America's Greatest Projects and Their Engineers - V

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Hoover Dam

Introduction

During the past 150 years, Americans have achieved phenomenal success on our way to becoming the greatest nation in the history of the world. Notwithstanding the many inventions that we have created, such as the electric light bulb and the telephone and the airplane and the internet, Americans have been responsible for some of the greatest and most beneficial projects in the modern era. This course is a synopsis of the design and construction of the Hoover Dam, an early twentieth century project that was on the forefront of engineering technology. Conceived following the end of World War I, the period of the 1920's saw a huge contrast in American culture and financial dynamics. The "Roarin' Twenties" gave way, however, to the worst recession in recorded history, and the United States as well as the rest of the world fell into a deep depression. Despite this huge setback, the Hoover Dam Project developed and implemented at a crucial time in American history. This course details the contributions of several engineers, manufacturers, and contractors who participated in one of the greatest and most formidable projects of the twentieth century. It also details the huge impact that this remarkable achievement had on the growth of our nation.

Another purpose of this course, one of a series of America's Greatest Projects and Their Engineers, is to determine how this project benefitted Americans in particular. Clearly, this project has positively impacted the entire world as well as the United States of America. THIS project, like so many other national projects, was on the so-called "drawing board" for several years in development before it was finally initiated.

The Hoover Dam Project is probably considered by most Americans to be strictly a construction project, but there is little doubt that this project would not have been successfully accomplished without administrative support or without the proper planning and design of quality engineers, architects and designers. The strong efforts of dedicated individual engineers as well as the commitments of engineering groups such as the Reclamation Service and the Army Corps of Engineers, combined with the vision and wisdom of quality project managers, all resulted in this project coming to a successful conclusion. This statement is not intended to demean the construction companies or the many manufacturers who were involved in this project, because their foresight and experience were paramount to the success of the Hoover Dam.

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A. Hoover Dam Approval and Administration

1. Early Political Issues

The Hoover Dam proved to be another engineering marvel of the early twentieth century. The continuing life-threatening flooding of the Imperial Valley in Southern California from the Colorado River led to the idea of the need for a dam on the Colorado River to provide flood control. A dam to control the sometimes raging waters of the Colorado River in order to protect rapidly developing property in the Southwestern United States had been in the talking stages for several years. Although several canals were built to distribute the Colorado more uniformly to various arid areas in the Southwest, there were times in the spring and early summer when the river would cause severe damage and loss of life, while in the fall and early winter the river bottoms were visible.

IN 1917, A YEAR BEFORE World War I ended, Southern California's Imperial Irrigation District sent a 33-year old lawyer named Phil Swing to Washington to urge Congress and the Department of the Interior (DOI) to build a canal that would deliver water from the Colorado River to the Imperial Valley bordering Arizona and Mexico, one of the nation's driest regions. After two years of Swing's effective lobbying, a congressional committee reported favorably on the canal scheme. Although Swing had been quite effective as a lobbyist, several high-powered landowners in the Imperial Valley sponsored him for the U. S. House of Representatives, believing that Swing would be more effective as a Congressman. Swing was elected to Congress in 1920, and co-sponsored legislation authorizing construction of the so-called All-American Canal, an 80-mile waterway that would stop just short of Mexico. But to the bafflement of Swing and his congressional sponsors, the legislation was defeated because of opposition from a single man: Arthur Powell Davis, Director of the U.S. Reclamation Service, a branch of the Department of the Interior (DOI).

As technologies developed in the areas of irrigation and electricity generation, the possibility of a dam finally became a potential reality in 1922 under then Secretary of Commerce Herbert Hoover. That year the Congress received a report from Reclamation Service Director Davis and Secretary of the Interior Albert Fall proposing that a concrete dam be built in the Black Canyon between the states of Nevada and Arizona.

2. Arthur Powell Davis

Arthur Powell Davis was a native of Illinois, and received his degree in Civil Engineering from George Washington University at the age of 27 in 1888. After graduation he worked with an uncle doing topography and hydrographic surveying, primarily in the southwestern states of New

Mexico, Arizona, and California. Davis was one of several co-founders of the National Geographic Society, and helped to guide it through its early years, becoming one of the nation's most respected civil engineers along the way. He played a leading role in the analysis, design and construction of numerous dams, canals and irrigation projects around the world, including the Panama Canal, renowned as one of the world's largest and most complex engineering feats. His singular effort to provide the U. S. Government in the early 1890's with dam and canal locations and designs was instrumental in a proposal by Congress in 1902 to pass the Reclamation Act, and the subsequent creation of the Reclamation Service.

Davis also had an intimate understanding of the Colorado Basin because of numerous trips he had undertaken to the area with his uncle, who was the first explorer to unravel, as early as 1869, the mystery behind the still-uncharted upper reaches of the turbulent Colorado River. Davis had come to work for the Reclamation Service in 1905, and had advanced to the position of its director by 1914. He served as the Director of the U. S. Reclamation Service from 1914 until 1923, where he developed the concept of a Colorado River Dam during that period.

Davis had become what may be considered a "technocrat" during his tenure as Director of the Reclamation Service. Davis was the first engineer to recommend design and construction of multi-purpose dams, and he was an early proponent of hydroelectric power plants. His vision of the power plants was that they would be more than self-sustaining, and that they could provide the revenue that would amortize the costs of the entire project.

Davis and his staff of Reclamation engineers outlined development plans for the entire Colorado River basin and presented it to Congress in 1922, with an aim to develop the area and tame the Colorado by building what would eventually become the Hoover Dam, the world's largest hydroelectric installation at the time and a model for dozens of the world's greatest dams. The Industrial Revolution in America had become a major economic force in the last quarter of the 19th Century, and the agrarian culture of the United States was slowly but surely giving way to a much broader national economy. Davis was apparently one of the very few in government service who recognized this trend. However, his ability to raise funds for his Reclamation Service was severely limited due to the infighting between those politicians who supported the farmers of America and those who favored the manufacturers in the big cities.

By opposing the All-American Canal, Davis appeared to violate the basic laws of politics and his own bureaucratic interests. However, Davis realized, as most politicians at that time were reluctant to admit, that America's economic culture was changing. Davis knew that the mission of the Reclamation Service wasn't only to bring water to the vast agricultural society that had been established during the relentless march westward by 19th-century pioneers, but rather to bring progress as well as relief to all communities, urban as well as rural. Davis believed that the Colorado River Project should only be undertaken as part of a much more ambitious program aimed not just at irrigation but also flood control, water storage and power generation.

During his tenure as Director, Reclamation Service outlined development of the entire Colorado River basin and presented them to Congress in 1922. Davis was the first engineer to recommend design and construction of multi-purpose dams, and he was an early proponent of hydroelectric power plants. His vision of the power plants was that they would be more than self-sustaining, and that they could provide the revenue that would amortize the costs of the entire project. He was reluctant to perpetuate the myth that America was once and for all time an agrarian society.

As technologies developed in the areas of electricity generation and irrigation, the possibility of a dam had finally become a potential reality in 1922 under then Secretary of Commerce Herbert Hoover. That year the DOI received a report from Reclamation Service Director Davis and Secretary of the Interior Albert Fall proposing that a concrete dam be built in the Black Canyon between the states of Nevada and Arizona. As the technology of electric power transmission improved, the potential for hydroelectric power from the Colorado River transmitted over long distances became a reality. As with the water supply, the power generated was to be evenly distributed among the states, with the largest recipients being Phoenix, Arizona and Los Angeles, California. One other city that was to benefit greatly was a small community of a few thousand residents called Las Vegas, Nevada. There were seven states which fell within the Colorado River's basin, and at least six of the seven states were required to become signatory to the agreement for the dam's ultimate approval. The river began its 1400 mile journey in the foothills of the Rocky Mountains and ran through seven states and a short stretch of Mexico before emptying into the Gulf of California. Five of the seven states reached an agreement to share both water and electrical power by Thanksgiving of 1922.

Because of his belief that harnessing the Colorado was too complex, costly and important to be undertaken in piecemeal fashion, Davis apparently antagonized many powerful leaders of special-interest groups such as the Imperial Irrigation District as well as major power company executives. When another new political appointee was made Secretary of the Interior and his Reclamation Service was newly named the Bureau of Reclamation in 1923, Davis chose to retire at the age of sixty-two. Davis was later appointed consulting engineer on the Hoover Dam Project in 1933 as a goodwill gesture by the Department of the Interior, but died only one month after his appointment. A dam which was a part of the original project and located approximately 70 miles downstream of the Hoover Dam was named the Davis Dam in his honor upon its completion in 1951.

3. Congressional Progress

Congress subsequently authorized a Board of Engineers to review the preliminary plans for the dam, which was now being proposed by the Bureau of Reclamation to be located at Black Canyon and designed to be of a curved arch-gravity configuration. Because a dam of a similar design for the City of Los Angeles had recently failed, killing more than 400 people, there was great concern for the construction of the arch-gravity dam that was being proposed for the Colorado River. Nevertheless, the Board found the project to be not only feasible but also necessary, fearing that the river might ultimately change its course and cause great destruction. The Board in its report cautioned that the Colorado River Dam must be designed and constructed using ultra-conservative practices to avoid a similar civil engineering disaster such as had occurred to the City of Los Angeles.

However, repeated efforts by House and Senate leaders to fund the project for the dam met resistance over the next five years from members of Congress who believed that the expense was too great and the project would only benefit the state of California. The thinking changed considerably after the Great Mississippi River Flood of 1927 devastated the states of Mississippi, Arkansas and Louisiana, causing untold damage and great loss of life, and resulted in more than 200,000 Americans of mostly African descent leaving their agricultural homes along the river and moving north to the northern industrial cities.

Initially the dam project was referred as the Boulder Dam, or even as the Grand Canyon Dam, even though the actual site for the dam had been shifted downriver by several miles to the Black Canyon. President Calvin Coolidge actually signed the dam into law in December, 1928 under the Boulder Canyon Act of 1928 just before he left office, but no name was assigned to the dam at that time. The bill appropriated $165 million for the new dam as well as for a portion of the All-American Canal and a smaller dam (later named the Davis Dam) about sixty-seven miles further downriver. It also permitted the States' agreement to go into effect as soon as six of the seven states had approved it. The State of Utah became the sixth state to ratify the agreement on March 5, 1929. As an integral part of the Project Act, each state was allocated a portion of the water that would flow through their basins. The State of Utah became the sixth state to ratify the agreement on March 5, 1929. For some inexplicable reason the State of Arizona did not ratify the agreement until 1944.

NOTE: When the Secretary of the Interior who was serving under President Hoover (1929-1932) spoke at a ceremony to commemorate the beginning of construction of a railway connecting the small city of Las Vegas, Nevada to the dam site, he was the first to call it Hoover Dam. The name was politically controversial for the next several years until it was officially named the Hoover Dam in 1947 by an act of the U. S. Congress.

B. Hoover Dam Planning and Design

1. Primary Specifications and Guidelines

Davis had originally proposed using dynamite to collapse the walls of Boulder Canyon and building a dam over the ensuing rubble; however, both Davis and the Reclamation Service Board later rejected this proposal as being impractical regarding technology as well as cost. Certainly there were critics at every phase of the design and planning of the new dam; some postulated that the fluctuations in the reservoir's elevation level would cause cracking of the earth's surfaces, which would result in the dam experiencing cracks and breaches. Others just simply believed that the dam would never hold the tremendous amount of water that would need to be contained in the reservoir.

Design of the Hoover Dam began in earnest in the spring of 1929. Having already concluded that the basic design would be an arch-gravity type, with the arch facing the upriver flow of the Colorado, many other engineering parameters had to be resolved. The exact location of the dam in the Black Canyon had to be determined. A method for diverting the upstream flow of the Colorado River around the dam site was devised, and the depth of the river bottom at the dam's precise location was also determined as best as possible. Calculations for the thicknesses of the tops and bottoms of the dam to safely hold the huge body of water (later named Lake Mead) that would accumulate behind the new dam were made.

There was considerable effort given to how much power generation could be designed and installed, based on the limits of existing transmission line technology. This factor was extremely important, inasmuch as payback for the initial investment of $165 million by the U. S. government was totally dependent on power sales, primarily to the residents and businesses of the City of Los Angeles. And, of course, there was considerable concern over where and how these transmission lines and their towers would be located in order to transmit the power out of the Canyon. This phase of the project was neglected until after the actual dam had been constructed, and it wasn't resolved until just before the first generators went into operation in 1936.

Prior to the planning and design of the Hoover Dam, there was no other dam in the world on which to base design calculations or to model as even a comparable example. The engineers who were designing the dam were unsure that their design would withstand the tremendous pressures of the reservoir behind the dam which they had calculated to be an absolute maximum of between 40,000 and 45,000 pounds per square foot. Such large quantities of necessary concrete had never been used before, and certainly not in such a hot and humid climate. Furthermore, the use of iron or steel rods to improve the overall strength of concrete placements was still not an exact science. To be absolutely on the safe side of the design parameters, the dam was designed as an enormously heavy and thick horizontal arch, with its convex arch facing upstream to the Colorado River flow.

a. Diversion of the Colorado River

The first step to the success of the Hoover Dam would be to divert the Colorado River around the Black Canyon area where the dam was to be constructed. In order to accomplish this, the specifications called for four tunnels to be drilled through the mountains surrounding the Black Canyon area, with sufficient size and flow characteristics to accommodate the river flow's worst case. These tunnels were each to be 56 feet in diameter, with a concrete lining of three feet on the circumference for the full length of each tunnel. The debris from the drilling activities plus the construction of two temporary coffer dams were to be used as temporary dams while the main dam was being constructed.

b. Primary Dam Specifications

Specifications for the main dam construction were extremely conservative, as mentioned earlier. Regarding the basic width and thickness of the dam from the bottom to the top, the estimated width at the bottom of the dam in order to withstand the calculated pressures of 40,000 pounds per square foot was approximately 660 feet, while the thickness of the dam at the top of the arch was calculated to be only about 45 feet. The dam was to be watertight, as we could understand, with no leakage at any point. This factor presented two problems to the construction teams:

1. A huge amount of reinforced concrete had to be placed in a very short period of time, thus creating a minimal allowance for proper curing time.

2. The Canyon walls, which were nearly vertical, were uneven and craggy and contained many conditions for potential leakage and breakthrough.

The depth of the riverbed at the base of the dam was assumed to be only slightly lower than the estimation by the Bureau of Reclamation. Even allowing for this realistic assumption by the Bureau, the resulting walls of the Hoover Dam would have to rise about 726 feet above bedrock, and the length of the crest of the top of the dam between the canyon walls of Arizona and Nevada would be nearly one-quarter of a mile.

c. Hydroelectric Generation

Hydroelectric power plants had become relatively commonplace in the United States by the early 1920's, although none were as large or as complex as the one being considered at the Hoover Dam. Hydroelectric power was very cheap at that time, somewhere in the range of 2 to 2.5 cents per kilowatt hour. Environmental issues such as salmon being able to swim upstream to spawn their young, or a small animal or bird losing its natural habitat and facing potential extinction, was not a concern, and humans were still able to improve their lifestyles as they deemed necessary.

d. Bid Documents

Once the basic designs and plans were developed, they were placed in bid packages that, for a project of this scope and size, were hardly common. The resulting success of the Hoover Dam is not only a result of superb construction practices, but also a tribute to the many and varied engineers who were intimately involved with the project. Regarding the bidding parameters, just the opportunity to bid on the Hoover Dam Project required a construction company to provide a bid bond of $2 million, while a performance bond had a $5 million bond requirement.

With hydroelectric power being so inexpensive, the Bureau of Reclamation had to develop a large enough system that would recoup the government's investment of $165 million, and still make it fit into the plans of the basic Hoover Dam design. They developed a design that would include a total of seventeen synchronous generators, nine in the north (Nevada) wing and eight in the south (Arizona) wing. These generators were expected to produce approximately 1,345 Megawatts of total capacity, which would realize a payback of the original investment in fifty years - incomprehensible by today's standards but, nevertheless, an accurate estimate which actually resulted. The genesis of the design was to produce supplemental power to the states that signed the 1928 compact; today the Hoover Dam supplies reserve electrical power to the grids of Arizona, California, Nevada, New Mexico and Utah.

The bid documents were made available in January of 1931 and consisted of more than one hundred pages of specifications in exhaustive detail as well as seventy-six design drawings. As a part of the specification the U. S. government would provide the necessary building materials, while the contractor was to prepare the dam site, provide the workforce, and construct the dam and associated structures. Because of the size and complexity of the project, no single construction company had either the financial resources or the financial backing of lending institutions to fulfill the financial requirements of the project, which included the huge sum of $2 million for a bid bond as well as the nearly prohibitive amount of $5 million for a performance bond.

2. John Lucian Savage

John Savage had been the chief engineer and supervisor for the design of numerous dams throughout the western United States. A graduate of the University of Wisconsin in 1903 with a B. S. in Civil Engineering, Savage began his career as an engineering aide with the Reclamation Service in Idaho. He left that position in 1908 and joined with A. J. Wiley to form an association that prospered greatly, due to the many dams, canals and power plants that were being constructed in the American Northwest as well as the Southwest.

Following a successful career with A. J. Wiley, Savage bought a cattle ranch in Idaho with the thought of retiring from the hectic life of dam and power plant building. However, he was apparently coaxed out of semi-retirement by Arthur Davis, who recruited Savage as the first design engineer in charge of all civil, mechanical, and electrical engineering for the Reclamation Service. After the Bureau of Reclamation lost considerable expertise with the retirement of Davis and the untimely resignation of Frank Crowe, a protege of Davis who had been involved in several dam construction sites, the newly appointed Chief Engineer for the Bureau gave Savage almost complete autonomy. Working in this independent capacity because of his abilities, Savage and his design team became responsible not only for the Hoover Dam, but also for the Parker Dam, the Shasta Dam, and even the Grand Coulee Dam.

3. Francis T. Crowe

Prior to 1925 the Reclamation Service (renamed the Bureau of Reclamation) had always been responsible for the design and construction of the many dams that were being built in the United States up to that time. When a dam needed to be built, the federal government did the project itself, using the U. S. Army Corps of Engineers and hiring its own workforce. In 1925 the government had made the decision to no longer self-construct future dams, but to bid the work out to outside sources in order to improve efficiency and save money.

At that time a leading dam designer in the United States and one of the pivotal engineers in the Bureau of Reclamation under the direction of Arthur Davis was a young engineer from Quebec, Frank T. Crowe. Crowe had graduated from the University of Maine in 1905, and had gone to work immediately with the Reclamation Service. Crowe had spent more than twenty years working for Reclamation as well as for private construction companies. He had helped to build Arrowrock Dam in Idaho, the Jackson Lake Dam in Wyoming, and Washington's Teton Dam. Much of Crowe's success and reputation were attributable to a cableway system which he had developed and perfected that delivered large batches of concrete to the work areas. This same system would also be used to deliver moving equipment to the construction site, and it was far more advanced than any other system of its time.

Crowe wanted very badly to work on the Hoover Dam project, which had actually been an ambition of his for a very long time. And after the Bureau had changed its way of doing business, Crowe was forced to choose between staying in his government job or working on the future projects such as the Hoover Dam with an outside contractor. Having been at the Bureau for all those years had allowed Crowe to learn the dam construction business first-hand, and he was considered by his peers to be the most knowledgeable dam constructor in the United States. However, in order to fulfill his seemingly life's ambition to build large and meaningful dams, Crowe had resigned his job with the Bureau of Reclamation. Upon leaving the Bureau, he joined the construction firm of Morrison-Knudsen of Boise, Idaho, which had recently signed a partnership agreement with the Utah Construction Company to build dams.

Everything Crowe had ever done during his career had helped to prepare him for the building of the Hoover Dam, which would be the biggest challenge of his life. Crowe had aided Reclamation Services Commissioner Arthur Powell Davis in developing a comprehensive cost estimate for a dam on the lower Colorado River as early as 1919, and he had also helped him with the preliminary design in 1924. There is little doubt that Crowe was instrumental in persuading Morrison-Knudsen to pursue the Hoover Dam project, and to assist in forming a joint venture. Crowe's knowledge and familiarity with the Bureau of Reclamation and with dam construction in the United States in particular undoubtedly convinced Harry Morrison, his boss at Morrison-Knudsen, that with the right supervision they could meet the performance criteria and still make a substantial profit. Crowe also realized that not only did no single company have sufficient financial means to manage the project, but also no construction company had either the manpower and equipment or the expertise to perform all aspects of such an enormous task of constructing the dam, and that a partnership with the right construction companies was a necessity.

Initially Morrison had approached financial institutions such as San Francisco banker Leland Cutler to seek financial backing for his construction company for the Hoover Dam project. Cutler refused, primarily because he didn't think any one company could raise the $5 million in capital that was necessary for the performance bond. However, he did give Morrison the names of several other construction companies who might be interested in a joint venture. Not only was the U. S. entering into a deep recession in 1931, but also there was strong skepticism that any one company could meet the rigid standards that had been established by the Bureau of Reclamation.

d. Six Companies, Inc.

Morrison was in total agreement with Crowe and went about contacting several interested construction companies in that region who were familiar with the project, and in short order was able to create a consortium called Six Companies, Inc., a joint venture made up of design/construct companies from the states that were affected by the Colorado River. The consortium included his company along with five others, each of which added a certain value and expertise to the project. In addition to Morrison-Knudsen they included:

1. Utah Construction Company (Wattis Brothers) - Utah

    Note: In 1922, Utah Construction Company had formed a partnership with the Morrison-Knudsen Company. With Frank Crowe as their chief engineer, the M-K/UCC partnership successfully built dams throughout the American west.

2. Henry J. Kaiser and Bechtel Corporation - San Francisco, California

3. MacDonald & Kahn Ltd. - Los Angeles, California

4. J. F. Shea Company - Portland, Oregon

5. Pacific Bridge Company - Portland, Oregon

6. Morrison-Knudsen Construction - Boise, Idaho

This consortium included many of the large design/build companies of that era which are still well-known today. Morrison was then primarily responsible for gathering together the construction companies that would make up the Six Companies, Inc. He then recommended that Frank Crowe be made the Chief Engineer/ Project Director/Construction Manager of the project for the joint venture. Since Crowe had two decades of experience building dams for the Reclamation Service and had actually been intimately involved in working up the Hoover Dam's project cost estimate for the government, he knew what went into the calculations that had been used to develop the estimated costs. Not surprisingly Six Companies, Inc., with their strength and experience, including having Frank Crowe in the position of authority, won the contract on 04 March 1931 with a bid of $48.9 million. This bid was just $24,000 higher than the Department of the Interior had budgeted for the actual construction of the project, and it was more than $20 million lower than the next closest bid. At the time this was the largest single contract that the U. S. Government had ever awarded, a contract that in today's dollars would be more than $1.1 billion. But now the onus to perform was on Frank Crowe and Six Companies, Inc.

C. Hoover Dam Construction

1. Construction Beginning

Initially there was no shortage of laborers for the workforce, as the Great Depression of the 1930's had officially begun the preceding year. The Depression was worldwide and had seriously affected all classes of people, but especially farmers in the United States. In 1930 men began to make their way to Nevada at least one full year before the actual contract was awarded to Six Companies, Inc. Some brought their wives and children and were barely able to afford to settle in Las Vegas, not realizing that Las Vegas was some thirty miles from the jobsite in Black Canyon. Others who could not afford to pay for accommodations or who wanted to be as close to the jobsite as possible set up temporary quarters in tents, cardboard shelters, or similar arrangements. The living conditions that year were brutal, as the summers were extremely hot while the winters were open and cold. After the contract was awarded by the U. S. Government in March of 1931 there was a steady stream of migrant workers from all over the country who moved into this tent city now known as Ragtown. The Bureau of Reclamation had recognized the potential of this situation occurring, and it had included in their plans that a city with the necessary worker and family accommodations be built as a first order of business. As one of the top priorities of the Hoover Dam construction, a city was planned and built before the end of 1931 which included decent housing, stores, schools, a hospital, and churches. It was located in the Nevada desert about five miles from the dam site and was called Boulder City; today it is a resort/retirement community of about 15,000 people and sits on the edge of Lake Mead.

2. Diverting the Colorado

The second priority of Six Companies, Inc. was to divert the Colorado River around Black Canyon in order to begin construction on the dam proper, and to initiate construction of the hydroelectric generating stations, which had a longer construction schedule The diversion of the Colorado River portion of the project was largely the responsibility of the J. F. Shea Company under the watchful eye of Frank Crowe. Shea had built its reputation and its workforce by constructing several hundred miles of railroad tracks in the Rocky Mountains and the Pacific Northwest, including drilling through mountains and constructing large tunnels. As this portion of the project was considered to be one of the more tedious as well as dangerous aspects of the overall construction, this work was scheduled to be completed in no less than two years.

Four Diversion tunnels were to be drilled through the canyon walls, each to be about 15 m (50 ft.) in diameter, starting with the two planned for the Nevada side in May of 1931, and shortly thereafter with the two planned for the Arizona side. Six Companies had a separate bonus-penalty clause in their contract for this diversion work, with a daily fine to be levied by the government. In the beginning large numbers of workers were employed to make even the slightest progress into the canyon. To hasten the progress, Shea developed a "Jumbo Truck", which was a large drilling rig equipped with two platforms on which workers could access the canyon walls. As many as thirty workers would be backed into the canyon openings, and simultaneously drill holes for the placement of dynamite. These trucks were so successful in allowing large sections of the tunnels to be blasted that eventually eight of them were employed.

After each explosion men and dump trucks would enter the blasted areas and the trucks, with their engines running and spewing carbon monoxide in the confined quarters would be loaded and would haul the loose debris downriver to be used as spoils at a later date. With rocks still falling as the result of the recent blasting, and although compressed air was being introduced into the tunnels, several dozen men died during this construction cycle. However, there was no OSHA or Workmen's Compensation insurance at that time, so most of the deaths were attributed to pneumonia and other natural causes. Irrespective of the circumstances that claimed the lives of more than ninety workers, within a year the tunnels had been bored through, a combined distance of more than three miles for all four tunnels, which was well ahead of schedule.

During this period there was also an attempt by national union organizers to form a union with the workers, which the workers themselves rejected. At about the same time Six Companies chose, for some unexplained reason, to reduce the hourly rate for the workers. This caused the workers to go out on strike and to present a list of grievances and demands which were given to Frank Crowe. Crowe considered their demands and met with the workers' committee briefly, then refused all of their demands, shut the project down entirely except for a few office workers, and laid every other employee off. Less than a week later Six Companies began to hire workers again, and the strike was called off, but the company agreed not to cut wages again.

Once a tunnel was broken through to the other side of the Hoover Dam location, it was rough bored to a diameter of approximately 56 feet and then lined with a three-foot thick concrete lining. Pneumatic guns were used to place the concrete into the overhead forms, thus resulting in a net tunnel diameter of fifty feet. During the diversion of the river, two coffer dams were constructed at the entrances to the tunnels so that they all worked in unison to divert the Colorado River flow around the Hoover Dam site. The coffer dams, made of rocks, rubble, sediment and more than one million cubic yards of concrete, were designed to protect the thousands of workers at the dam site. The specifications for the coffer dams were nearly as stringent as the specs for the main dam itself, with the upper coffer dam having a total thickness at the base of more than 750 feet and a height of about 96 feet.

A temporary earth and rock dam had been built at the entrance to the tunnels, forming a barrier ahead of the tunnels. When the tunnels were each cured and ready to accept Colorado River water, this temporary dam was breached with explosives, forcing the river water to be diverted and the Colorado River to begin flowing through the two tunnels on the Arizona side. These two tunnels were the primary carriers of the river flow, while the Nevada tunnels were kept in reserve for high water conditions in the spring and summer. Due to innovation and a hard-charging Frank Crowe, the diversion tunnels and coffer dams were completed one year ahead of the construction schedule. Now the construction of the Hoover Dam could begin in earnest.

3. Preparation and Excavation

In the five or six years prior to the Colorado River being diverted around Black Canyon, the Bureau of Reclamation engineering group (some estimates were that more than two hundred engineers and designers were involved) under the direction of Chief Engineer John T. Savage had made the decision that the dam would be an **arch-gravity type.** This meant that the arch, or convex portion of the dam, would be facing upriver against the river's flow and would allow for much of the force vectors of the accumulated water being directed against the canyon walls. Nevertheless, this wedge-shaped design would still need to be about 660 feet thick at the bottom, gradually tapering at the top of the dam to approximately forty-five feet. When the roadway was constructed across the top of the dam which connected Nevada to Arizona the elevation was slightly more than 762 feet above the riverbed.

The first phase of the dam's construction involved preparation of the riverbed and the canyon sidewalls. To prepare the canyon sidewalls Six Companies hired mostly athletic types called "high scalers", men who would hang from a long rope anchored at the top of the canyon and could climb up and down the sheer canyon walls. These men, many of whom were native Americans, would remove loose rock and other debris from the canyon walls while being suspended from these ropes. Many used heavy hammers, jackhammers, and even core drills for dynamite in order to prepare the sidewalls for a grout surface that would provide a tight seal with the concrete of the dam. Even though their pay was higher than the other workers, the "high scaler" job was considered the most dangerous by far. One such high scaler had invented a hat with a hard tar top to protect himself from falling debris, and soon nearly all of the high scalers had followed suit with similar hats. When the Six Companies supervision saw the effectiveness of these hats that were hard on top, they proceeded to order "hard hats" for every worker and supervisor. Although many lives were lost during the construction of the Hoover Dam, the hard hats were credited with saving many lives and avoiding many serious injuries, and the "hard hat" became a standard safety fixture on nearly every future construction site.

Clearing the riverbed down to the bedrock was an equally tedious task. Not only did all loose material and sediment have to be removed, but also holes had to be drilled and tested for cavities to prevent future leakage. More than one million cubic meters of loose materials and erosion soils were removed in order to reach the river's bedrock and allow a thick curtain of grout to be laid as the base for the dam's bottom seal. The project was apparently under considerable time constraints during this period, so that the effort to fill larger cavities with grout and to confront underground springs was not given the time necessary to fill those voids.

Although there was no condition that would create "uplift" due to pressure from water seeping under the dam, completion of the dam and the filling of Lake Mead would later reveal that there were several instances where the cavities had not been filled, or else the grouting had been done improperly. There was no evidence that constant visual inspection of these areas would have given any assurance that these problems could have been prevented. Once the reservoir began to fill and leaks began to occur, the Bureau of Reclamation was called to examine the situation.

They determined that the work of nearly sixty voids had been incompletely or improperly done and that there was also a misunderstanding of the geology of Black Canyon.

As a "fix" to this serious and potentially catastrophic problem, Bureau of Reclamation engineers determined that new holes could be drilled deep into the canyon bedrock from cavity positions inside the dam, and a supplemental grout curtain could be added into each leaking void. This process was actively carried out during the next nine years without any knowledge of the general public, and success was achieved. This coordinated effort by the Reclamation engineers and the construction forces from Six Companies, Inc. eliminated the leaks and resulted in the Hoover Dam being leak proof at last.

4. Constructing the Dam Proper

Going back to 1922 when the Reclamation Service presented its first report, which was principally authored by Arthur Davis and co-signed by Interior Secretary Albert Fall, the Boulder (Hoover) Dam had been designed and planned to be a monolithic pour. As the years passed and the dam project became a reality in 1929, the design of the dam by the Reclamation engineers as a monolithic structure became impractical. The engineers had calculated that a monolithic pour could take upwards of 125 years to cool and cure, in the meantime causing stresses and cracks in the dam that would result in catastrophic failure. In light of this potential disaster the engineers developed a plan to mark the ground where the dam would rise with rectangles, and to form columns with blocks of concrete. Furthermore, they worked with the construction companies to develop an ingenious, possibly heaven-sent plan to quickly cool and cure the concrete blocks. Each concrete block, roughly fifty feet square and five feet high, contained a pre-designed arrangement of one-inch steel pipes. To accelerate the cooling of the concrete blocks, first river water and then refrigerated water was circulated through the steel pipes. Once the concrete had been cured, the empty steel pipes were filled with grout as were the small gaps between the blocks of the adjacent columns.

Two massive concrete plants were set up on the Nevada side of the Black Canyon, where they mixed huge quantities of cement, sand and different sizes of aggregate, from pea gravel to large stones, depending on the placement location of the blocks. Another blessing of the Hoover Dam builders was that they **JUST HAPPENED** to use a non-reactive aggregate which was not subject to deterioration, and core samples taken some sixty years after the last concrete was placed show that the concrete had continued to gain in strength.

The batches of concrete were poured into huge steel buckets invented by Frank Crowe (one if his many patents) and delivered to the site by railcar. Each bucket, weighing more than eighteen tons when full, was then suspended from an aerial cableway (another Frank Crowe patent) and delivered to the correct column. When the bottom of the bucket was opened, about 8 cubic yards of concrete were placed inside the forms of that particular column and were quickly and evenly spread.

When concrete placement had ceased in May, 1935, more than 3 million cubic yards of concrete had been used to build the dam, while another one million plus cubic yards of concrete were used for the coffer dams, diversion tunnels, power plants, and intake towers. The story that was circulated back in the late 1930's was that there is enough concrete in the Hoover Dam to pave a two-lane highway from San Francisco to New York City. That is probably a very accurate statement, but more importantly, that highway would likely still be in service today.

5 Spillways

The Hoover Dam was designed to have all Colorado River water flow through and out of the hydroelectric generator stations, one on the Nevada side and one on the Arizona side. There is, however, a spillway on either side of Lake Mead about one thousand feet ahead of the dam, and these spillways were to be used in an emergency in the event the water level in Lake Mead approached approximately fifty feet to the top of Hoover Dam. The spillways presented a difficult engineering problem and caused numerous design challenges to the Bureau of Reclamation engineers.

The spillways run roughly parallel to the canyon walls, with each spillway being controlled by four 16 ft. high drum gates. Each drum gate can be operated automatically as well as manually, although each gate weighs close to five million pounds. Water flowing over the spillways free falls into separate tunnels that are 600 feet in length by 50 feet wide. These tunnels then connect to the downstream side of the outer diversion tunnels, and the water reenters the Colorado River channel well below the dam and generating stations. Each spillway was emergency tested about thirty years ago when Lake Mead reached a record elevation. Although the design concept proved to be empirically sound, the walls of the spillway tunnels were badly damaged, resulting in replacement of the tunnel linings which are high-impact and smoothly polished.

6. Hydroelectric Power Plants

Controlling the flow of the Colorado River and providing an irrigation system for the arid regions of Nevada, Arizona and Southern California were the primary reasons for the building of the Hoover Dam. Nevertheless, the dam could not have been financed, especially during the era of the 1930's depression, without the benefit of hydroelectric power production. The financing of the dam was to be spread out over a fifty-year period beginning in 1937, and the costs were to be paid back by the sales of cheaply generated power to those three states. Even today Nevada and Arizona receive a combined total of about forty-two percent of the power generated, Los Angeles and other Southern California cities are the beneficiaries of about fifty-two percent, with the balance going to native American communities in the region (five percent) and the remainder being used for Hoover Dam maintenance.

The initial design concept was to have eight large turbine-generators in each power generation station, with one on the Nevada side of the river and one on the Arizona side. When the Hoover Dam was designated as complete and a formal dedication was held by President Franklin Roosevelt on 30 September 1935, the federal government settled all claims with Six Companies, Inc. and arranged for formal transfer of the Hoover Dam to the U. S. The construction companies stayed on site for the next six months to complete the unfinished powerhouses. The Bureau of Reclamation inherited the dam, including the powerhouses, in the spring of 1936.

As water levels in Lake Mead began to increase in the latter half of 1936 the first three Allis-Chalmers synchronous generators powered by Francis turbines, all located in the powerhouse on the Nevada side, began generating power. Francis turbines had become the turbines of choice for all hydroelectric generation during the previous fifty years since their invention by James B. Francis, an engineer at a textile mill in Lowell, Massachusetts. Their unique design allowing them to use a broad range of head pressures was their primary technical advantage, while their efficiencies exceeded 90%, and they could each produce upwards of 800 MW.

Allis-Chalmers, based in Milwaukee, Wisconsin, manufactured primarily farm equipment in the early part of the twentieth century. During the 1920's it expanded into the large generator business, primarily for the greatly expanding industrial complex in the United States, and it was positioned to devote its high efficiency electric generators to hydroelectric generation. Allis-Chalmers provided the vast majority of electrical generation equipment to the Hoover Dam powerhouses and continued to prosper as an open shop manufacturer throughout World War II and into the 1950's. Eventually the unions made enough headway into the many Allis-Chalmers manufacturing facilities, including one lengthy strike of nearly one year, that the company was forced to divest most of its facilities by the early 1980's, and today Allis-Chalmers is simply a name brand.

In March, 1937 a fourth generator went online on the Nevada side, and the first generator on the Arizona side went online that August. By 1939 a total of nine generators were in operation, and Hoover Dam was by then the largest hydroelectric generating station in the world. The final generator was not placed into service until 1961, at which time the maximum generating capacity was nearly 1,345 megawatts. Eventually there were eight large generators on the Nevada side as was originally planned, but there were seven large generators and two smaller generators on the Arizona side to serve smaller communities. This was done at a time before the power grid concept had materialized, and the power generating stations were supplying specific communities.

In order to rotate these giant generators, they were each coupled by long vertical shafts to the water turbines in order to keep the water that rotated the turbines isolated from the generators.

There are also two smaller self-starting, waterwheel stations - one in each wing - which provide electrical services in their respective areas to auxiliary equipment such as overhead cranes and elevator operations, emergency pumping of water, and exciter voltages for the synchronous generators. This system also allows the power plant to black start any of the 130 KW generators without outside assistance, thus assuring that the Hoover Dam power plant can operate through any unforeseen grid catastrophe. The primary voltage is 2300 VAC, three-phase, and was coordinated with an initial system of thirty-eight 2300 volt isolation breakers and tie-breakers.

Each wing sits on a large plateau carved out of the canyon walls on either side of the Black Canyon approximately 240 feet above the Colorado River bed and 400 feet downriver from the base of the Hoover Dam. Each power plant wing is 650 feet long and nearly 300 feet high from the base of the foundation to the top of the roof.

7. Intake Towers and Penstocks

Not only did Bureau of Reclamation engineers have to determine the minimum elevation of the powerhouses, they also had to calculate the optimum flow rate of the penstocks in order to maximize hydroelectric generation. Walls of the canyon between 200 and 600 feet upstream of the dam on both the Nevada side and the Arizona side were blasted and jack hammered to give the intake towers a relatively level rock table for its foundation. Similarly, the large bases required for the two powerhouses on the Nevada side and the Arizona side were also carved out of the canyon walls during the initial excavation.

Large sections of the canyon walls were blasted and contoured along the dam abutments on either side of the river to connect the penstocks coming from the intake towers to the powerhouses. Each of these four intake towers, measuring more than 1000 feet above the riverbed of the Colorado river, contained a penstock system, much of which was more than thirty feet in diameter, and was designed to be gradually reducing in size in order for the water at the turbines to achieve an optimum velocity of 85 miles per hour (approximately 125 feet/second) at a constant head of 590 feet.

The water of the Lake Mead reservoir is channeled through the four penstocks, two on each side of Lake Mead, and the delivery of water to the turbines is controlled by wicket gates resembling large butterfly valves operating against sealed openings. Water travels through the penstocks at a maintained elevation, although drought conditions in the Rockies and in the southwestern United States as well as Southern California have caused the water elevation in Lake Mead to fall precipitously low in the past decade. Inasmuch as power generation in a hydroelectric plant is a direct function of head pressure and water flow, this factor has caused much concern regarding power output by the Hoover Dam in the Southwest. There is wide speculation that, unless the area affected by the power generation, particularly Southern California, receives at least its average rainfall over the next few years, irrigation and the amount of electric power generated by Hoover Dam will be greatly restricted.

D. Summary

The success of the Hoover Dam is a prime example of how well the end result can be achieved when there is strong coordination among the parties involved: the planning by the Interior and the Bureau of Reclamation, the specifications and design by the Reclamation engineers and designers, and the construction efforts of the supervision and workforce of Six Companies, Inc. There was also some divine intervention with the realization that a monolithic pour would have required 125 years to properly cure (that may be a slight exaggeration), but a relatively complex solution was developed and implemented for that potentially perplexing dilemma. The fact that the actual construction of the Hoover Dam took less than five years to complete, and even the hydroelectric system was generating power in less than six years, was an enormous undertaking for its era, and a great tribute to all who were involved.

Furthermore, the conditions associated with the Hoover Dam's planning, design, and construction were extremely hazardous. Many lives were lost because of the harsh environment, beginning with J. G. Tierney, a surveyor who accidentally slipped and fell into the swift-moving Colorado River in 1922 and drowned. Ironically, his son Patrick died while working on the Hoover Dam almost exactly thirteen years later in 1935. Overall there were an estimated 100 workers who were killed at the dam site, a staggering number by today's standards, but many times fewer in number that what had occurred during the construction of the Panama Canal. Furthermore, this number of fatalities does not reflect the several dozen workers who, while working in the Diversion Tunnels, were overcome by heat exhaustion and asphyxiation from carbon monoxide, and who were later pronounced dead due to pneumonia and other natural causes.

The construction of the Hoover Dam has had a major impact on the Southwest. Not only has it changed the environment and the estuary of the land, but it has also allowed large communities such as Los Angeles, Phoenix and even Las Vegas to develop and prosper. In addition, many smaller cities, primarily in Southern California, are beholden to the Hoover Dam for their electrical and water supplies. The Hoover Dam is a technological marvel in which all Americans should be proud.