Hoover Dam: Scientific Studies, Name Controversy, Tourist Attraction, and Contributions to Engineering

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ABSTRACT: Hoover Dam was a monumental accomplishment for its era which set new standards for post-construction performance evaluations. Many landmark studies were undertaken as part of the Boulder Canyon project which shaped the future of dam building. Some of these included: comprehensive surveys of reservoir sedimentation, which continue to the present; the discovery of turbidity currents operating in Lake Mead; the nature of nutrient-rich sediment contained in these density currents; cooperative studies of crustal deflection beneath the weight of Lake Mead; and reservoir-triggered seismicity. These studies were of great import in evaluating the impacts of large dams and reservoirs, world-wide, and have led to a much better understanding of reservoir siltation than previously existed. Hoover Dam was also the first dam to be fitted with strong motion accelerometers and Lake Mead the first reservoir to have an array of seismographs to evaluate the impacts of reservoir triggered seismicity. Along the way, there has been considerable confusion about the name of the dam, which was changed in 1931, 1933, and 1947. Most of the project documents are filed or referred to by the several names employed by Reclamation between 1928-1947. The article concludes with a brief description of the Boulder Canyon Project Reports, which have been translated into many different languages and distributed world-wide. This is followed by a summary of the unprecedented influence Hoover Dam has exerted on dam and reservoir construction, not only in the United States, but also abroad.

MONITORING MILESTONES

First Crustal Deflection Studies

During the design of Hoover Dam, it was recognized that the tremendous weight of the dam and lake, more than 41,000,000,000 tons, might have a localized effect on the Earth's crust. Bell (1942) estimated that the Colorado River deposited 232 million tons of sediment, or 875,000 tons per week, in just six years, between February 1935 and

June 1941. Estimates made prior to construction indicated that there could be as much as three feet of deformation due to the weight, assuming a granitic continental mass lying on basalt, lying upon a somewhat denser crustal layer (Westergaard and Adkins, 1934).

Three series of precise leveling surveys were carried out between 1935 and 1950 to measure the actual movement of the Earth's crust (Figure 1). These measurements were carried out over a triangulation net of 711 miles, running the calculations to one-third higher accuracy than had ever been carried out previously on permanent benchmarks across the United States (Raphael, 1954). The leveling surveys used Cane Springs, north of Moapa, as the reference datum point. The three leveling surveys were carried out in 1935-36 (zero reservoir condition), 1940-41 (reservoir pool at el. 1221.5 ft), and 1949-50 (reservoir pool at el.1174 ft), allowing the crust to adjust to the reservoir load. These revealed up to seven inches of settlement of the Earth's crust in the fifteen years following completion of the dam and 8-1/2 years after the reservoir pool reached its normal operating level (Figure 2).

FIG. 1. Triangulation surveying of established monuments around Lake Mead began in 1935, to ascertain the extent of crustal deformation caused by the weight of the rising reservoir (USBR).

These precise leveling surveys also noted that the rate of sinking of the crust was increasing during the first 15 years, Hoover Dam having dropped about 2 inches in 1940, increasing to 5 inches by 1950. Since the reservoir weight did not increase after 1941, this suggested that plastic flow or creep (continuing strain under sustained loading) was playing some sort of role in the movements. By extrapolating the leveling data Raphael (1954) concluded that the ultimate maximum settlement would reach a value on the order of 10 inches. He also assuaged that the somewhat patchy pattern of settlement suggested some sort of regional warping of the crust, towards the south. This suspicion was confirmed by subsequent work (Smith, et al., 1960; Angelier et al., 1985).

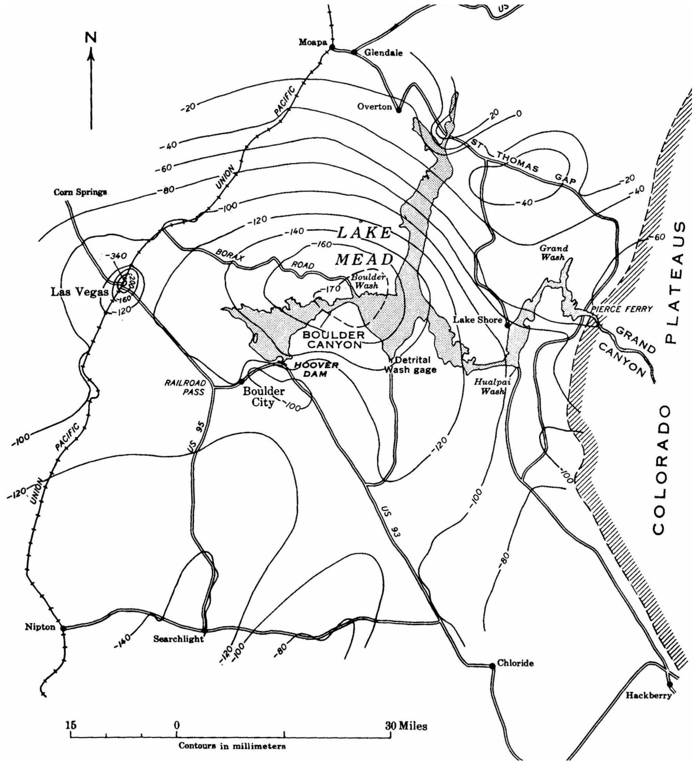

FIG. 2. Ground settlement contours, based on measurements around Lake Mead between 1935 and 1950 (Longwell, 1960).

First Evaluations of Reservoir Triggered Seismicity

A few weeks after Lake Mead reached its peak elevation of 1025 ft in the summer of 1936, a number of earthquakes began occurring, which garnered some publicity. The first seismograph had been installed at Boulder City in 1935, but the paucity of other nearby instruments prevented any meaningful triangulation to determine the precise epicenters and focal depths. The following year earthquakes began occurring in the eastern end of the reservoir, where the greatest volume of sediment was beginning to accumulate. Their interest piqued, seismologists gathered for the annual meeting of the Seismological Society of America in 1938 drafted a resolution asking the Bureau of Reclamation to install a seismic array around Lake Mead to record any possible relationship between reservoir filing and seismic activity. This suggestion met with positive approval of Reclamation's Board of Consulting Engineers, which included

Professor W.F. Durand at Stanford, a colleague of Professor Bailey Willis, one of the originators of the resolution.

In response to this inquiry, Reclamation contracted with the U.S. Coast & Geodetic Survey and the National Park Service to undertake a cooperative seismological investigation of Lake Mead and vicinity. In February 1938 two additional seismograph stations were established at Overton and Pierce Ferry (Figure 3). With the station already established at Boulder City, the seismographs were arranged in a rough equilateral triangle, about 50 miles apart, allowing the first study of reservoir triggered seismicity (Berkey and Nickell, 1939). In addition, that same year three strong motion accelerographs were installed in vicinity of the dam; one on the dam, one in the oil house, and another in the Nevada intake tower (Raphael, 1954).

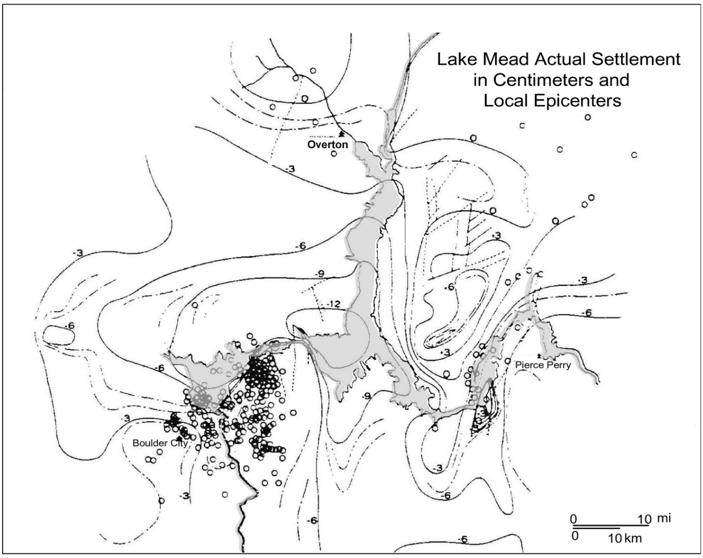

FIG. 3. Crustal settlement in vicinity of Lake Mead, showing the locations of the three seismographs and earthquake epicenters between 1937 and 1947 (modified from Carder and Small, 1948). This was the first documented study of reservoir triggered seismicity.

Recorded earthquakes from these seismographs were triangulated to locate the epicenters of earthquakes. During the first ten years of operation, more than 6,000 minor tremors were recorded in the vicinity of Lake Mead where no tremors had been recorded for the fifteen years prior to construction of the dam (Carder and Small, 1948). Lake Mead reached an average mean lake level of ~1174 ft in 1938 and the seismic activity shafted back to the deepest portion of the lake, closer to the dam. Most of the felt earthquakes varied in magnitude between 3.0 and 5.0. The strongest of these early events was a Magnitude (M) 5.0 quake that occurred on May 4th, 1939, setting off the accelerographs at the dam. This quake was felt as far away as Parker Dam, 200 miles to the south. This earthquake was associated with a swarm of 509 quakes recorded in May 1939, which garnered considerable interest (Berkey, and Nickell, 1939; Carder, 1945).

The vast majority of earthquakes recorded during the first 15 years were clustered within 10 miles of Hoover Dam (Figure 3), in an area of intermediate subsidence (having dropped just 3 inches over 15 years). Scientists sought to unravel any obvious pattern between earthquake activity, the rate of reservoir filing, or the total reservoir load. Longwell (1936) had mapped several potentially active faults through Boulder and Black Canyons, as well as other parts of the reservoir and its margins.

Throughout the 1940s earthquake activity in vicinity of Lake Mead seemed to correlate somewhat with the annual high water stands in 1940-45, then with the low water stands between 1946 and 1952 (Carder and Small, 1948). A sizable quake occurred in 1958 after rapid filling of the reservoir during the previous year, while another Magnitude 4 quake occurred after a rapid filling sequence in 1962-63. This was followed by a series of Magnitude 3.4 to 3.9 quakes when the reservoir dropped again, between 1963 and 1965. No correlation was ever found between the measured subsidence and the pattern of earthquakes.

Since 1965 only four Magnitude 3.7 to 3.9 earthquakes have occurred, despite repeated cycling of the reservoir. Post-1966 records suggest that seismic activity in vicinity of Lake Mead is no greater than that of the surrounding area (Rogers and Lee, 1976). There continues to be abundant microseismic activity ($M < 4$), especially when the reservoir pool cycles more than 35 ft. Subsequent work by a host of scientists working on Basin & Range tectonics has revealed that the Black Hills and Frenchman Mountain faults are seismically active, expressing northwest-directed tectonic extension. A swarm of microearthquakes were recorded along the Black Hill fault in 1972-73. Small magnitude quakes and fresh scarps along the Mead Slope fault several miles east of the dam suggest that it is tectonically active (O'Connell and Ake, 1995).

First Comprehensive Studies of Reservoir Sediment Accumulation

The river's name Rio Colorado is Spanish for "colored" or "colored red," so-named because of its distinctive reddish-brown color during the late summer months, when it is choked with red mud and silt from the highly erodible San Juan River and Little Colorado River watersheds. In December 1928 the Colorado River Board estimated the silt load of the Colorado River was likely between 80,000 and 137,000 acre-feet per year (ENR, 1928). For purposes of planning they recommended that silt accumulation during the 50-year repayment period be estimated to be about 3,000,000 ac-ft. Before infilling of Lake Mead, Chester Longwell detailed studies of the reservoir area (Longwell, 1936). These geological and topographic data provided a basis for evaluation of sedimentation processes after the reservoir filled. At the time the project was approved (December 1928) the maximum reservoir capacity of 30.5 million acre-feet was made before the project was constructed, which was subsequently adjusted to 30.25 million ac-ft (Smith et al., 1960).

A fascinating aspect of Hoover Dam is that the lower half of the dam only retains 1% of the reservoir's original design volume (Figure 4), based on the rating curve. When the dam was designed some allowance was made for sediment accumulation in the deepest portions of the reservoir floor, below the sill elevations of the dam's cylinder gates, at the base of the four intake towers, at elevation 895 ft. When the reservoir began filling on February 1, 1935 the estimated sediment storage below this elevation was 3,223,000 ac-ft (Smith et al., 1960). Accumulation of sediment above this elevation served to reduce the useable storage space of the reservoir, and thereby impacted the regulation of river flow.

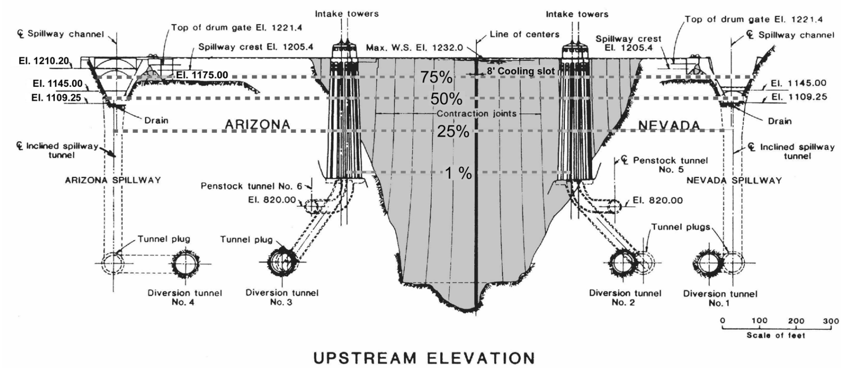

FIG. 4. Upstream elevation view of Hoover Dam, with lines delineating 1%, 25%, 50%, 75%, and 100% levels of the design reservoir storage, based on the original stage curve. The "dead storage" is that zone lying below el. 895, at the base of the intake towers. (USBR)

At the spillway design crest elevation Lake Mead extends 120 miles upstream of the dam, into Lower Grand Canyon, with a maximum surface area of 160,000 acres and 550 miles of contiguous shoreline. The reservoir occupies Boulder, Virgin, Temple, and Gregg Basins, which are separated by narrow canyons, where the Colorado River crosses resistant ridges (Figure 5). These basins were up to 650 ft deep when the dam was constructed and up to five miles wide. The reservoir includes several arms in tributaries that have been inundated, the longest of which is the Overton Arm, along the lower reaches of the Virgin River.

The largest tributaries are the Colorado River, Virgin River, Moapa River, Muddy Creak, and Las Vegas Wash. Other tributary valleys are normally dry and only contribute runoff during brief periods of storm activity (Twichell et al., 2003; Smith, et al., 1960).

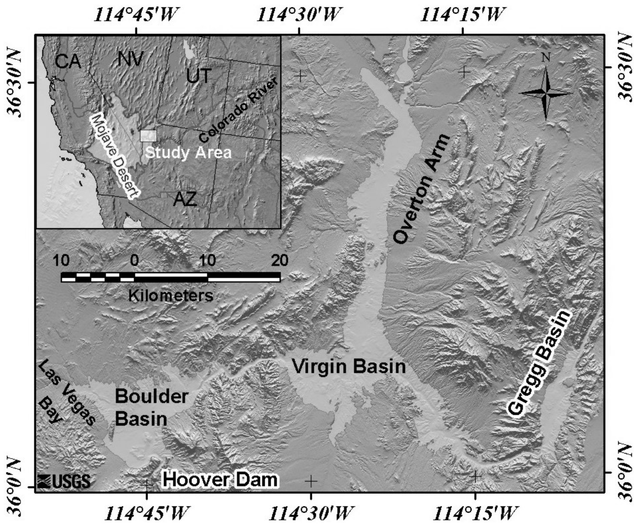

FIG. 5. Lake Mead extends 120 miles upstream of Hoover Dam. It is divisible into five distinct basins, separated by narrow bedrock canyons. The Pierce Basin is upstream, off the right side of the map (from Twichell et al., 2003).

Detailed studies of sediment accumulation were undertaken at Lake Mead as soon as the dam's diversion tunnels were shut down on February 1, 1935 (Figure 6). Despite warnings from several prominent engineers that sediment accumulation could endanger the economic models used to justify megaprojects like Hoover Dam (Stevens, 1946), the storage capacity of Lake Mead was only reduced about 5% through sediment accumulation during the first 14 years of operation (1935-49).

The post-war sediment studies included intensive surveys of the Lower Grand Canyon and Pierce Basin, where sediment accumulation reached a maximum thickness of 270 ft by 1948 (Smith et al., 1960). These studies revealed that the Colorado River delivered a daily average of 400,000 tons per day of sediment into Lake Mead. The post-war studies also revealed that the reservoir actually stored about 12% more water than predicted by reservoir stage plots because reservoir water in "bank storage," that moisture which seeps into pervious beds and banks of the reservoir (Horton, 1933). In addition, the sediment compacts under its own weight, as shown in Figure 7.

By combining these two unforeseen dividends, the total storage capacity in 1948 was actually increased by 13%, to 35 million ac-ft, over that predicted by the 1935 reservoir stage curve (Gould, 1960). But, the lake's sediments are deposited in two principal deltas, one along the Colorado River channel, and a much smaller delta within the inundated Virgin River channel, beneath the Overton Arm. The Virgin

River only supplies about 10% of the accumulated sediment, so the Overton Arm will likely never fill completely with sediment.

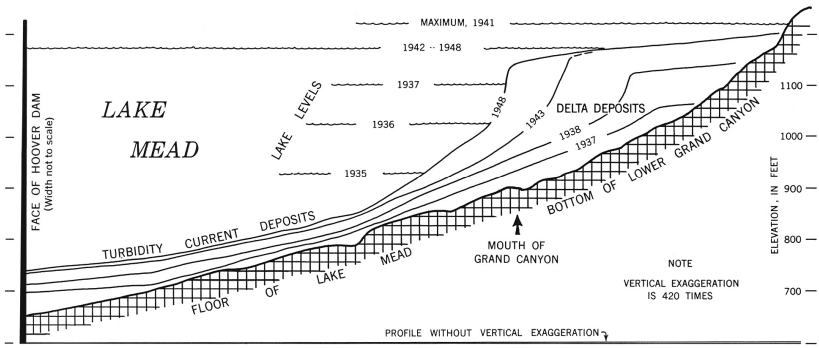

FIG. 6. Vertically exaggerated profile of the Colorado River channel in Lake Mead, showing the advancing sediment delta surveyed between 1935 and 1948. In the first 13 years 105 ft of sediment had already accumulated against the dam (modified from USGS PP 295, 1960).

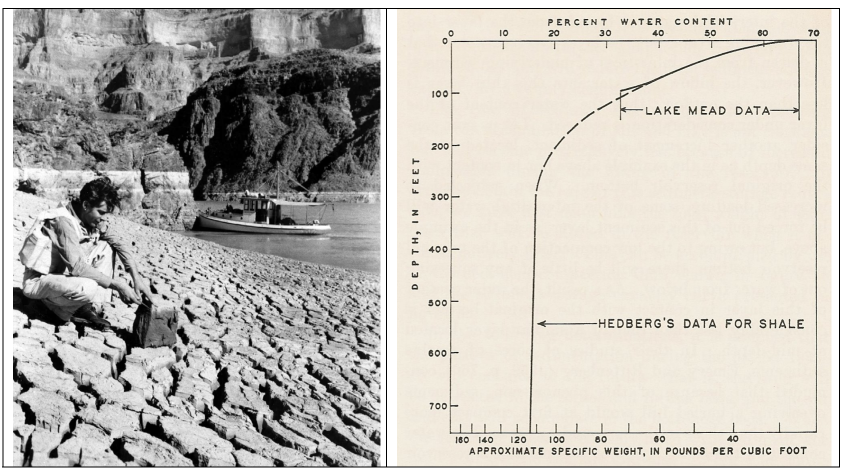

FIG. 7. Left – Geologist sampling recently deposited silt beds in Pierce Basin of Lake Mead in March 1939 (USBR). Right – Sediment water content versus specific weight for silt and clay, plotted as a function of depth, showing the sediment compaction data for Lake Mead (from USGS-PP295).

The sediment brought down by the Colorado River averaged about 45% sand and 55% silt and clay, with very little bed load. Practically all of the silt and clay was deposited by turbidity flows into the lowest parts of the reservoir (described below). The slope of the advancing delta has consistently been observed to dip sharply for a distance of about 1-1/2 miles, while the slope of the accumulated sediment diminishes with increasing distance downstream, as shown in Figure 8.

The volume of suspended sediment measured at Bright Angel Creek in the Grand Canyon (after the station was established in 1923) compared favorably with that deposited in the reservoir over the first 14 years, being within 2%. This unexpected loss of sediment was a source of considerable consternation and controversy, leading to pioneering studies within the Grand Canyon in mid-1965, soon after the gates at Glen Canyon Dam were closed (Leopold, 1969).

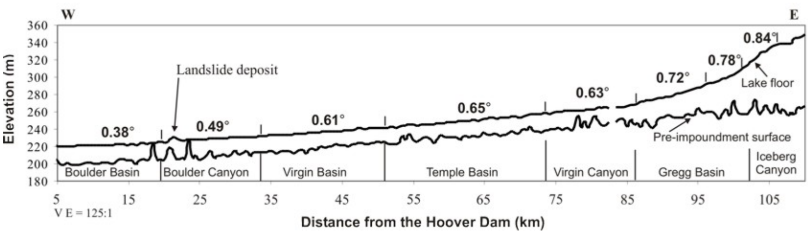

FIG. 8. Sediment accumulation along thalweg of Colorado River through Lake Mead, between 1935 and 2002 (from Twichell et al., 2003). Note diminishing gradient with distance from the river's delta, which by 2000, had advanced to the mouth of Iceberg Canyon, 65 miles upstream of Hoover Dam.

The scientific teams reported that if sediment transport rates continued more or less at the levels recorded in Grand Canyon between 1926 and 1950, it would take slightly more than 400 years for before Lake Mead filled with sediment, noting that the rate of accumulation after 1935 was actually about 20% below the 15-yr average. Construction of sizable upstream reservoirs at Glen Canyon (1963), Flaming Gorge (1964), and Fontenelle (1965) served to intercept much of the sediment along the upper Colorado and Green Rivers, reducing the sediment load impacting Lake Mead by over 90%.

Between 1935 and 1963, an average of 91,000 acre-feet of sediment was deposited in Lake Mead each year (Figure 9). Before construction of the Glen Canyon Dam (370 miles upstream), the Colorado River transported about 500,000 tons of silt and sediment per day through the Grand Canyon into Lake Mead. The peak flow rate of the Colorado before construction of the dam would normally have been around 85,000 cfs for the month of June. By examining river sediments, scientists determined that on a number of occasions over the past 4,000 years, the river reached peak flows of over 250,000 cfs (Swain, 2008). The peak flows routed through the Grand Canyon after construction of Glen Canyon Dam are normally between 12,000 and 30,000 cfs, depending on the severity of the snowpacks in source areas (1983 and 1984 were exceptions, see Vandivere and Vorster, 1984). Since the gates at Glen Canyon Dam were closed in March 1963 the rate of sedimentation in Lake Mead has dropped by about 91.5% (from an average rate of 93,300 ac-ft/yr to just 7,900 ac-ft/yr), as shown in Figure 9.

The sediment studies in the early years within Lake Mead electrified everyone working in sedimentation because so much new information was gleaned from the ongoing measurements (Fry, 1950), which were among the first to utilize Sonar profiling for bathymetry as well as sediment profiling of the accumulated sediments, which revealed sediment "drapes" over the pre-existing topography.

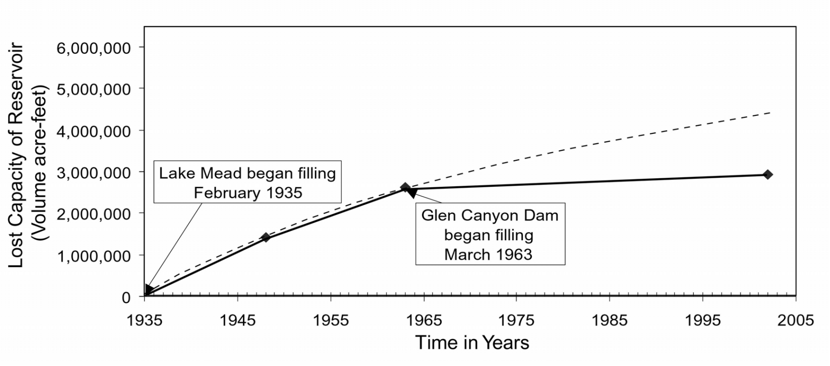

FIG. 9. Loss of storage capacity in Lake Mead due to sediment accumulation between 1935 and 2002, based on bathymetry surveys in 1947-48 and 2002-03. The apparent flattening of the curve between 1935 and 1963 is ascribable to compaction of the silt and clay fraction. Dashed line shows pre-Glen Canyon Dam prediction, accounting for compaction of the accumulated sediment.

Discovery of Turbidity Currents

The bypass gates at Hoover Dam were initially closed to initiate reservoir storage on February 1, 1935, about 18 months ahead of schedule. The last diversion tunnel was closed on May 1, 1936. During that 15-month period there were at least four sequences of turbid underflow being passed through the diversion tunnels, which drew water from the lowest elevations of the rising lake. The first turbid outflows were noted in March and April 1935, when turbidity tests at Willow Beach, 10 miles downstream of the dam verified a sudden shift to more turbid outflow.

Lake Mead crested at elevation 928.5 ft in 1935, about 422 ft above the lowest point of its foundation. In late September a noticeably turbid flow passed the Bright Angel Canyon stream gage in Grand Canyon, 265 miles upstream of Hoover Dam. About 45 hours later this turbid mixture disappeared into the clear waters of Lake Mead over an abrupt line, like that shown in Figure 120-left. The inflow at the time was about 9,360 cfs. Six days later a turbid outflow suddenly issued from the dam, which was passing 9,900 cfs. The increased turbidity and dissolved solids suites were again noted at Willow Beach. Grover and Howard (1938) showed that the percentages of sulphate recorded at Bright Angel Canyon and Willow Beach followed one another with convincing regularity. These 'sediment streams' continued downstream and were similarly noted at Topock. Bell (1942) estimated that the flow moved through Lake Mead with an average flow velocity of about 0.86 ft/sec over a distance of about 87 miles. That subsurface flows would be carried all of the way to the dam in such a short span of time, so soon after the lake partially filled, was a startling development.

A similar pattern of turbid sediment flow through Lake Mead was noted during 1936, when the lake rose to el. 1026 ft. Up through May 1, 1936 there were 46 days of turbid discharge being passed by the dam, carrying approximately 8.4 million tons of sediment, the great majority of which was fine silt and clay (90% finer than 20 microns). During this time the reservoir was between 70 and 90 miles long and contained 4 to 5 million ac-ft of water. The four density current events recognized in 1935-36 passed about 6 million tons of silt and clay through the dam (Howard, 1960). After May 1st, 1936 the lowest elevation from which water could be released from Lake Mead was the base of the intake towers at el. 895 ft, about 270 ft above the original channel.

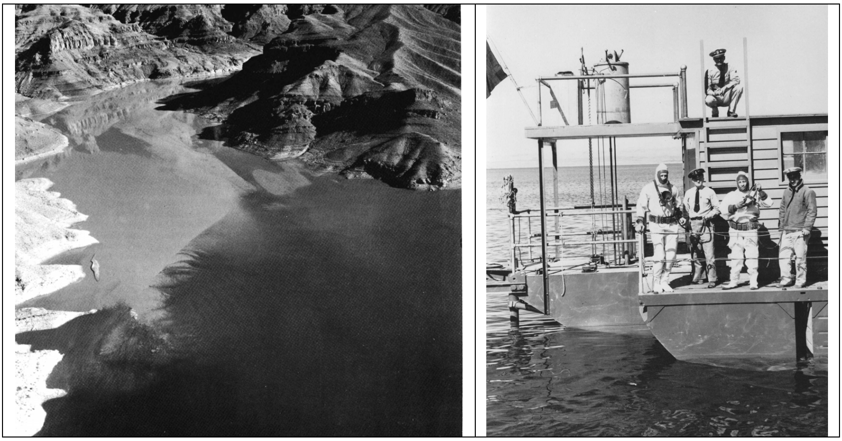

FIG. 10. Left - Turbid flow of the Colorado River being subducted as underflow at the precipice of the delta being formed in Pierce Basin in 1948, 77 miles upstream of Hoover Dam. Enormous "islands" of driftwood accumulated at the demarcation between the fluids of contrasting density. Right – Divers engaged in sampling sediments in the floor of Lake Mead in the 1940s (both USBR).

Around this same time the National Bureau of Standards had been making preliminary studies of density currents, comparing field data with physical and analytical models, using data provided by Reclamation and the U.S. Geological Survey (USGS). The Soil Conservation Service made a series of laboratory studies at the California Institute of Technology, which seemed to replicate what was being observed at Lake Mead (Bell, 1942). The National Academy of Sciences decided to convene a special panel of the National Research Council to investigate the density flow phenomenon in the spring of 1937. This committee was comprised of individuals selected from the National Research Council's Division of Geology and Geography and christened the Interdivisional Committee of the National Research Council on Density Currents, headed by Herbert N. Eaton of the National Bureau of Standards, which initially convened in June 1937. Two subcommittees were then appointed to study density current phenomena at Elephant Butte Reservoir and at Lake Mead (Reclamation began monitoring sediment accumulation at Elephant Butte in 1931, 16 years after completion). The Subcommittee on Density Currents in Lake Mead was chaired by Carl P. Vetter, an engineer with the Bureau of Reclamation. The results of these studies were compiled in three volumes containing 900 pages of data, which were released between 1940 and 1949 (National Research Council, 1949).

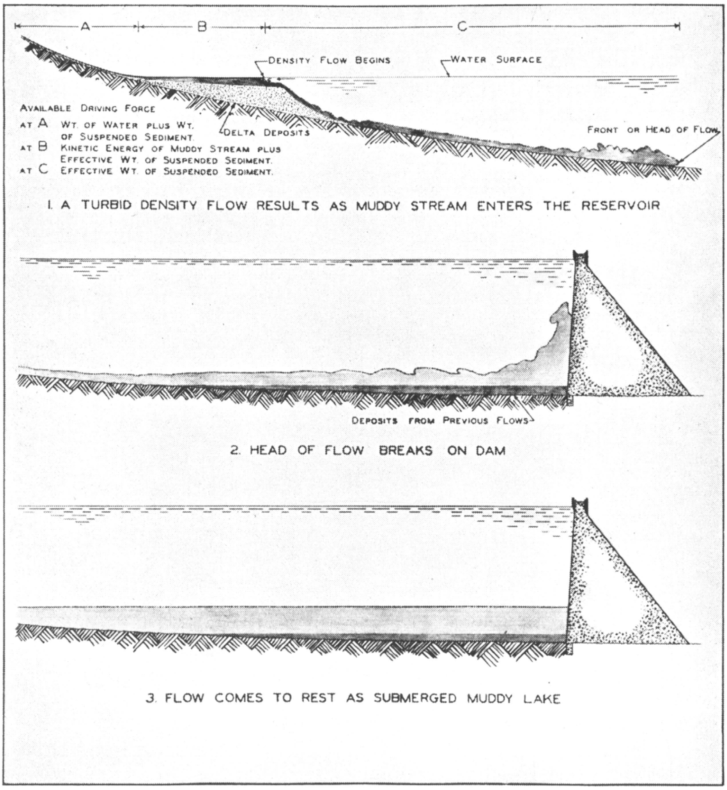

FIG. 11. Diagrammatic representation of a subaqueous density flow in a reservoir, showing the advancing delta in the upper part of the lake and the manner by which the fine grained debris piles up against the dam (from Bell, 1942).

C. S. Howard of the USGS and T.C. Mead of Reclamation began collecting samples and taking measurements of the Lake Mead sediments in May 1937 (Figure 10-right). They initiated a program of taking samples each month at five locations between the Virgin River and Hemenway Wash, as well as from behind Hoover Dam and at Pierce Ferry. Other locations were sampled less frequently (two or three times per year). They soon learned that the density currents only occurred when conditions were favorable to their development at certain times of the year, when flash floods spilled down the major tributaries in the Grand Canyon, increasing sediment concentrations markedly. These usually occur in the late spring and/or late summer, driven by thunder storms. Howard (1960) reported that 21 such events were documented between 1935 and 19 50, and only one of these, in 1941, persisted for more than a week (the 1941 sequence lasted almost five months, while that in 1983 persisted for three months).

The Subcommittee on Lake Mead discovered large accumulations of fine silt and clay were being deposited in the old river channel, at times with densities as low as 1.0008 times that of water. This fine debris was basically moving as a “submerged stream” within the lake, infilling all of the lowest spots in the reservoir, extending all of the way to the dam (Figure 11), where it reached a maximum thickness from piling up against this obstruction (Bell, 1942). The ability of these fine materials to be transported over such a great distance through broad basins and sinuous bedrock narrows on an initial hydraulic gradient of about five ft/mile was of great interest to the engineering and scientific communities, evidenced by the fact that Grover and Howard’s 1938 article generated 57 pages of technical discussions from 20 contributors (Grover and Howard, 1938; Vanoni, 1990).

This widespread interest led to the development of the multi-agency team led by Carl Vetter, Chief of the Office of River Control for the Bureau of Reclamation, which made comprehensive evaluations of reservoir sedimentation in Lake Mead in 1947-48, summarized in Smith et al. (1960).

Unexpected Discovery of Warm Sediment

Another intriguing aspect of the density currents was the temperature of the muddy fine-grained sediment, which was noted by Grover and Howard (1938) in the recent sediments deposited in Virgin Canyon, Boulder Canyon, and Black Canyon in 1937. In addition, the temperature sensors embedded in the dam’s concrete detected anomalously high temperatures towards the upstream heel of the newly completed dam (Carlson, 1977). The elevated temperature of the oozy low-density sediment was unanticipated, and it quickly drew considerable attention. Page (1938) thought it ascribable to the hot springs along the river channel just upstream of the dam, but this was discounted by Grover and Howard (1938) because all of the fine-grained sediment deposited by density currents was giving off measurable heat (68 to 70^{o} F), while the deep lake water (greater than 100 ft deep) varied from 52 to 55^{o} F.

Sampling soon revealed that the organic silt was hosting more than one million bacteria per gram, comparable to the bacteria count in raw sewage! Near the surface of this mud the bacteria concentration soared to 10 million bacteria per gram, producing methane (Sisler, 1960). Reservoir water just 12 inches above the mud contained only

100 bacteria per gram. These were much higher concentrations of bacteria than had been previously encountered in either marine or lacustrine clays. The Lake Mead samples were also unique insofar that the high bacterial populations were distributed uniformly throughout the deposited layer, which was of very low relative density (Sisler, 1960).

Laboratory tests suggested that the activity of microflora (bacteria and other microorganisms) caused heat to be generated in the nutrient-rich silt and clay. This activity also depletes the hydrogen ion concentration of the entrained water, which shifts the pH from 7.25 to 10, hastening a 22-percent volume reduction, resulting in accelerated compaction of the colloid clay particles (Sisler, 1960).

The heat against the upstream heel of the dam was insufficient to cause uncontrolled tensile cracks because the concrete's curing cycle had been accelerated through the use of cooling pipes and use of low heat cement (Carlson, 1977).

Page (1938) showed remarkable insight in noting that the density currents were predominately fine grained mixtures of colloidal clay, which contained "a high percentage of salts." The role of salts in promoting dispersion of clay was subsequently recognized, four decades later (Sherrard at al., 1976). Most of the red shales exposed in the San Juan, Little Colorado, and Lower Colorado Basins are of dispersive character, which promotes their suspension (marked turbidity), increasing the density of the water-sediment mixture. This increased density serves to increase susceptibility to debris flows and density currents (Rogers, 1985).

Continued Monitoring of Sediment Accumulation

Reclamation has continued monitoring sediment accumulation in Lake Mead, even though the rate of sedimentation has dropped dramatically since the completion of Glen Canyon Dam in 1964 (Figure 9). A comprehensive study of the lake floor was undertaken between 1999 and 2002 by the U.S. Geological Survey, in cooperation with the Lake Mead/Mohave Research Institute, and the University of Nevada-Las Vegas (UNLV) (Twichell, 1999; 2001; 2003). In 1999 the Boulder Basin portion of the lake was surveyed. In 2000 surveys were carried out in the northwestern portion of Las Vegas Bay, and in 2001 the eastern part of the lake bed was mapped. In 2002 UNLV researchers evaluated cores of the lake sediments to ground-truth of the results of the geophysical surveys, conducted from boats. Evaluation of sediment accumulation and the distribution of sediment and any associated pollutants were the principal objectives of this study.

The reservoir floor was remotely mapped using sidescan-sonar and high-resolution seismic-reflection profiling. High resolution seismic reflection profiling is derived from recording impulse signals reflected from the floor and subsurface interfaces. It allows a graphic "picture" of the floor geology along the profile of observation, like that shown in Figure 12. The sidescan-sonar also records the acoustic energy scattered on the lake bottom and the resulting digital images provide considerable detail about the structure of the sediments and the underlying strata.

The most recent sedimentation studies show that sediments are concentrated in the deepest parts of the lake along the pre-impoundment tributary valleys. These sediments have accumulated as a "continuous cover" along the Colorado River trough, from the eastern part of Lake Mead all the way to Hoover Dam. The thickest sediment through Lake Mead has accumulated in the Lower Granite Gorge, where the channel is most narrow.

The sediment also reaches thicknesses of 225+ ft in the delta it has deposited in the Pierce Basin and Grand Bay (Twichell, 2003). The sediment thickness decreases to 50 to 80 ft in the central part of the reservoir, and gradually increases to 100 ft at Hoover Dam. The maximum sediment thickness in Boulder Basin at the west end of the lake is 148 ft. In the Overton Arm, occupying the original Virgin River valley, there is only 3 to 13 ft of sediment because Muddy Creek and the Virgin River have relatively low mean annual discharge (Twichell, 2003).

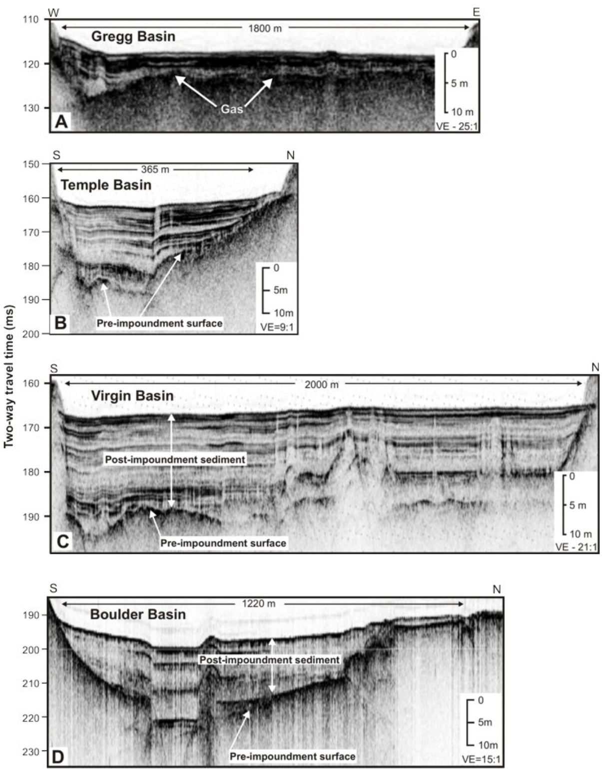

FIG. 12. High-resolution seismic reflection profiling used to measure sediment accumulation across Gregg, Temple, Virgin, and Boulder Basins of Lake Mead between 1999 and 2001. Gas-saturated sediments tend to attenuate the acoustic signal, as seen in profile A. Note high definition of original lake bottom (from Twichell, 2003).

These most recent analyses suggest that the Colorado River contributes about 98% of the sediment in Lake Mead. The geometry of the sediment lenses suggests its accumulation is due to the density flows that run from the mouth of the Colorado River to the Hoover Dam (Twichell, 2003).

The high-resolution seismic surveys also internal layering of the sediment deposited in the western basins, which appears to be sand covered by mud. The bulk of recent deposition in the eastern portion of the reservoir was found to be coarse sand. This shift from sand deposition may be explained by the reduced sediment loads and mollified flows since the construction of Glen Canyon Dam in 1964 (Twichell et al., 2002).

THE NAME CONTROVERSY

Boulder Canyon Dam

In 1921 Congress authorized detailed studies of the Lower Colorado River Basin, with particular emphasis on Boulder and Black Canyons, below Grand Canyon. The Fall-Davis Report released in February 1922 concluded that a great dam could be constructed at either Boulder or Black Canyons. This was the seminal document that led to the Boulder Canyon Project Act, introduced in the first session of the 67th Congress in April 1922.

The other Colorado Basin states reacted warily to California's zealous proposition of an appropriation of unprecedented magnitude that would funnel the great majority of the Colorado River water into southern California, where it might easily be swallowed up in perpetuity under the common law doctrine known as "prior rights."

The Coolidge Administration sought to head-off an impasse between the basin states by convening a commission to draft a Colorado River Compact, which would seek to establish an equitable distribution of water between Wyoming, Colorado, Utah, New Mexico, Arizona, Nevada, and California. The commission was organized formally in January 1922, with an appointed commissioner from each state and a chairman appointed by the President. Calvin Coolidge chose his Secretary of Commerce Herbert Hoover, who had technical training as a mining engineer and had distinguished himself in a myriad of public service roles, most notably, as head of European relief efforts for President Woodrow Wilson after the First World War (25 years later he was appointed to a similar position by President Truman after the Second World War).

Public hearings began in March 1922 and negotiations wound along till November 24th, when the Colorado River Compact was agreed upon at Bishops Lodge in Santa Fe, New Mexico. It was the most notable water agreement in American history up to that time and Hoover gained a considerable degree of notoriety, for his encouragement of equitable development of the nation's natural resources. Many newspapers portrayed him in a favorable light, noting his high level of education and apparent incorruptibility because he was independently wealthy.

Boulder Canyon Project

The name 'Boulder Canyon Project' was chosen by Reclamation engineers because they assumed the great dam would be built near the head of Boulder Canyon, where the granite outcrops create an extremely narrow channel, perfect for a dam. Most dam engineers believed granite to be about as stable of a foundation for a dam as could be found, anywhere. The Boulder Canyon Project Act was introduced twice each year, to the 67th, 68th, 69th, and 70th Congresses.

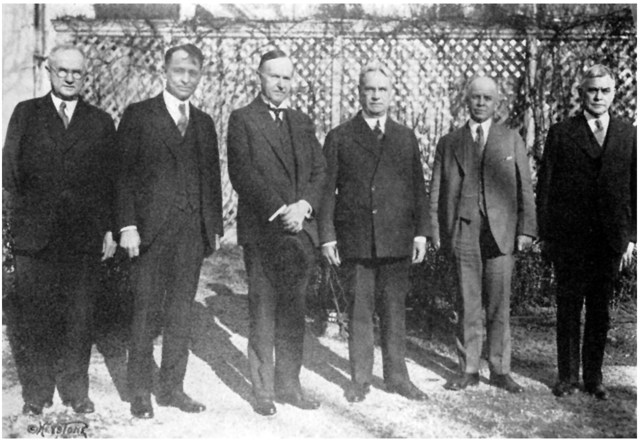

FIG 13. Witnesses to the signing of the Boulder Canyon Project Act on December 21, 1928, from left: Reclamation Commissioner Elwood Mead, Congressman Phil Swing of Imperial Valley, President Calvin Coolidge, Senator Hiram Johnson of California, Congressman Addison T. Smith (Chair of the House Committee on Irrigation & Reclamation), and W. B. Matthews, counsel to the newly formed Metropolitan Water District, who subsequently purchased long term contracts for 28.5% of all the power generated by Hoover Dam. President-elect Herbert Hoover was not present because he did not endorse the maximum height dam at Black Canyon, believing it to be unnecessary. (USBR)

The Act finally succeeded in gaining approval in late 1928, passing through the Senate on December 14th and the House on December 18th, with approval by President Coolidge on December 21st (Figure 13). By that juncture Herbert Hoover was the President-elect, but he refrained from partaking in any of the publicity attached to the Act's passage because he had stopped short of endorsing a dam of record height, maintaining that major dam of somewhat less proportions would be adequate to the tasks at hand.

Hoover's support for a lower dam did not endear him with the project's boosters in southern California, although he always enjoyed the support of the Los Angeles Times (Hiltzik, 2010). The Bureau of Reclamation saw the mighty dam as an instrument of unspoken manifest destiny, which would allow them to transform the west from barren wasteland into a 'perennial breadbasket' by irrigating the Palo Verde, Yuma, Imperial, and Coachella Valleys, whose crops could supply the nation with green vegetables year round (Lyons, 1947).

Black versus Boulder Canyons

Prior to the Act's passage it was pretty clear that there were many advantages in siting the dam in Black Canyon as opposed to Boulder Canyon. These were summarized by Professor W.F. Durand in a report to Congress titled "Development of the Lower Colorado River" (Emerson et al., 1928, pp. 394-95), dated January 9, 1928. After listing nine advantages posed by the Black Canyon site, Durand summarized the consensus view on why the Boulder Canyon name should be retained:

> *"In order to avoid confusion with the name it should be noted that the name Boulder Canyon dam and reservoir was first given to a proposed dam to be located in Boulder Canyon and to the reservoir formed thereby. Subsequent investigation gave evidence that a site some 20 miles lower by the river, and located in Black Canyon, might be more advantageous in certain respects. The reservoir, in either case, would flood approximately the same territory.*
>
> *Actually, therefore, it is one project with a choice of two dam sites and in order to emphasize this viewpoint it has seemed desirable to retain the original name for the general project. When, however, it is desired to distinguish the Black Canyon site and development in a specific manner it may be designated as the Boulder (Black) Canyon project or development."*

By the time the fourth version of the Boulder Canyon Act with all the amendments recommended by the Colorado River Board was put forth for congressional approval in late 1928, the decision had long since been made that the dam would be constructed in Black Canyon, not Boulder Canyon. As stated above, no one in Washington, DC seemed to think that it would serve any good purpose to change the bill's title to the 'Black Canyon Project Act,' which had a rather sinister ring to it.

Naming it Hoover Dam (1931)

Republican President-elect Herbert Hoover took the oath of office on March 4, 1929. On May 27th Democratic Congressman Ed Taylor of Colorado introduced a bill to name the proposed dam in Black Canyon after the new president, but this effort failed. Through the following 16 months various legal opinions were issued from the Department of Justice concerning water and power contracts being negotiated by the government, and the dam was referred to as 'Boulder Dam' or the 'Boulder Canyon Dam.' Even the order Interior Secretary Ray Lyman Wilbur issued to Reclamation Commissioner Elwood Mead on July 7, 1930 authorizing construction referred to the 'Boulder Canyon Project' and mentioned 'Boulder Dam' four times.

On September 17, 1930 Ray Lyman Wilbur went to Nevada to commemorate the beginning of the project. In his dedication speech, he announced that the dam would from that point on be officially known as Hoover Dam, in honor of the dominant role

Hoover played in effecting original Colorado River Compact and in encouraging congressional approval of the Boulder Canyon Project.

After Wilbur's announcement at the 'Silver Spike Ceremony' on September 17th all references to the dam's name were changed. The new water and power contracts were changed from 'Boulder' to 'Hoover Dam' as they were amended and published. During Congressional hearings for the dam's initial appropriations on December 12, 1930, Congressman Ed Taylor, by now the ranking Democratic member of the Interior Department Subcommittee on Appropriations, made a florid speech justifying his committee's official naming of the project's kingpin structure as 'Hoover Dam' in the appropriations bill before them, stating: "*There is another feature of this... bill under consideration that I feel ought not to be passed over in silence. I refer to the three words in the second line, "The Hoover Dam.*"

This appears to have been the first time that 'Hoover Dam' appeared in any bill or official act of Congress. Taylor justified the committee's decision:

> "*Members of the committee felt this decision was simply following precedents that had previously been applied in the naming of the Roosevelt Dam during Theodore Roosevelt's administration, Wilson Dam during Woodrow Wilson's administration, and the Coolidge Dam during Calvin Coolidge's administration, so President Hoover was justly entitled to the same distinction, so we unanimously and very gladly wrote into this action those words... so that the dam is now officially named by both the Secretary of the Interior and by Congress.*"

The appropriation passed on February 14, 1931, and in the next four appropriation acts passed by Congress in 1932-33, the structure was referred to as 'Hoover Dam.' For the remainder of Hoover's administration all official references to the dam, as well as tourist and other promotional material issued during this period called it Hoover Dam.

After his first year in office, Hoover's popularity as president waned as the Great Depression put more and more people out-of-work. Hoover was soundly defeated in his bid for re-election by Franklin Roosevelt on November 8, 1932, just six days before the Colorado River was initially diverted through the project's bypass tunnels. Hoover made his only trip to the dam site by making a slight detour on his way back to Washington, D.C. from California, shortly after losing his re-election bid. He arrived and departed from the dam site in the cloak of darkness on the evening of November 12th-13th. When he visited one of the mess halls in Boulder City workers booed him. He then paid a visit to the dam site to view the massive diversion tunnels (Figure 14), making a brief speech, but never referring to the dam by name:

> "*This is not the first time I have visited the site of this great dam. And it gives me extraordinary pleasure to see the great dream I have long held taking form in stone and cement... This dam is the greatest engineering work of its character ever attempted at the hand of man... The waters of this great river, instead of being wasted in the sea, will now be brought into use by man*".

FIG. 14. The presidential entourage accompanying Herbert Hoover's midnight visit to the dam site on November 12-13, 1932, four days after he was defeated by Franklin Roosevelt. Some of the notables included: Walker R. Young (far left), Reclamation Chief Engineer Raymond F. Walter (third from left), Mrs. Lou Hoover and the President (center), Mrs. Wilbur, Interior Secretary Ray Lyman Wilbur, Reclamation Commissioner Elwood Mead, and Frank Crowe of Six Companies. It would be another seven months until the first concrete was poured for the dam. (USBR)

Re-naming it Boulder Dam (1933)

Franklin Roosevelt took office as president on March 4, 1933, and he named Harold Ickes as his Interior Secretary. Roosevelt had initially offered the Interior Secretary position to California Senator Hiram Johnson, a Republican and co-sponsor of the Boulder Canyon Project Act. Johnson turned him down, but suggested Ickes because he was an ex-Republican. Even as a Republican Ickes had never supported Herbert Hoover, only those candidates who opposed him. Enjoying considerable consensus support, Ickes went onto serve as Interior Secretary for an astonishing 13 years, the longest tenure of any cabinet secretary in American history.

On May 8, 1933 Ickes sent a telegram to Reclamation Commissioner Elwood Mead informing him that the name of the new dam would thereafter be 'Boulder Dam.' He assuaged that this was the "original name," but that was actually "Boulder Canyon Dam" (used in Reclamation designs dating back to 1920). No one doubted that this decision was politically motivated, but nobody in Washington barked too loudly about it because Hoover's approval rating was at an all-time low.

Boulder Dam was dedicated by President Franklin Roosevelt on September 30, 1935. Among the dignitaries in attendance was Elwood Mead, Commissioner of Reclamation; Harold Ickes, Secretary of Interior; John Savage, Raymond Walter, and Walker Young, of the Bureau of Reclamation; and the Governors of California, Utah, Arizona and Wyoming. Representing the Six Companies was Harry Morrison of

Morrison-Knudsen; Steve and Kenneth Bechtel of the Bechtel Corporation; and Frank T. Crowe, Six Companies General Superintendent. President Roosevelt's remarks were carried by radio stations and appeared in numerous newsreels. Speaking to thousands of onlookers, the President referred to the dam as "*an engineering victory of the first order - another great achievement of American resourcefulness, skill and determination.*"

When his turn came to speak at the lectern, Reclamation Commissioner Dr. Elwood Mead referred to the structure as 'Hoover Dam' instead of Boulder Dam, infuriating Interior Secretary Ickes. But, his miscue drew little attention from anyone else. Mead was by that time 77 years old. He had been reclamation commissioner for almost 12 years and his retirement seemed imminent. Mead died a few months later in Washington, D.C., on January 26, 1936, 10 days after his 78th birthday. A grateful nation moved quickly to memorialize his contributions. On February 6th, a motion was made in Congress to name Boulder Reservoir after him, christening it as 'Lake Mead,' an integral part of the new Boulder Dam Recreation Area that was to be administered by the National Park Service, beginning May 1, 1936 (the name was changed to the Lake Mead National Recreation Area in 1964).

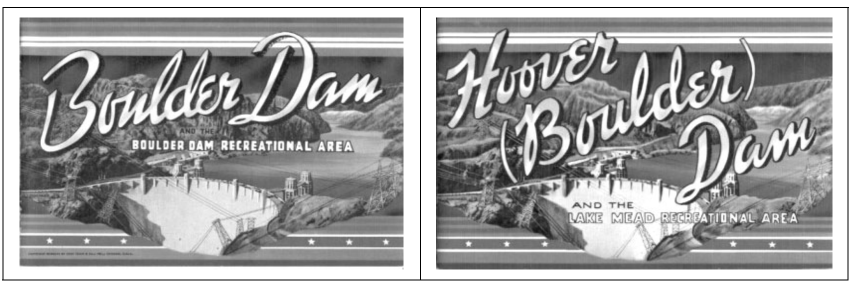

FIG. 15. National Park Service brochure covers before (left) and that which appeared for years following (right) the name change in April 1947, when the name of the surrounding area also changed, from Boulder Dam Recreational Area to the Lake Mead Recreation Area (becoming the first national recreation area in 1964). As the memory of the Boulder Canyon Project faded, so did confusion about the name (USBR-LCR files).

Re-naming it Hoover Dam (1947)

In April 1947 the Republican-controlled 80th Congress officially changed the name back to Hoover Dam, creating more confusion, which gradually subsided over the years (Figure 15). In part, this bi-partisan change of heart came about after Herbert Hoover served admirably as President Truman's Chief of the European Relief Commission (the same post he was appointed to following the First World War, by President Wilson). By this time, most people realized that Hoover was not solely responsible for the Great Depression.

ENGINEERING FEAT BECOMES TOURIST ATTRACTION

During Construction (1931-36)

Hoover Dam became a tourist attraction almost from the day construction commenced in the sweltering heat of May 1931, as newsreels in theaters throughout America heralded its construction, which rivaled that of the Panama Canal a generation previous. During the first few years there were insufficient accommodations in Boulder City or Las Vegas to even house project workers, let alone tourists. But, that soon changed.

Throughout 1933 and 1934 numerous hotels sprang up, mostly in Las Vegas, because it lay along the Union Pacific Railroad and U.S. Highway 91, which ran between Los Angeles and Salt Lake City. Boulder City even constructed a hotel for guests in 1933. By 1934 Las Vegas was rapidly emerging as a serious tourist destination, especially during the cooler winter months. It offered a frontier Wild West ambiance with gambling, speak-easys (before Prohibition ended), marriage chapels, even tourist flights over the Grand Canyon. It also sat a few miles from the record-setting dam that was taking shape in nearby Black Canyon (Figures 16 and 17).

FIG. 16. "Gawkers" gather at the temporary overview at the terminus of the government highway about 3/8 mile downstream from the dam's Nevada abutment, as seen in February 1935 (USBR).

FIG. 17. Once the dam was dedicated and opened to the public the National Park Service had to cope with traffic congestion and finding suitable parking areas. This 1938 view shows the first parking lot, just upstream of the voluminous Arizona Spillway intake. Another higher lot, from which this photo was taken, was added a short while later. Visitors walked to the dam and took the public elevator down to the power house (USBR).

FIG. 18. Union Pacific's M10000 Streamliner excursion train stopped at the steel fabrication plant, on March 9, 1934. The streamlined Art Deco style of the high-tech diesel-electric engines seemed futuristic in an age of steam locomotives (USBR).

In 1934 alone a staggering 266,436 visitors secured entry to the federal reservation to view the massive dam under construction, being heralded as one of the 'Seven Man-

Made Wonders of the World' (a title that was officially conferred in 1955). The dam is still listed as one of the 'Seven Man-Made Wonders of the United States' and among the 'Seven Wonders of the Industrialized World' (Cadbury, 2004).

In 1930 the government paid for a branch rail line from a junction on Union Pacific's Los Angeles & Salt Lake rail line, from a point just south of Las Vegas to Boulder Junction, at the Boulder City town site. The first passenger train on this new line arrived on April 25, 1931, just as construction of the dam was starting.

During the dam's last two years of construction the Union Pacific Railroad began running special excursion trains to the dam site weekly throughout the cooler months. On March 9, 1934 they staged a publicity photo op by running their ultra-modern diesel electric streamliner train the M10000 to the site, driving the train through a 30-foot-diameter section of pipe next to Babcock & Wilcox's fabrication plant, memorialized in all the government's subsequent project films (Figures 18 and 19).

In October 20, 1934 ten trainloads of Shriners descended upon the dam site, using Six Companies' lower spur line to convene a candlelight ceremonial service on the upstream cofferdam. Such special privileges were likely secured through Frank Crowe or one of the other Six Companies' officers who were Shriners.

FIG. 19. Another view of the M10000 Streamliner visit in 1934, on the wooden trestle of Six Companies' low-level spur, at the Nevada abutment on the dam's upstream face (USBR).

The Government line and Six Companies' low spur rail line leading to the Colorado River and around Cape Horn were abandoned after the dam's completion and Lake Mead began filling. The last government train took a generator to the dam's Nevada abutment in 1967 and this line was removed a few years later, after being used in some Hollywood films. The Union Pacific continued to actively use its spur line as far as Henderson, and still does today. In 1985, the railroad donated the Henderson-Boulder City segment to the Nevada State Railroad Museum. This segment remains intact, although the grade crossing near Railroad Pass has been paved over. Once restorative work is completed the museum hopes to start operating excursions over the old line.

Post Construction (after 1936)

The first Visitor's Center was constructed by Reclamation in 1936, and a one-story concrete exhibit house was opened to the public in October 1946 (Arlt, 1954). The number of visitors to Hoover Dam and Lake Mead has steadily increased since visitor services began in 1937.

During World War II the Las Vegas Valley and adjoining area underwent rapid growth, driven by the establishment of the Army Air Corps Aerial Gunnery School at Las Vegas Army Airfield (renamed Nellis Air Force Base in 1951) and Indian Springs Airport, which handled 6,000 students at a time for 6-week training courses; the military police school at Camp Siebert in Boulder City; and the construction of the Basic Magnesium Industries Plant between Las Vegas and Boulder City. In 1940 the population of the Las Vegas area had been 8,400. By mid-1942 these figures had swelled to over 30,000 people (Moehring, 1986).

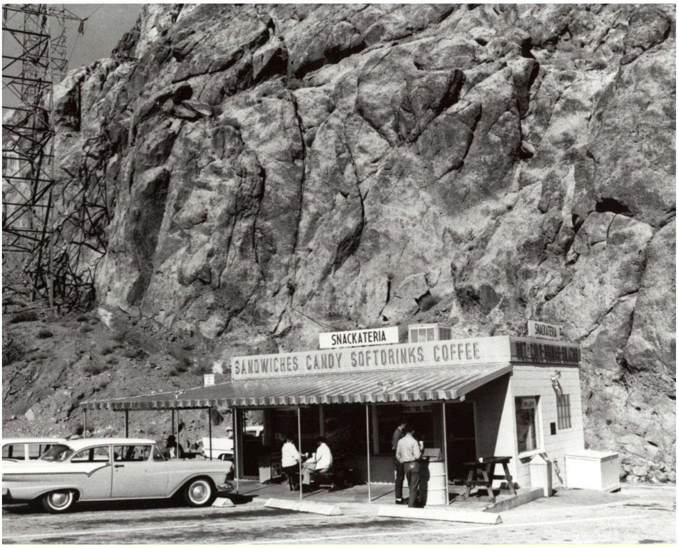

FIG. 20. The 'snackateria" on the Nevada abutment of Hoover Dam as it appeared in 1961. More and more people were venturing to Las Vegas by automobile from southern California, increasing the demand for services at the dam (USBR-LCR).

Prior to the emergence of Las Vegas as a tourist destination after the Second World War few people appreciated that the Las Vegas area would eventually draw so many permanent residents. The low property cost and common employment of central conditioning eventually succeeded in attracting many vacationers and retirees.

In a strange twist of fate, it would be Las Vegas, situated next to the largest man-made lake in the world, that would have to "make do" with an annual water allotment of just 300,000 ac-ft and 4% of all surplus water, which the Nevada representative had agreed to back in 1922, when the Colorado River Compact was signed.

By 1951, 2,000,000 people per year were visiting the Lake Mead Recreation Area (of which, almost 400,000 toured the dam). In 1953, 448,081 people toured Hoover Dam, and by the end of 1958, over 7,000,000 people had toured the dam and powerplant since it was opened to the public-at-large. In 1959, a new annual record of 472,639 visitors was set, and in 1962, the record was raised to 500,000 visitors.

During the 1960s Las Vegas began billing itself as "The Entertainment Capital of the World" as increasing numbers of talented entertainers performed live in floor shows and a number of the biggest headliners settled there, performing in specially-constructed theaters. As Las Vegas grew, so did visitation to the dam (Figure 20). By 1967, the number of yearly visitors exceeded 600,000, and in 1968, the 12,000,000th visitor toured the facilities.

The 15,000,000th visitor was recorded in 1972, and in 1983, on the eve of the dam's fiftieth anniversary, the 23,000,000th person visited Hoover Dam. In the late 1980s Las Vegas began a rapid expansion driven by lower house prices and attractive climate for people retiring from California, and a conscious shift aimed at attracting families as an annual vacation destination. By 2008 it has become the 28th most populous city in the United States with a population of 558,383. The estimated population of the Las Vegas metro area was 1,865,746 in 2008. In 1989 the Bureau of Reclamation began construction of a new Visitors Center and a multi-level parking structure at Hoover Dam. The new visitor facilities vastly improved visitor safety, interpretive capability, and visitor capacity at the dam.

Traffic congestion continued to worsen through the 1980s and 1990s. Semi-trailer commercial truck traffic was banned from U.S. Hwy 93 over the dam after the 9/11 attacks in 2001. In 2004 construction began on a prestressed concrete arch bypass bridge over Black Canyon a mile downstream of the dam, which will eliminate almost a mile of highway and allow vehicles to cross Black Canyon in five minutes instead of 17 minutes (absent any traffic). The Hoover Dam Bypass Bridge for U.S. Hwy 93 is scheduled to be opened in late 2010.

CONCLUSIONS

Boulder Canyon Project Final Reports

The scale of the Boulder Canyon Project was so massive that it gave rise to an unprecedented volume of scientific research and engineering analyses, which was of inestimable value to the civil engineering community, which was so voluminous it could not be summarized in short articles within traditional engineering journals. This information was of enormous interest to those nations contemplating water resources development in the post-World War II era, as well as the financial institutions funding such mega-projects, such as The World Bank.

The Bureau of Reclamation envisioned publishing a series of 34 bound volumes summarizing the technical aspects of planning, design, construction, and operation of the Boulder Canyon Project. Over the years, they revised this effort downward and eventually published 21 of the 32 volumes, between 1939 and 1950. These were collectively known as the "Boulder Canyon Project Final Reports," and they were sold at 1940s prices of $1 to $1.50 each for blue soft-bound and $1.50 to $3 for dark blue cloth bound volumes. They were sold to the general public by over-the-counter sales or by mail order from Reclamation offices in Washington, D.C. and Denver (and Boulder City from 1939-46). They were purchased by many engineering students between 1945 and 1965, by engineers working in water resources engineering, and most of the docents at Hoover Dam Visitor's Center. Many of the volumes remained available until the stocks were eventually exhausted in the late 1980s.

The Boulder Canyon Project Final Reports were originally subdivided into seven broad categories, Parts I thru VII are summarized below:

1) Part I – Introductory reports, consisted of three volumes that provided an overview of the entire project, titled: General Description of the Project; Hoover Dam and Water Contracts and Related Data. The third volume was titled Legal and Financial Problems. Scheduled for release after all the other technical volumes, no titles from Part 1 were ever released.
2) Part II – Hydrology reports, was to have consisted of two volumes titled: Stream Flow and Project Operation; and Utilization of Water. No titles from Part II were ever published.
3) Part III – Preparatory Examinations were summarized in a single volume titled: Geological Investigations (this was the last report to be released, which included several color plates)
4) Part IV – Design and Construction reports was the most expansive of the seven categories, consisting of 10 separate volumes, titled: General Features; Boulder Dam; Diversion, Spillway, and Outlet Structures; Concrete Manufacturing, Handling, and Control; Penstocks and Outlet Pipes; and Imperial Dam and Desilting Works. Proposed volumes titled Hydraulic Valves and Gates; Power Plant Structures and Handling Facilities; Power Plant Generating Equipment; and All-American Canal and Canal Structures were never published.
5) Part V – Technical Investigations was divided into seven major categories, six of which were eventually published: Trial Load Method of Analyzing Arch Dams; Slab Analogy Experiments; Model Tests of Boulder Dam; Stress Studies for Boulder Dam; Penstock Analysis and Stiffener Design; Model Tests of Arch and Cantilever Elements. A proposed volume on Research Measurements at Dam was never published.
6) Part VI – Hydraulic Investigations were summarized in four of the five volumes originally proposed. Those published included: Model Studies of Spillways; Model Studies of Penstocks and Outlet Works; Studies of Crests for Overfall Dams; Model Studies of Imperial Dam and Desilting Works, All-

American Canal Structures (the studies on Imperial Dam and the All-American Canal were combined in to a single volume).

7) Part VII - Cement and Concrete Investigations were summarized in four of six proposed volumes, as follows: Thermal Properties of Concrete (largely covering the various tests and measurements carried out at Owyhee Dam and incorporated into Hoover Dam); Investigations of Portland Cements; Cooling of Concrete Dams; and Mass Concrete Investigations. The proposed volumes on Contraction Joint Grouting and Volume Changes in Mass Concrete were never released.

The first volume that appeared was from Part V - Stress Studies for Boulder Dam, which was released in 1939. The last one to be published was from Part III – Geological Investigations, released in late 1950. The remaining volumes were released during the 1940s. As described above, the name Hoover Dam was not re-established until April 1947, so the reports were always referred to as the "Boulder Canyon Project Final Reports." Many of the more important volumes were translated into other languages, including French, Italian, Portuguese, Russian, and Mandarin Chinese.

When the author first visited the Three Gorges Project office near Wuhan, China in 1989, he was amazed to see the entire 21-volume set of the Boulder Canyon Project reports on the senior Chinese engineer's office book shelf! Most of the senior Chinese engineers (educated before the Cultural Revolution in the mid-1960s) had been educated in the Soviet Union. They were familiar with these volumes because they were the model texts for mass concrete dam design engineers used around the world for the half century following Hoover Dam's completion.

Great Engineering Feat of the 20th Century

In 1955, the American Society of Civil Engineers selected Hoover Dam as one of the Seven Modern Civil Engineering Wonders of the United States. In 1985, the Society named the dam as a National Historic Civil Engineering Landmark. Also in 1985, in recognition if the dam's contribution to the history of the southwest, it was designated as a *National Historic Landmark* by the Department of Interior. In 2000 the American Society of Civil Engineers christened Hoover Dam as a 'Monument of the Millennium.' For years engineers and politicians have touted the benefits of Hoover Dam to society. These benefits include the following:

1) Storing a two year supply of average flow of the Colorado River, which can be released as needed;

2) Over 15 million people use water taken from the Colorado River, including cities in Los Angeles, Orange and San Diego Counties, and Phoenix and Tucson;

3) Water from the Colorado River is diverted to irrigate 750,000 acres in California and Arizona, as well as 470,000 acres in Mexico;

4) 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, cash crop valued at over $1 billion annually;

5) The Hoover powerplant produces 4 billion kilowatt hours of clean non-polluting electrical energy each year, providing power for 1.3 million people in Nevada, Arizona, and California;
6) The project generates $1 billion in economic benefits to the American Southwest each year;
7) Hoover Dam attracts more than 700,000 visitors each year; and
8) The Lake Mead National Recreation Area encompasses the largest man-made lake in North America and recreation activities generate about 9 million visitors per year.

Unprecedented Influence on Dam and Reservoir Construction

Even before it was completed, Hoover Dam was recognized as one of the greatest engineering feats of the 20th Century. For more than two decades after its completion, Hoover Dam stood as the tallest dam in the world. Today, more than twenty dams are higher, but all owe their existence to the advancements that were made during the design and construction of Hoover Dam. The unprecedented size of the dam led to studies in almost every aspect of dam design and construction, including concrete composition and cooling, stress analysis, hydraulic design, and hydraulic and structural modeling. Even the form of the contracting organization was a new development that changed the face of the construction world. Too large for a single contractor, the project required the formation of a joint venture of six contractors, pooling their talents and resources and sharing the risks. This organizational structure became a model for future large construction projects.

The economic success of Hoover Dam had an enormous influence on the engineering profession all over the world, providing a model for funding high dams through the sale of hydro-electricity over typical terms of 50 years. Many countries were influenced to devise similar schemes to pay for mega dam projects. These included the Indians at Bhakra, the Egyptians at Aswan, the Pakistanis at Tarbella, the Brazilians at Guri, the Taiwanese at Chinman, the Hondurans at El Cajon, and the Chinese at Three Gorges. Everyone sought to emulate the concept for providing a master operating unit controlling a significant river, using hydroelectric generation to pay for the project while providing flood control and irrigation releases as the justification. It was probably over-emulated, especially in less favorable locations, like Aswan.

No one can deny the enormity of Hoover Dam's impact, not only on dam engineering world-wide, but in the industrial development of the American West, where the hydroelectric power proved essential to critical wartime industries (twinning of aluminum and magnesium, and production of plutonium, for many years thereafter), and the construction of water resources infrastructure that has been the pivotal element sustaining agricultural and urban development in arid and semi-arid climes of the western United States, where land values depend, more than anything else, on the availability of water.

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 visited the dams along the lower Colorado River and took an extended tour of Hoover Dam.

In 2008 the author served as one of the speakers participated in a Conference on The Fate and Future of the Colorado River, sponsored by the Huntington-USC Institute on California & the West and the Water Education Foundation at the Huntington Library. This led to many valuable contacts which led to a myriad of sources for information and photographs relating the Boulder Canyon Project and subsequent water resources development in the Lower Colorado River Basin.

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

Between 1976 and 1988 the author conducted interviews with Roy W. Carlson (1900-1990) and Jerome M. Raphael (1912-1989), professors in the civil engineering program at U.C. Berkeley. Jerry Raphael had worked for the Bureau of Reclamation from 1938 to 1953 and had served as head of Reclamation's Structural Behavior Group between 1949 and 1953, when he supervised the evaluations of crustal deformation at Lake Mead and reservoir-triggered seismicity.

In 1990 interviews were also conducted in Pasadena with Caltech Professor Vito Vanoni (1904-99), regarding some of the hydraulics research issues that emanated from Hoover Dam and Lake Mead, which were examined by Caltech faculty, staff, associates, and alumni.

Special thanks is also due to Allen W. Hatheway, Jeffrey Keaton, Richard Proctor, and William K. Smith of the AEG Foundation, who provided original documents from Frank A. Nickell, former Chief Geologist of the Bureau of Reclamation, who in addition to being the resident geologist, had supervised studies of reservoir triggered seismicity and crustal deflection at Lake Mead from 1935 till 1949.

Sincere appreciation for assistance is also rendered to the following people and their respective organizations: Reclamation GIS specialist Steven Belew; Dr. Brit Allan Storey and Christine Pfaff, historians with the U.S. Bureau of Reclamation at the Denver office, Dianne Powell of the Bureau of Reclamation Library in their Denver office; Reclamation archivists and staff Bonnie Wilson, Andy Pernick, Bill Garrity, and Karen Cowan of Reclamation's Lower Colorado Region (LCR) office in Boulder City; Boulder City Library Special Collections; Eric Bittner at the National Archives and Records Service Rocky Mountain Region depository at Denver Federal Center; Paul Atwood and Linda Vida at the University of California Water Resources Center Archives in Berkeley; Su Kim Chung of the University of Nevada-Las Vegas Libraries; civil engineering historian Edward L. Butts; 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, who moved to Las Vegas in 1986. Over the last 24 years 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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