yield to one of the between-shift blasts in 1933 (USBR).

Hard-hats Issued to Every Worker

In the fall of 1931 some of the high scalers working on the cliffs began fashioning "hard boiled" work hats by overlapping two baseball caps with bills front and back, then dipping it to form a thin layer of tar and quenching it with cold water, to create a hard shell (Figure 33). Others used shellac applied to leather hats. Six Companies liked this idea so much, they eventually contracted for thousands of these so-called 'hard hats,' from a number of different suppliers, including the E.D. Bullard Company in Sausalito, California.

Six Companies stopped short of requiring the hats be worn, because of the oppressive heat, but issued them to each worker and suggested strongly that men wear them when working in exposed areas, where loose materials could fall on them (Pettitt, 1935). A large proportion of the men working in exposed areas began wearing the hard hats, as shown in Figure 34. Sadly, the most deadly of these falling projectiles were not loose rocks, but tools dropped by other workmen! Hand tools were so crucial to the work at hand that at one point on the job Frank Crowe actually ordered 144,000 crescent wrenches (Stevens, 1988).

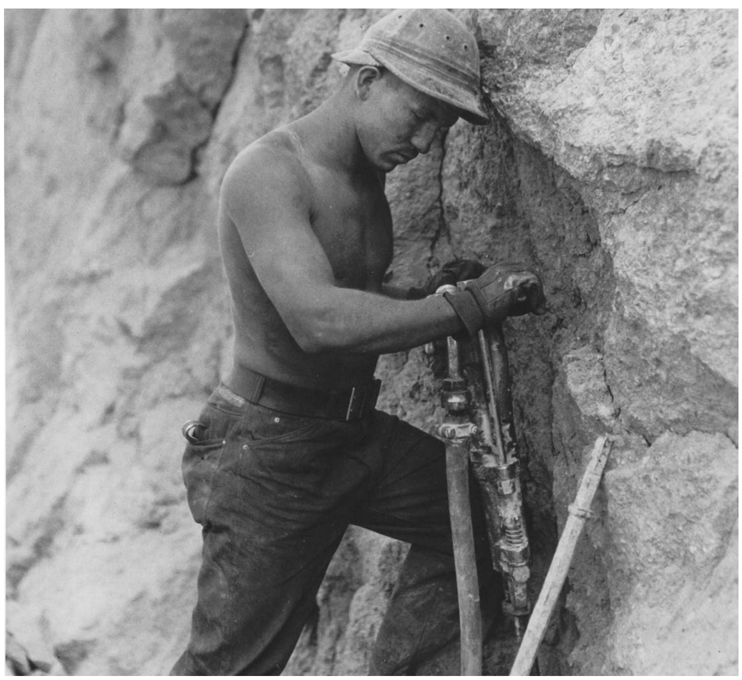

FIG. 33. One of the high scalers at Hoover Dam wearing a home-made 'hard-boiled hat" fashioned by overlapping two baseball caps and dipping them in tar and chilling or brushing leather hats with shellac (USBR).

In 1915 the Bullard Company began designing protective hats made of leather for miners in California, based on the protective helmets then being used in the First World War. In 1917 the U.S. Navy asked Bullard to provide them with a protective cap for shipyard workers. Bullard responded with the first "hard-boiled hat," crafted from steamed canvas, glue, and black paint, which they patented in 1919 (because they employed a unique steam processing method to speed up production). Bullard employed headband liners similar to those used in steel ‘Kelly helmets’ used by American at that time. The Bullard “hard-boiled hats” used in the Navy shipyards were similar to the home-made hard-boiled hats fashioned by the high scalers before Six Companies began providing head wear.

FIG. 34. Six Companies worker wearing one of the mass-produced hard hats they issued free-of-charge to their workers, encouraging them to wear them wherever loose materials might fall upon them. They purchased five different kinds of hard hats, from different suppliers/manufacturers (USBR).

Bullard claims that the first “hard hat job” where workers were actually *required* to wear hard hats was in 1933, when work on the Golden Gate Bridge in San Francisco commenced. The project faced an unforeseen problem when the steel arriving by train from Pennsylvania began rusting rapidly in the foggy, salty air. To protect workers who were sandblasting the rusty steel Bullard designed a sand-blast respirator-helmet that covered worker's faces, provided a window for vision, and an air supply via a hose connected to an air compressor.

In 1938, Bullard designed and manufactured the first aluminum hard hat, which was considered very durable and reasonably lightweight for the time. This quickly became a favorite of forest-fire fighters, but utility workers soon learned that its one serious drawback was that aluminum is a great conductor of electricity. Bullard’s three-ribbed heat resistant fiberglass hard hat was developed in the 1940s, and employed across the nation at various defense plants.

CONCLUSIONS

The unprecedented scale of Hoover Dam led to numerous innovations in construction management, especially with regards to critical path scheduling. All subsequent mass concrete dams more or less owe their existence to the advancements that were made during the construction of Hoover Dam. The innovations in mass concrete batching, handling, and placement left an indelible mark on the heavy construction industry, which had never witnessed such an efficient operation previously. Much of this was innovation grew out of the diverse and talented organization assembled by Six Companies, which was focused on problem solving to enhance the job's progress. This was impressive when considering that Reclamation required many more construction details requiring inspection and approval than any previous project they had supervised. Each new challenge was met with equally impressive and innovative technologies, including the most extensive system of overlapping cableways and standard gage rail spurs ever constructed, supplemented by multi-level rail trestles and an ever-changing array of stiff-leg derricks, which had to be managed 24-hours-per-day to avoid entanglements. The sheer scale of steel penstock elements necessitated unusual fabrication and method of transportation to the side-canyon tunnels. Although Six Companies did a poor job of ventilating their diversion tunnel excavations, they made numerous concessions during the course of the job to increase worker safety and morale, which became more of less standard for the heavy construction industry shortly thereafter.

ACKNOWLEDGMENTS

The author is most indebted to retired Reclamation engineer Richard Wiltshire, who appreciates civil engineering history and organized this symposium commemorating the 75th anniversary of Hoover Dam's completion. The author's interest in Hoover Dam was originally piqued by his initial viewing of the hour-long documentary film profiling the Boulder Dam Project which he viewed in high school. A year later he took his first extended tour of the dam.

In 2009-10 the author was a Trent Dames Civil Engineering Heritage Fellow and was a Dibner Research Fellow at the Huntington Library in San Marino, California. This fellowship and the residency it afforded allowed the author to review of numerous serial publications, collections, archives, and ephemera that provide invaluable to understanding the engineering decisions and political pressures influencing those decisions, not just during construction but during the decade preceding and following the dam's completion. Huntington Archivists Dan Lewis and Bill Frank proved to be particularly valuable in ferreting out rare or obscure accounts from the Huntington's civil engineering and scientist manuscript collections, as well as rare maps and historic photos.

Sincere appreciation for assistance is also rendered to the following people and their respective organizations: Reclamation historians Brit Allan Storey and Christine Pfaff, Dianne Powell of the Bureau of Reclamation Library; Reclamation archivists and staff Bonnie Wilson, Andy Pernick, Bill Garrity, and Karen Cowan of Reclamation's Lower Colorado Region (LCR) office in Boulder City; Boulder City Library Special

Collections; Eric Bittner at the National Archives and Records Service Rocky Mountain Region depository at Denver Federal Center; Paul Atwood and Linda Vida at the University of California Water Resources Center Archives in Berkeley; Su Kim Chung of the University of Nevada-Las Vegas Libraries; civil engineering historian Edward L. Butts; journalist and author Michael Hiltzik; and a special thanks to the author's best friend Steve Tetreault, who accompanied the author of his first tour of the dam in February 1973. Over the past several decades Mr. Tetreault has provided invaluable support and logistical connections in support of the author's numerous visits to the University of Nevada-Las Vegas, Boulder City, and Hoover Dam.

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