Engineering Innovation at Bonneville Dam

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Bonneville Dam was constructed on the Columbia River in the 1930s by the United States Army Corps of Engineers, and that single government agency took on all of the tasks associated with the engineering of this multipurpose dam project, including the planning, the design, the supervision of construction, and the operation of the facility following completion. The complex engineering process involved technical challenges from each of the major branches of engineering: civil, mechanical, electrical, and chemical. The construction of Bonneville Dam was intended to meet two goals: improve river navigation, and provide hydroelectric power. To achieve these objectives, the Corps developed three significant engineering innovations: a new type of concrete, a new spillway design, and the use of a new kind of water turbine, which was the largest of its kind ever built. But, above all, the Corps of Engineers' work at Bonneville Dam became a breakthrough project for the United States because it integrated innovations in the central areas of engineering—structure, machines, materials, and process. Even Hoover Dam, with its immense symbolic power, did not create innovations in concrete, in spillway design, or in turbine type, and its massive structural form is conservative.[1]

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[1] In chronicling the design innovations at Bonneville Dam, we referred substantially to contemporary technical journals. The most comprehensive civil engineering journal at the time in the United States was the *Transactions of the American Society of*

By using the term "innovative dam," we wish to emphasize the way that Bonneville illustrates innovation in public works, as opposed to private industry. A significant part of American engineering differs fundamentally from the commonly held view that engineering is essentially a profession focusing on "problem solving so that goods and services can be invented, developed, produced, and used."[2] This interpretation of engineering can be helpful in studying private enterprise and manufacturing industries, but it is misleading in understanding the immense public works that have restructured our nation and created the infrastructure that allows other engineering works to thrive.

In the planning, design, and construction at Bonneville, the Corps of Engineers gained its first experience with a concrete dam for both power (a new mission) and navigation (an old mission) in the same structure.[3] To approach this new challenge, the Corps relied on previous engineering experience, which, crucially, it combined with careful study of the specific engineering problems at Bonneville, creating a structure that included significant technological innovations in concrete material, hydraulic design of

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Civil Engineers. Bonneville designers used the *ASCE Transactions*, and to a lesser extent other journals, to share their research and design innovations with the civil engineering profession. The *ASCE Transactions* are also a good indicator of the dissemination of engineering knowledge; most engineering issues related to large dams were reported in detail and debated in related commentaries. In addition, articles relevant to Bonneville were published in the *Journal of the American Concrete Institute*, *Civil Engineering*, *Transactions of the American Society of Mechanical Engineers*, *Transactions of the American Institute of Electrical Engineers*, *The Military Engineer*, and *Electrical Engineering*, among others. Features of Bonneville's design and construction were also frequently reported in *Engineering News-Record*, a weekly civil engineering news magazine. The Columbia River 308 Report (*Report on the Columbia River and Minor Tributaries*), completed by the Corps in 1933, documented critical details about the planning and preliminary design for Bonneville. In addition to these sources, we used published and unpublished reports by the U.S. Army Corps of Engineers for the details and calculations of Bonneville's engineering design. These reports were obtained from the U.S. Army Corps of Engineers Library in Portland, Oregon, the National Archives in College Park, Maryland (Record Group [RG] 77), and Multnomah County Library in Portland, Oregon. The National Archives RG 77 also included letters and design documents.

[2] Thomas P. Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm, 1870–1970* (Chicago, 2004), 6.

[3] The U.S. Army Corps of Engineers also constructed Wilson Dam (1924) on the Tennessee River, but the design process there was led by Hugh Cooper, a private consultant to the Corps. As reported in *Engineering News-Record*, "On May 19, 1920 the Chief of Engineers made a contract under the terms of which Hugh L. Cooper and Company have since that time been designing and supervising engineers" (*Engineering News-Record*, 23 April 1925, 676–77). Cooper had enlisted as an officer in the Corps of Engineers during World War I, but at the time of his involvement in the design and construction of Wilson dam, he was a consultant. This arrangement was substantially different from that at Bonneville. Other projects such as the Corps' construction of locks and dams on the upper Mississippi River focused on navigation, rather than the combined mission of navigation and power.

energy dissipation in spillways, and turbines. In the development of these innovations, the project served as a full-scale laboratory for future Corps dams, as well as a stimulus to a series of laboratory experiments in the Corps' own hydraulics laboratory nearby, at the University of California at Berkeley, and in a testing flume in York, Pennsylvania. In each case, the Corps carefully chose an innovative technology despite the availability of conservative options or other established precedents at a time when the other major government dam-building agency, the Bureau of Reclamation, made different choices.

To provide context for the technological innovations at Bonneville that are the focus of this study, we begin with a brief summary of the Corps' prior experience in planning and engineering mainstream dams and of the political climate in which Bonneville was authorized in 1933. Two important contextual elements of this story are the political planning process of river-basin restructuring initiated by Congress in 1927 (with the so-called 308 Reports) and the social reality of the Great Depression that made the construction of huge public works politically feasible. As this latter story is well-known, we will describe it here in outline form, focusing our attention instead on the dam's three principal design innovations and describing how the Corps' process of creating engineering knowledge facilitated these innovations at Bonneville. We also discuss the fish-passage system installed at Bonneville, another effort at innovation, albeit a less successful one. Finally, we briefly describe the construction procedure and the marketing of hydroelectric power, which transformed Bonneville from design to major power producer by 1937. Two other characteristics of Bonneville that have been treated thoroughly elsewhere are the creation of the Bonneville Power Administration and Bonneville's role as a critical component of the eight dams that structure the lower Columbia and Snake rivers, whose network of power distribution fueled the growth of the Pacific Northwest and disrupted the salmon industry. These issues will be treated only briefly here.[4]

The Corps' 308 Reports

The United States Congress had explicitly mandated the U.S. Army Corps of Engineers to maintain safe navigation on the nation's rivers since the early nineteenth century; the Corps' responsibilities in river-basin development gradually expanded in the early twentieth century. On 5 June 1920, the Rivers and Harbors Act authorized the Corps of Engineers to make preliminary examinations and surveys of the Tennessee River and its

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[4] For a more detailed study of engineering and politics, see David P. Billington and Donald C. Jackson, *Big Dams of the New Deal Era: The Confluence of Engineering and Politics* (Norman, Okla., 2006). For references to discussions of fishways, see note 53 below; for the Bonneville Power Administration, see note 60.

tributaries. General Lansing Beach ordered Major Harold Fiske to make the survey, stating

> the intention of Congress to include studies of present or potential hydroelectric developments, the mineral and industrial resources of this region, drainage, flood protection and such other allied subjects as may reasonably appear to have an appreciable influence on the project that may be finally recommended for adoption for the improvement of navigation.[5]

In short, Beach asked the Corps for a comprehensive report on the Tennessee River Basin, including—but not solely based on—navigational needs. The stated purposes of Fiske's survey significantly increased the Corps' jurisdiction over river engineering. Fiske carried out the Tennessee River survey, submitting a detailed report to the House Committee on Rivers and Harbors in 1924.[6]

Fiske's 1924 report was instrumental in setting the precedent for the national rivers survey that soon followed. In the Rivers and Harbors Act of 3 March 1925 (section 3), Congress authorized and directed the U.S. Army Corps of Engineers and the Federal Power Commission jointly to prepare cost estimates for comprehensive surveys of all navigable streams and their tributaries where hydroelectric power appeared to be practical. Responding to the 1925 act in a letter report of 7 April 1926, the Chief of Engineers detailed the costs needed to study "navigable streams upon which power developments appear to be feasible." This document, known as House Document No. 308, laid out a national program of immense scope for which the surveys would cost $7,322,400.[7] More than 10 percent ($734,100) of these funds were to be used to investigate the Columbia and Snake rivers.

The task of surveying the Columbia River was a monumental one. The Army Corps of Engineers, led by division engineer Colonel Gustave Lukesh, with district engineers Major John Butler and Major Oscar Kuentz, collected

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[5] Beach ordered Major Harold G. Fiske to make the survey by letter of 30 June 1920. For a full description of the Tennessee River survey, see Leland R. Johnson, *Engineers on the Twin Rivers: A History of the Nashville District Corps of Engineers* (Nashville, 1978), 181–84.

[6] *House Committee on Rivers and Harbors*, 68th Cong., 1st Sess., 31 March and 1 April 1924. Fiske's reports: Harold C. Fiske, "Preliminary Examination of Tennessee River and Tributaries," 15 January 1921, p. 9, in *Tennessee River and Tributaries, North Carolina, Tennessee, Alabama, and Kentucky*, House of Representatives, 67th Cong., 2d Sess., Document No. 319, 19 May 1922; Harold C. Fiske, "Partial Survey of Tennessee and Tributaries," 15 March 1922, in Johnson, 155, 178; *Tennessee River and Tributaries, North Carolina, Tennessee, Alabama, and Kentucky*, House of Representatives, 71st Cong., 2d Sess., Document No. 328, 24 March 1930. A complete description of the Tennessee River 308 Report is available in Billington and Jackson, 85–87.

[7] H. Taylor and O. C. Merrill, "Estimate of Cost of Examinations, etc. of Streams where Power Development Appears Feasible," House of Representatives, 69th Cong., 1st Sess. (7 December 1925 to 10 November 1926), Document No. 308.

information on virtually every aspect of the river basin, including topographic and hydrographic data, irrigation potential, flood danger, and stream- and river-discharge studies. They also developed preliminary designs for future dams.[8] In this work, the small number of Corps officers relied heavily on their large staff of civil engineers for detailed studies of "water resources, including power, navigation, and irrigation potentialities," supplemented by surveys done by the Bureau of Reclamation on the upper Columbia.[9] After 1931, Major Kuentz led the investigations in the southern portion of the river basin, aided by civil engineer Claude Grimm, who worked on the report after his move to the Pacific Division office in 1930.[10]

The Corps' final report on the Columbia, completed in 1932, filled 1,845 pages. It recommended the construction of eight dams. The lower Columbia dam at Warrendale—the dam that would become Bonneville—was identified as the Corps' top priority. Its appeal lay in its proximity to Portland (approximately forty miles away). In addition, the Columbia's large flow at Warrendale meant that a substantial amount of power could be produced in a low, mainstream dam. Because of the poor foundation conditions, the Corps' report recommended further investigation to identify possible sites for relocating Warrendale Dam. One site under consideration to replace Warrendale was Bonneville, a few miles upriver.[11]

In his inaugural speech on 4 March 1933, President Franklin Roosevelt, aiming to reassure an American public suffering from the Great Depression, acknowledged the country's economic woes, but his rhetoric was optimistic. "Our distress comes from no failure of substance," he said. "We are stricken by no plague of locusts. . . . Nature still offers her bounty and human efforts have multiplied it. . . . This nation asks for action, and action now. Our greatest primary task is to put people to work."[12] With these words, Roosevelt identified his primary priorities for his first term, including expanding employment. The special session of Congress that coincided with his first 100 days in office established an assortment of initiatives

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[8] Lukesh served as division engineer from 1927 to 1931. In 1931, Thomas Robins became the division engineer, but he was based in San Francisco, rather than Portland, until 1934. Kuentz served as district engineer from 1931 to 1933. Following his departure, his role was filled by Lieutenant Colonel C. F. Williams.

[9] The Columbia River 308 Report: US. Army Corps of Engineers, *Report on the Columbia River and Minor Tributaries*, 73rd Cong., 1st Sess., House Document No. 103, 1933. The ratio of civilian personnel to Corps officers is large. For example, in the early twenty-first century, the Corps includes approximately 34,600 civilian employees and 650 military members (including 200 officers). See William Willingham, *Water Power in the "Wilderness": The History of Bonneville Lock and Dam* (Portland, 1997), 1.

[10] For a brief outline of Grimm's career, see J. C. Stevens, "Memorial for Claude Irving Grimm (1896–1942)," *Transactions of the American Society of Civil Engineers* (hereafter *ASCE Transactions*) 108 (1943): 1585–87.

[11] Columbia River 308 Report. See also Oscar O. Kuentz, "The Lower Columbia River Project," *The Military Engineer* 25 (1933): 40.

[12] Franklin Delano Roosevelt, "Inaugural Address," 4 March 1933.

designed to reach this goal. New government organizations included a public works agency, the Civilian Conservation Corps; a dam-building and regional-planning agency, the Tennessee Valley Authority; and a program of farm subsidies, the Agricultural Adjustment Act, among others. It was in the context of this burst of legislation and presidential action that work began on Bonneville Dam.

Roosevelt's dedication to unemployment relief, together with the engineering expertise demonstrated in the Corps' 308 Report and the committed advocacy of Oregon's politicians, led to the Federal Emergency Administration of Public Works' allocation of funds for Bonneville Dam on 30 September 1933. Almost immediately, the Portland district engineer, Lieutenant Colonel C. F. Williams, hired a distinguished group of engineers to consult on the design, including D. C. Henny, L. C. Hill (who would be elected president of the American Society of Civil Engineers [ASCE] in 1937), John Hogan (ASCE president in 1940), J. C. Stevens (ASCE president in 1945), L. F. Harza (an expert on dam design and hydroelectric developments), and Raymond Davis (professor of civil engineering at the University of California at Berkeley). These were some of the leading civil engineers in the United States, and, in addition, Henny and Stevens were from Portland. Hill and Henny had already served as consultants on Fort Peck Dam and on Hoover Dam for the Bureau of Reclamation. Davis was the foremost academic engineer in the West for concrete, Stevens was a national expert in model analysis and the design of spillways, while Harza and Hogan were leaders in the study of turbines for hydroelectric plants. These consultants played a central role in devising the innovative features that would characterize Bonneville's design.

Concrete and the Heat of Hydration

By the time the Corps began to design Bonneville Dam, the engineering profession knew that in massive concrete structures, the heat released during the chemical reaction between cement and water could result in serious cracking as the concrete sets, presenting a clear danger to water-retaining structures such as dams. As the concrete dam–building era began in the early twentieth century, engineers developed a series of different methods to reduce that heat: casting concrete in thin layers (lifts) and allowing much of the heat to escape from the surface before placing the next lift, installing pipes within the cast concrete through which cooling water is pumped to remove excess heat, or using a special type of finely ground cement.

In a 1931 paper, D. C. Henny discussed the problem of this cracking in concrete dams and offered potential solutions. He wrote that the negative effect could be at least partly avoided by reducing the height of the lifts from five to four feet, by slowing down construction to allow each layer to

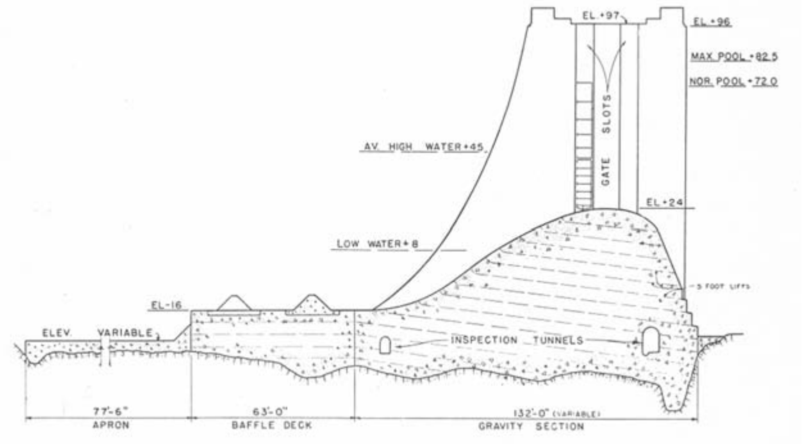

FIG. 1 Cross-section of the spillway at Bonneville Dam. (Source: U.S. Army Corps of Engineers, *Improvement of the Columbia River at Bonneville, Oregon* [Bonneville, Ore., 1938], 8. Reproduced courtesy of the U.S. Army Corps of Engineers.)

exhaust the heat at its surface before casting more concrete, and even by pre-cooling the water and aggregates before mixing them into the concrete. Henny's paper did not mention either cooling pipes or the use of special cements.[13]

The first significant American use of cooling pipes came in a small experimental section of the Owyhee Dam in Oregon in 1931, the tallest dam in the world at the time of its completion. The Bureau of Reclamation considered the Owyhee experiment a success, which justified the method's use in its subsequent large dams, Hoover (1936), Grand Coulee (1941), Friant (1942), and Shasta (1945). The TVA also installed cooling pipes at Fontana Dam (1944).[14]

As the cross-section in figure 1 shows, the Bonneville spillway's concrete form is radically different than that of a high-gravity dam such as the Grand Coulee. The Bonneville spillway is low (60 feet) to allow substantial overflow during floods, whereas the Grand Coulee is high (330 feet) to create a large storage lake as part of a major irrigation project. Figure 1 indicates the nearly horizontal lines that represent the layers cast in five-foot

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[13] D. C. Henny, "Classification, Selection, and Adaptation of High Dams," *ASCE Transactions* 95 (1931): 139–48.

[14] Wallace Chadwick, "Influence of Some Related Technologies on Technology of Dams," in *Development of Dam Engineering in the United States*, ed. Eric B. Kollgaard and Wallace L. Chadwick (New York, 1988), 27–29. A slightly earlier use of cooling pipes in the Merwin Dam on the Lewis River appeared to have no influence on their use at Owyhee (see Jan A. Veltrop, "Concrete Arch Dams," in *Development of Dam Engineering*, 284).

lifts to help control the heat of hydration. However, the speed of construction (for economic reasons) dictated additional means of lowering the heat. The structural differences between low and high dams made cooling pipes less suitable at Bonneville and stimulated the Corps to initiate an extensive experimental program, commissioning the University of California at Berkeley to conduct a large series of tests on various types of cement used in concrete and their potential for reducing heat-induced cracking. Modified portland cement, low-heat portland cement, and a portland-pozzolan mix were all investigated.

On 29 May 1934, the Corps issued a contract for building the spillway dam to the Columbia Construction Company for $8,972,650.[15] In August of the same year, the Corps established a field laboratory at the Bonneville site to conduct tests on concrete mixtures, especially those using Portland-pozzolan cement—a mixture of standard portland cement and silica-based pozzolanic materials, such as volcanic ash. At the Bonneville laboratory, Irwin Burks, along with Corps civilian engineers R. R. Clark, the designing engineer of the spillway, and H. E. Brown Jr., Clark's assistant, ran tests on the cement mix. Berkeley professor Raymond Davis consulted on these tests, leading the Corps to contract with the Engineering Materials Laboratory at Berkeley that he directed in December of 1934. There, they ran another parallel set of tests in the presence of a representative from the Corps' Bonneville personnel. In general, the Berkeley results checked well with those obtained from special test #115-A made at Bonneville. The tests at Berkeley continued until April 1935, when the construction schedule dictated that the Corps make a decision on the cement type for the spillway dam.[16] The results of both the Bonneville and Berkeley tests were published and disseminated to the civil engineering industry.

The experimental studies at both Berkeley and Bonneville showed that when compared to more conventional portland cements, the portland-pozzolan cement resulted in "lower heat of hydration, higher tensile strength, [and] greater impermeability."[17] The lower heat of hydration assured the engineers of a reduction in temperature-induced cracking. The difficulty was that Americans had little experience using this type of cement in any but very small projects, and European use appeared not to have led to adequate specification for practice in the United States. In the San Francisco–Oakland Bay Bridge (1936), the engineers had added high silica

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[15] *Engineering News-Record*, 7 June 1934, 750.

[16] See Irwin E. Burks, "Report of Operation, Concrete Division: 1934–1935," Bonneville Power-Navigation Project, Bonneville, Oregon, 1935; Raymond E. Davis, "Cement and Concrete Investigations for Bonneville Dam," Final Report to Corps of Engineers, United States Army, Second Portland District, February 1938, p. 4.

[17] R. R. Clark and H. E. Brown Jr., "Portland-Pozzolan Cement as Used in the Bonneville Spilling Dam," *Journal of the American Concrete Institute* 33 (1937): 191. Clark and Brown were, respectively, the designing engineer and the assistant design engineer for the Bonneville cement mix.

cement to some portions of the concrete, noting in a paper submitted to the *Journal of the American Concrete Institute* that "there was some reason to believe that owing to the pozzolanic nature of the added silica compound it might be a more durable product in the presence of sea water than any of the standard commercial Portland cements manufactured by California Mills."[18] From this paper and others, it is clear that the bridge engineers viewed the portland-pozzolan cement as a means of producing a more durable concrete in seawater, and there is no mention in these published papers of the use of such cement for reducing the heat of hydration.

In an innovative project like Bonneville, it was not enough to test the properties of different cements and different concrete mixes; once the unusual portland-pozzolan cement mix was chosen, it also had to be specified, inspected, and shipped, and a fabrication process had to be developed. In May of 1935, the government requested bids for supplying the portland-pozzolan cement, awarding the contract to supply 500,000 barrels (at 376 pounds per barrel) to the least expensive of these bidders, the Pacific portland Cement Company. Professor Davis and the engineers from the Corps together settled on the concrete-mix design and proportions, and the San Francisco laboratory of the National Bureau of Standards carried out the inspection of this special cement. In addition to the other challenges, the Corps needed a new manufacturing process, which Professor Davis worked out with Corps personnel and the Pacific Portland Cement Company.[19] The Corps engineers had to manage the work of all of these different organizations as they focused on the goal of completing the project rapidly. They also faced the serious political constraint of putting people to work, which meant rushing the design (which employed only a few people) and moving quickly to begin construction (which put large numbers of people to work).

In the evaluations of the dam during and following construction, the designers found that the portland-pozzolan mix generally met expectations. Investigations during the first few years after construction showed the structure to be remarkably free of cracks or other evidence of segregation of the larger aggregate from the sand-cement mortar. When compared to other dams, including the Bureau of Reclamation's Owyhee (1931), or TVA's Norris (1936), Bonneville exhibited less serious cracking and, as a result, smaller amounts of leakage or concrete deterioration. Designers at several large dams took advantage of experiences gained at Bonneville and the related University of California investigations to develop similar mixes for use at Friant (1942), Hungry Horse (1953), and Dworshak dams (1973), among others.[20]

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18. Thomas E. Stanton Jr., "Cement and Concrete Control: San Francisco–Oakland Bay Bridge," *Journal of the American Concrete Institute* 32 (1935): 4.

19. Davis, "Cement and Concrete Investigations," 4–7 (cement testing) and 36–38 (cement manufacturing).

20. The Bonneville investigations and the use of pozzolans at Bonneville were re-

Spillway Dam Design

Bonneville Dam's spillway structure (fig. 1) had to be designed with sufficient capacity for the Columbia's annual spring floods. Although the basic static and hydraulic principles of spillway design were well established, the spillway shape was governed by the large and variable flow of the Columbia and by the site's relatively weak foundation. Claude Grimm, then chief engineer for the Corps on the Bonneville project, and his engineering staff based their design on the maximum flood, or volume of water per second, the Bonneville spillway needed to be capable of passing without harm to the structure, which they determined themselves. However, because of the incomplete rainfall and runoff records for the Pacific Northwest during the 1930s, the engineers' determination of the maximum flood for spillway design had to rely on reasoned guesswork, inferring from the available data from their earlier experience in the region. As designed, the Bonneville spillway's capacity of 1,600,000 cubic feet per second (cfs) was significantly larger than any existing American dam; Wilson Dam on the Tennessee River has a spillway capacity of 900,000 cfs.[21] To accommodate the spillway flow, H. G. "George" Gerdes, the chief civilian engineer for the spillway

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ported in several journals and symposia: see H. S. Meissner, "Pozzolans Used in Mass Concrete," p. 16, and Raymond Davis, "A Review of Pozzolanic Materials and Their Uses in Concretes," p. 3, both in *Symposium on Use of Pozzolanic Materials in Mortars and Concrete, Presented at the First Pacific Area National Meeting, American Society for Testing Materials, San Francisco, Calif., October 10–14, 1949* (Philadelphia, 1950); Raymond Davis et al., "Properties of Cement and Concrete Containing Fly Ash," *Journal of the American Concrete Institute* 34 (1937): 557–612; Clark and Brown, 183–221, esp. 212–17; Raymond Davis, "Discussion of Clark and Brown's Paper of January," *Journal of the American Concrete Institute* 34 (1937): 222-1–5; *Transactions of the Second Congress on Large Dams* (Washington, D.C., 1936), 214–23.

[21] Before design work began in 1933, the flow at Bonneville had been measured as low as 40,000 cfs and as high as 1,170,000 cfs. The Bonneville spillway structure has eighteen gates that can be used to allow water to flow over the spillway when the water level is high, and not all the water can pass through the turbines to produce energy. Twelve of these gates are 50 ft by 50 ft; six are 50 ft by 60 ft. The Corps of Engineers had the results of tests at Wilson Dam to guide it in determining the capacity of the spillway at Bonneville Dam. See Louis G. Puls, "Spillway Discharge Capacity of Wilson Dam," *ASCE Transactions* 95 (1931): 316–19, with discussion on 330–33. In his report on the spillway tests, J. C. Stevens gives the maximum capacity as 1,600,000 cfs. From the standard weir equation, Stevens calculates only 1,400,000 cfs as follows: $Q = CLH^{3/2}$, where $C = 3.62$, $L = 50 \times 18 = 900$ ft, and $H = 81 - 24 = 57$ ft, giving 1,400,000 cfs. (Stevens does not give C, but he does give the other quantities so that we can compute the value he used.) To compute the maximum capacity, Stevens needed to use the developments presented by Puls in his analysis of Wilson Dam, where $Q = ML\ (h_2^{3/2} - h_1^{3/2})$ for the case where the pool level is above the gate opening. Stevens gives H maximum of $86 - 24 = 62$ ft, and hence $h_2 = 62$ ft and $h_1 = 86 - 82.5 = 3.5$ ft. Also, he takes C to be slightly larger as Q increases, so that with $C \approx M = 3.68$, $Q = 3.68 \times 900\ (62^{3/2} - 3.5^{3/2}) = 1{,}600{,}000$ cfs. See J. C. Stevens, *A Report on Model Studies Made in Connection with the Bonneville Dam*, vol. 1 (n.p., 1937), 5, 14, 19.

dam, and the engineering staff studied previous dams, including Wilson Dam, and the hydrology specific to the Columbia River. From these studies, they determined the primary dimensions of the basic dam form (fig. 1), as well as the eighteen 50-foot-wide spillway gates.[22]

The engineers further faced the challenge of providing structural stability on a weak foundation. The foundation material at Bonneville is composed mostly of volcanic fragments solidified by pressure. As a result, it does not provide significant strength or resistance to sliding forces. The designers had to account for the low strength of the rock, limiting design pressures at the base to 110 pounds per square inch and notching the dam into the rock material to avoid sliding (fig 1).[23]

The problem of energy dissipation at the base of the spillway was a primary source of concern for the engineers. As water falls over the spillway, potential energy is converted to kinetic energy. If provisions are not made to dissipate this kinetic energy, the falling water will scour and erode the riverbed at the base of the dam, potentially reducing structural stability. By the early 1930s, few dam engineers had studied the problem of energy dissipation in detail, and very few dams had incorporated specific structural enhancements for this purpose in their design. Designers found scour particularly worrisome at Bonneville because of the very large flow that was possible and because of the weak foundation conditions. As the Bonneville design process began, the Corps decided to construct a special laboratory in Linnton, on government moorings close to Portland, to perform hydraulic model studies starting on 1 March 1934. R. B. Cochrane, a civilian engineer working for the Corps, directed the Bonneville Hydraulics Lab. An important aspect of the model studies investigated the best method to reduce scour and cavitation damage to the spillway structure by facilitating energy dissipation through what is known as "hydraulic jump."[24]

Hydraulic jump occurs when the high-energy flow of water over the spillway suddenly results in a rise in the water height at the base, thereby losing energy and diminishing the danger of scour (fig. 2).[25] The Corps

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[22] The spillway gates are operated by gantry cranes.

[23] For the foundation's conditions, see J. S. Gorlinsky, "The Bonneville Dam," *The Military Engineer* 27 (1935): 210–13, and drawings 10–13 (dated 18–19 May 1935) in the Army Corps of Engineers' unpublished drawings for the *Bonneville Power Navigation Project*, obtained courtesy of Kevin Perletti of the U.S. Army Corps of Engineers. See also C. F. Williams, "Letter to Chief of Engineers, re: Design data for Bonneville Dam, May 11, 1934," National Archives, College Park, Maryland (hereafter NA), RG 77/111, box 132, folder 3529; and William Willingham and Donald Jackson, "Historical American Engineering Record for Bonneville Dam," HAER No. OR-11, April 1989, p. 56.

[24] Edward A. Elevatorski, *Hydraulic Energy Dissipators* (New York, 1959), 22–38.

[25] The energy dissipated in hydraulic jump is measured by the ratio y_2/y_1, where y_1 is the water depth before jump occurs, and y_2 is the water depth after jump occurs. In a smooth, rectangular basin (assuming uniform velocity distribution and neglecting wall friction), this ratio can be calculated from Bernoulli's equation for incompressible flows: $v_1{}^2/2 + gy_1 = v_2{}^2/2 + gy_2$ (equation 1), and the equation of continuity (conser-

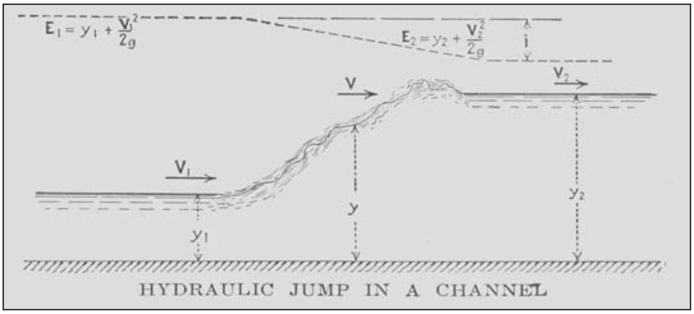

FIG. 2 Energy dissipation through hydraulic jump. (Source: J. C. Stevens, "Determining the Energy Lost in the Hydraulic Jump" *Engineering News-Record*, 4 June 1925, 929. Reproduced with permission.)

hired J. C. Stevens, who had expressed the mathematics of hydraulic jump in a simplified functional form in a publication in 1925, to carry out model tests in the Linnton laboratory for the design of the new dam. By relating energy loss to the size of the flow, the number of spillway gates opened, and the height of water above and below the spillway, Stevens could calculate the energy loss due to hydraulic jump.[26] At Linnton, he made numerous laboratory tests on different baffles and other structural appurtenances designed to create turbulence and further minimize scour, conducting investigations of forty different types of baffles in a total of 172 experiments. The tests were crucial in helping to determine both the arrangement and shape of baffles installed at Bonneville Dam. In addition, to reduce scour of foundation material, the designers required the construction of a five-foot-deep concrete apron extending more than seventy feet downstream from the dam.[27]

Engineering journals covered in detail both the original design of baffles to reduce scour as well as the 1950s repair work; indeed, Bonneville's baffles graced the cover of the 21 April 1955 edition of *Engineering News-Record*. The Corps' careful hydraulic studies demonstrated the effectiveness of empirical investigations and contributed to structural energy-dissipation studies.[28] The Bonneville structural appurtenances represented a sig-

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vation of mass), $v_1 y_1 = v_2 y_2$ (equation 2). v_1 and v_2 are the average velocity of the flow before and after jump occurs. If these two equations are combined, we find that an increase in the energy dissipated in hydraulic jump (represented by y_2/y_1) results in a decrease in the velocity of the water after jump occurs (v_2). See e.g. Frank M. White, *Fluid Mechanics* (Boston, 1999), 174–76.

[26] J. C. Stevens, "Determining the Energy Lost in the Hydraulic Jump," *Engineering News-Record*, 4 June 1925, 928–29.

[27] Stevens, *A Report on Model Studies* (n. 21 above), 7.

[28] Publications included J. C. Stevens, "Models Cut Costs and Speed Construction,"

nificant advancement in the study and design of energy-dissipating devices in spillway dam structures, which were utilized in designing subsequent run-of-the-river dams on the Columbia and elsewhere.

Kaplan Turbines

In 1937, at the time of Bonneville's completion, its Kaplan turbines were easily the largest in the world, with power capacity over 50 percent higher than any other, and over 70 percent higher than any outside the United States. Adopting Kaplan turbines was a major step for hydroelectric power plants, because they had never been designed, tested, and built at the scale required for installation at Bonneville.[29]

The Kaplan turbine can accommodate large variations in flow thanks to its ability to automatically change the angle of its blades, referred to as "variable pitch blading." From a design perspective, this virtue was especially important for rivers with a relatively small change in elevation, but flows large enough that immense power was possible without building high dams.[30] Low spillway dams must operate efficiently under widely variable hydraulic conditions; on the Columbia River, the seasonal flow can range from 40,000 cfs to 800,000 cfs, with a mean annual flow of 211,000 cfs.[31] In

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Civil Engineering 6 (1936): 672–77; and Donald Basgen, "Bonneville Dam Spillway Erosion Repaired," *Engineering News-Record*, 21 April 1955, 36. Following construction, the baffles' effectiveness was carefully monitored by divers, who observed gradual erosion at the baffles and spillway. When the first major dewatering occurred in 1954, the Corps observed significant pits in the baffles caused by cavitation, which is a particular problem at Bonneville because of the high amounts of sediment in the water (1,000 ppm sand and silt). By 1954, some of the baffles, especially those in the upstream row, had twenty-two inches of cavitation on the sides. In addition, the deck, apron, and piers showed significant signs of erosion in some areas. To determine the best method of repair, Corps engineers returned to the Linnton hydraulic laboratory. Finding the cost of changing the length of the baffle deck or locations to be too high, the engineers determined that slight modification of the shape of the upstream baffles moved the jet of water farther downstream, decreasing the scour of the concrete. Furthermore, a solid end-wall downstream (replacing the baffles) proved to be more effective in making the basin function as a bucket. The Corps conducted additional material studies as well; the designers developed a cement with a low water/cement ratio and a metallic aggregate to cover the baffles.

[29] See C. C. Galbraith, "Kaplan Turbines for Bonneville," *Engineering News-Record*, 27 May 1937, 765–67.

[30] The mean flow at Bonneville was reported in a Corps Report: U.S. Army Corps of Engineers, Bonneville District, *Improvement of the Columbia River at Bonneville, Oregon* (Bonneville, Ore., 1938), 5. In other documents, the flow rates reported sometimes differ slightly; these differences likely result from the data used to make the calculations and from variations in what was meant by "mean" or "average" flow.

[31] The amount of power produced by water falling through a turbine depends on both the amount of water (the flow, Q) and the hydraulic head (the height from which the water is falling, $H = \text{headwater} - \text{tailwater}$). Although Bonneville is a low dam, the Columbia River's flow at Bonneville is large enough to produce a significant amount of

retrospect, it seems obvious that the Corps would choose Kaplan turbines for Bonneville, as the Kaplan design seemed a perfect fit for the river, but after the success of the Wilson Dam and powerhouse, the often conservative army engineers might easily have taken the proven route of installing Francis-type turbines for their first design.[32] That they did not is largely due to the process of writing those 308 Reports, which required detailed research and encouraged the engineers to go beyond the recent designs and to take advantage of newly published research.

As early as its 308 Report, the Corps engineers had proposed to use Kaplan turbines for Warrendale (later Bonneville) Dam and Umatilla (later McNary) Dam, though they planned to retain the traditional Francis-type turbine for the two other planned lower Columbia River dams, the Dalles and John Day. The distinction between these two pairs was that in this preliminary planning phase, the Corps conceived of the latter two as high masonry dams rather than low spillway ones (although, in the end, they were all built as mainstream, low, concrete spillway dams). When preparing the southern section of the Columbia Basin 308 Report, Colonel Lukesh had secured the help of a consultant already familiar with power issues in the West, but the choice of the Kaplan-type turbines for Warrendale and Umatilla appears to have come from Lukesh's study of previously published documents, referenced in the report as early as 1931.[33] The proposed Kaplan turbines, called "adjustable blade propeller type wheels," appear on a plate in the 308 Report dated 27 July 1931.[34]

The Corps' consideration of Kaplan turbines represented a significant

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power. At Bonneville, $H = 60$ ft and $Q = 211{,}000$ cfs (the average Columbia flow at Bonneville). These calculations assume normal water levels, according to the Army Corps of Engineering drawings, with a 60-ft difference in elevation between headwater and tailwater levels. Accordingly, the horsepower of the power produced equals 1,440,000 hp. The electrical power is, therefore, 1,440 khp × 0.746 = 1,074 megawatts (MW) under average flow conditions. The installed turbine capacity at Bonneville, including the turbines in the second powerhouse, is 1,087.7 MW. Thus, the installed turbines have sufficient capacity to use all of the water available for power production under average flow conditions; in fact, the flow can be slightly larger than the average before it is necessary for the operators to release water over the spillway.

[32] In a Francis-type turbine, water enters through an outer horizontal ring and passes into a movable ring with blades that create a vertical rotation. The water is exhausted through an opening in the center to reduce turbulence. See, for example, Jonas M. K. Dake, *Essentials of Engineering Hydraulics*, 2d ed. (London, 1983).

[33] Columbia River 308 Report (n. 9 above), 34. The consultant, Barry Dibble, had written several discussions of other papers on the general subject of irrigation and power; see *ASCE Transactions* 89 (1926): 1477, and *ASCE Transactions* 90 (1927): 980. Dibble was not an expert on turbines, however.

[34] The Columbia River 308 Report (pp. 1540, 1544–1604) notes the use of "adjustable blade propeller type wheels." Such turbines are shown on part 2, plate 88 (facing p. 1599), and are taken by the 308 Report to be used only when the heads are no higher than 68 ft.

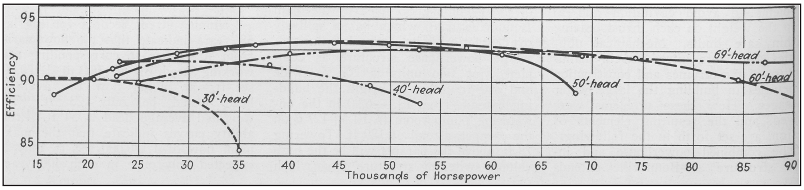

FIG. 3 Efficiency of the Kaplan turbines installed at Bonneville. (Source: C. C. Galbraith, "Kaplan Turbines for Bonneville," *Engineering News-Record*, 27 May 1937, 766. Reproduced with permission.)

departure from previous experience. On earlier major mainstream dams, including McCall's Ferry (later renamed Holtwood), Keokuk, and Wilson, engineers chose Francis-type turbines originally invented by James Francis in Lowell, Massachusetts, in the 1850s. Since Francis's invention, hydraulic engineers had developed improvements and other types of water turbines, and as the size of hydroelectric power plants escalated in the early twentieth century, there was a more intensive and laboratory-based search for a new type. Shortly before World War I, Czech engineer Victor Kaplan invented the new type of turbine that bears his name. The first Kaplan turbine, built and tested in 1919, produced only thirty-five horsepower, but it had one major advantage over turbines then in use: its efficiency remained high over a wide range of load (fig. 3).[35]

The first major American publication on turbines designed for low-head hydroelectric power plants came at a meeting in New York City early in 1925, where six authors presented a review of recent research and practice. Stimulated in part by the content of the 1924 London World Power Conference and in part by the number of planned, large, mainstream hydroelectric plants in the United States, the New York meeting brought together the leading American engineers on water turbines and led to the first significant publication on Kaplan turbines to appear in the U.S. civil engineering literature in 1926.[36] Earlier publications on water turbines related to hydroelectric power development had appeared in the *ASCE Transactions* in 1922 and 1923, but they did not recognize the emerging trend in Europe of using the Kaplan design.[37]

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[35] Norman Smith, *Man and Water: A History of Hydro-Technology* (New York, 1975), 189–99. It is noted that the Tennessee Valley Authority's Wheeler Dam of 1936 did use propeller turbines, but these had fixed blades and hence were not Kaplan turbines. TVA works had no influence on the Corps' decision to use Kaplan turbines.

[36] "High Specific Speed Hydraulic Turbines in Their Bearing on the Proportioning of the Number of Units in Low-Head Hydro-Electric Plants: A Symposium," *ASCE Transactions* 89 (1926): 615–79, with discussion on 680–95.

[37] Arthur T. Stafford and Edward Pierce Hamilton, "The American Mixed-Flow Turbine and Its Setting," *ASCE Transactions* 85 (1922): 1237–1356 (including discus-

Four of the six papers presented at the New York meeting provided critical background for the Corps' development of its design for the Bonneville project. The opening paper explained the European development and experience and stressed the advantages of the Kaplan turbines. In the fourth paper, George Jessop described tests on turbines carried out in the Holyoke Flume, and in the specially designed and built testing flume of the S. Morgan Smith Company in York, Pennsylvania, for whom he served as hydraulic engineer. Although none of the tests was on Kaplan turbines, the Smith Flume provided a major new facility for testing the newer type of turbines for Bonneville. The fifth paper described some European designs using the Kaplan-type turbines or similar variable-angle types. In the final paper, John Hogan, a distinguished civil engineer from New York, noted that for high-speed turbines in low-head hydroelectric power plants, Francis turbines "do not promise a solution to the problem," and he observed that economy will lead away from Francis turbines and in some cases to turbines that have "characteristics similar to those of the Kaplan wheel."[38]

Following that 1926 publication, interest in Kaplan turbines grew until, in the early 1930s, the Safe Harbor Water Power Corporation began a detailed study for the Safe Harbor project on the Susquehanna River, just upstream from the McCall Ferry Dam. L. M. Davis, an engineer on the Safe Harbor project, noted: "Engineering studies in connection with these units [Kaplan turbines] required the construction of a new hydraulic laboratory for testing model turbines."[39] The Pennsylvania Water and Power Company completed the Holtwood hydraulic laboratory adjacent to McCall Ferry Dam in the summer of 1930, and this laboratory was used to study models of the Kaplan turbines for the Safe Harbor Dam. Davis and G. W. Spaulding, another Safe Harbor engineer, stated in the journal *Electrical Engineering* that, "as in any pioneering development of this magnitude, an unusual amount of experimental and engineering study was necessary involving not only the hydraulic and mechanical design of the plant but affecting the structural and electrical design as well."[40] As at Safe Harbor, the Corps' civil engineering designers at Bonneville would face this challenge of integrating work in many of the major branches of engineering in a complex project.

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sion), and John D. Galloway, "Hydro-Electric Developments on the Pacific Coast," *ASCE Transactions* 86 (1923): 803–15.

[38] See the essays comprising the "High Specific Speed Hydraulic Turbines" symposium, especially George A. Orrok, "High Specific Speed Turbines," 616–24; George A. Jessop, "High Specific Speed Hydraulic Turbines in Their Bearing on the Proportioning of the Number of Units in Low-Head Hydro-Electric Plants," 659–65; Charles C. Egbert, "Some Applications of the Propeller Type Water Turbine in Europe," 666–76; and John P. Hogan, "Proportioning of Units in Low-Head Plants," 677–79.

[39] L. M. Davis, "Cavitation Testing of Model Hydraulic Turbines and Its Bearing on Design and Operation," *ASME Transactions* 57 (1935): 455.

[40] L. M. Davis and G. W. Spaulding, "Kaplan Turbines at the Safe Harbor Hydroelectric Plant," *Electrical Engineering* 51 (1932): 728–33.

When the Corps' Portland District prepared the 308 Report section on power plants for the Columbia River, the Safe Harbor project had just begun, but little had been published on it. Nevertheless, it was a significant precursor to Bonneville, and it did represent the largest Kaplan turbines yet projected. However, the increase in the scale of Bonneville compared to Safe Harbor required a major experimental and engineering study in its own right, although the Columbia River project could now benefit from the new laboratory and experience at Holtwood. As completed and as reported in a 1940 edition of the journal *Engineering*, the capacity of each of Bonneville's turbines—66,000 horsepower (hp)—greatly exceeded the 42,500-hp turbines installed at Safe Harbor. The original Bonneville powerhouse had capacity for ten such turbines; all ten had been installed by the 1940s.[41]

Because the turbines were such a major feature of the project, the Corps decided to hire two consultants already expert in waterpower works, John P. Hogan and Leroy F. Harza. Hogan had been a major figure in the 1925 symposium that introduced Kaplan turbines to the American profession, and Harza was an even more influential engineer, according to engineering historian Norman Smith: "It seems to have been the American engineer Leroy H. [*sic*] Harza, who in 1919 and 1924 signposted the way with his patents for the very first tubular turbines."[42] The Corps' consultation of Hogan and Harza is evidence that it sought the best advice possible. Hogan and Harza worked closely with two civilian employees of the Corps: C. C. Galbraith, the senior civilian engineer, and Paul Heslop, chief of the structural and mechanical section at Bonneville.

The Corps awarded the contract for constructing the turbines to the S. Morgan Smith Company in October 1935. It had already built Kaplan turbines for the Safe Harbor project, and its chief engineer, George Jessop, was thoroughly familiar with turbine testing and design, as illustrated by his paper in the *ASCE Transactions* of 1926 and in additional publications in the *AIEE Transactions* of 1931 and the *ASME Transactions* of 1939.[43] The Corps' contract with the S. Morgan Smith Company additionally required that the manufacturer carry out tests in its laboratory; these tests would serve as a basis for designing and building the turbines, after the standard numerical adjustment to account for scale. As stipulated, the company made tests and proceeded to manufacture the Kaplan turbines for Bonneville, finding that efficiencies were 90 percent or higher for a range of power from just below 20,000 hp to 66,000 hp.[44]

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[41] J. R. Finniecome, "The Development of the Kaplan Turbine," *Engineering*, 15 November 1940, 382. A second powerhouse was constructed in the early 1980s.

[42] Smith (n. 35 above), 194.

[43] Paul L. Heslop and George A. Jessop, "The Kaplan Turbines at Bonneville," *ASME Transactions* 61 (February 1939): 99, 101. "Hydraulics and Electrical Possibilities of High Speed Low Head Developments," *AIEE Transactions* 50 (1931): 114–19.

[44] Heslop and Jessop, 101.

The scale and turbine size created unprecedented problems of manufacturing, especially the means of forming the parts of the turbine. The company decided to use welding to connect parts, rather than the usual method of using cast iron or cast steel. *American Machinist* reported that the Bonneville installations were "the first time that oxy-acetylene flame and metallic arc have ever been called upon, to such an extent, in the manufacture of hydraulic turbines."[45] The scale of the turbines at Bonneville, as measured in terms of size, river flow, and range of flow variation, demanded such innovation. In fact, almost every major detail of design and manufacturing had to be deliberately examined, often by Corps engineers first or by S. Morgan Smith Company engineers working with the Corps staff. Another example was the design of embedded parts (mostly steel) in the concrete regions within which the turbines were to be set. These needed to create space with extraordinarily low tolerances, sometimes less than 0.1 inch in a radius of over eleven feet. Such precision is highly unusual for large-scale reinforced concrete construction.[46] At its hydraulic laboratory in Linnton, the Corps also carried out experimental studies to guide the design of the shape and type of intake, scroll, and draft tubes for the Kaplan turbines.[47]

A further concern about the Kaplan turbines was the danger of cavitation, or erosion of the turbine by water that dislodges pieces of the material due to the high speed of the machines. The Corps studied cavitation through a series of specially commissioned tests at the Pennsylvania Water and Power Company's Holtwood laboratory. The Corps also used the Holtwood lab to check the S. Morgan Smith Company's results for efficiency and power, for which they showed "remarkable agreement." The cavitation results indicated a large factor of safety "whether considered in horsepower or in feet head."[48]

These innovative decisions, and the detailed tests at the Smith Company's flume, Holtwood laboratory, and the Corps' hydraulic laboratory at Linnton, had to occur more or less simultaneously while work on other aspects of the dam design and construction continued apace. A significant difficulty at Bonneville was that the turbine tests to determine greatest efficiency could not be completed and evaluated before the contractor had completed casting much of the concrete structure for the passageways. This concurrent design and construction work illustrates the necessary integration of engineering branches on such a project, and the fact that the key engineers had to be conversant in these various branches. In addition,

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[45] Curtis W. Law, "Giant Turbines for Bonneville," *American Machinist*, 24 February 1937, 175. See also George A. Jessop, "Welded Structures for Hydraulic Turbines," *The Welding Journal* 16 (1937): 2–6.

[46] Heslop and Jessop, 107.

[47] Stevens, *A Report on Model Studies* (n. 21 above), 7.

[48] Heslop and Jessop, 102; see also Davis, "Cavitation Testing" (n. 39 above), 455–62.

because of the constricted time schedule, the Corps had to carry out and oversee research on the new type and scale of turbine—all while concurrently initiating design and construction of the concrete mix, spillway dam, and fishways.

Fishways and Bonneville Dam

In addition to the spillway and concrete-mix designs and the necessary turbines for power production, the provision of an upstream passage system for Columbia River anadromous fish provided engineers with a formidable challenge and figured prominently in the design process. By the early 1930s, the salmon industry was of significant economic importance to the Pacific Northwest. Those with a vested economic interest in the industry exerted political pressure on local politicians to ensure that funding would be allocated toward the fishways during Bonneville's design and construction.[49]

The U.S. Army Corps of Engineers' studies in the late 1920s and early 1930s clearly recognized the need to provide fish passage over the planned Columbia River dams. In 1929, Colonel Lukesh wrote that "it appears that the provision should be made for the passage upstream of fish," and that "such provision may have an important effect upon the cost of the dam."[50] In the 308 Report, plans for the dam at Warrendale (later moved to Bonneville) included two fishways.[51]

Up until this time, the construction of fish-passage structures in conjunction with dams had been both sporadic and uncertain. A series of studies presented to the National Academy of Sciences in October 1927 on the effects of dams on the migration of salmon highlighted the lack of sophistication in the engineering profession's understanding of fishway design of the time. In his presentation to the academy, zoologist Henry Ward noted: "Such bypasses have been constructed in numerous instances and while in some cases they have worked with a certain degree of success, it is equally clear that in others they have failed to appeal to the fish."[52] In short, the Bonneville engineers tackled the fishway design problem at a time when there was no scientific consensus for good design.[53]

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[49] Mary E. Reed, *History of the North Pacific Division* (Portland, Ore., 1991), 56; U.S. Army Corps of Engineers, "Fish Protection at Bonneville Dam," 22 October 1935. See also "Letter from District Counsel to Commissioner of Indian Affairs," NA, RG 77/111, box 148, folder 6500.

[50] Reported in Willingham (n. 9 above), 47.

[51] Columbia River 308 Report (n. 9 above), 10, 1476, 1599.

[52] Henry Ward, "The Influence of a Power Dam in Modifying Conditions Affecting the Migration of the Salmon," *Proceedings of the National Academy of Sciences of the United States of America* 13 (1927): 829.

[53] On the development of fishway design, see Lisa Mighetto and Wesley Ebel, *Saving the Salmon: A History of the U.S. Army Corps of Engineers' Efforts to Protect Ana-*

The Corps of Engineers approached the fishway design as they did other design challenges, by consulting some of the most knowledgeable people in the field. The design of the upstream fish-passage systems at Bonneville constituted a multi-agency effort, involving staff from the Corps, the U.S. Bureau of Fisheries, the fish and game commissions of Oregon and Washington, regional fishing associations, Stanford University aquatic biologist Harlan Holmes, and hydraulic engineers Henry Blood and Milo Bell. Holmes described the nature of the fish-passage problem at Bonneville in 1935:

> The magnitude of the problem of fish protection at Bonneville, the size of the stream, the great fluctuation in river flow and consequent variation in water levels, the number and variety of fish that must be handled, the height to which they must ascend—made it necessary to diverge from standard fishway practice as it applied in smaller projects.[54]

A fundamental issue was the choice of fish ladders or fish locks to serve as the central element in the fish-passage system. The ladders planned at Bonneville would have to be higher (approximately seventy-five feet) than any existing ladders the planners were aware of, and they would have to function under widely fluctuating headwater and tailwater conditions; there was no previous experience to indicate the ladders' effectiveness under these conditions. Fish lifts (or locks) had been used in smaller rivers in the Midwest, and the Wisconsin Conservation Commission wrote to recommend them to the Bonneville designers. Reflecting the uncertainty in the engineering and fisheries communities and in keeping with a spirit of experimentation, the designers (led by Holmes and Bell) decided to install both, establishing the dam as a sort of laboratory for future fishways study. The Corps' experience at Bonneville showed fish ladders to be more effective than the fish locks, and the Corps later installed similar fishway systems at the three other lower Columbia dams and throughout the country, effectively standardizing the weir-type fish-ladder design of Bonneville.[55]

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dromous Fish on the Columbia and Snake Rivers (Seattle, 1994), 103. See also Robert T. Morris, "Mills and Fishways," *Science* 52 (1920): 365–66; Ward, 829; and C. H. Clay, *Design of Fishways and Other Fish Facilities* (Boca Raton, Fla., 1961), 12.

[54] Holmes is quoted in Mighetto and Ebel, 55. Other evidence of the Corps' early concern with fish passage includes a 1935 U.S. Army Corps of Engineers document on "Fish Protection at Bonneville Dam." Holmes also produced a "Progress Report on Bonneville Fishways Investigations," which he submitted on 31 October 1935 (NA, RG 77/111 Bonneville Dam, box 150, folder 7245, pts. 1–3).

[55] "Letter from Wisconsin Director of the Department of Fish Culture to members of the commission of Portland, Oregon, August 15, 1934," U.S. Army Engineers archives. Arguments advocating either fish ladders or fish locks can be found in the Corps' 1935 "Fish Protection at Bonneville Dam," and in this 1934 letter. The Corps also studied how to attract a large number of fish to the entrances of the fish ladders and locks, find-

At the ceremony marking Bonneville's completion, President Roosevelt offered this observation: "All I can hope is that the salmon will approve the [Bonneville fishways] and find them really useful even though they cost almost as much as the dam and the electric power development."[56] In the seven decades following Bonneville's construction, the effectiveness of upstream and downstream fish-passage systems at dams and the fate of the Columbia River's salmon populations have been the subject of heated debate. Indeed, Bonneville's fishways have acquired a maligned reputation. Regardless of the long-term outcome, however, it is important to acknowledge the methodical manner in which the Corps approached the fish problem, consistent with its approach to other challenges on the project.[57]

From Design to Construction

Timely production of the cement mix and the construction of the turbines, powerhouse, and spillway presented an array of problems to the construction engineers, who were charged with building the massive structure in the face of the Columbia's depth and high velocity and its annual spring flood. At Bonneville, the Columbia valley is wide and lacks steep rock walls, so the only practical procedure was to narrow the channel sufficiently to provide a dry area for construction, but not to completely divert the river.

The hydraulic conditions effectively shortened the working season to the seven months from August to March, exacerbating the already-rushed construction schedule. George Gerdes, the dam's chief engineer, designed the construction plan and devised the compressed construction schedule, using systems of timber cofferdams to dry half the river at a time. First, a U-shaped cofferdam (fig. 4) dried the south side of the river during the 1935–36 construction season, and contractors constructed the lower portion of the southern half of the spillway. During the next construction season (1936–37), the engineers allowed water to flow through the uncompleted south side to give them time to complete the entire north section.

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ing high-velocity attraction flow necessary to entice the salmon to leave the turbulent waters at the base of the spillway and enter the fish ladders. The use of attraction water and artificial guidance to attract fish to the entrance was one of several new design features.

[56] A. L. Riesch Owen includes Roosevelt's remarks in *Conservation under FDR* (New York, 1983), 27.

[57] The failure of the fishways and the symbolic importance of dams in the environmental movement, particularly in the Pacific Northwest, are an interesting story that is, however, outside the scope of this work. See, for example, Richard White's *The Organic Machine* (New York, 1995) and Joseph Cone's *A Common Fate: Endangered Salmon and the People of the Pacific Northwest* (New York, 1995); the National Resource Council Committee on Protection and Management of Pacific Northwest Anadromous Salmonids, Board on Environmental Studies and Toxicology, also published a relevant report titled *Upstream: Salmon and Society in the Pacific Northwest* (Washington, D.C., 1996).

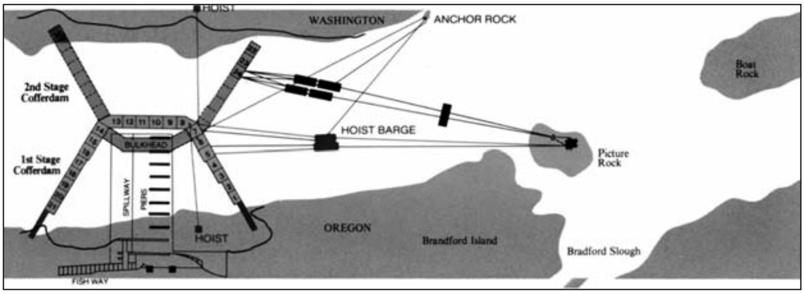

FIG. 4 Diagram of construction procedure. (Source: William Willingham, *Water Power in the "Wilderness": The History of Bonneville Lock and Dam* [Portland, 1997], 17. Reproduced courtesy of the U.S. Army Corps of Engineers.)

Finally, the Corps finished the south-side piers by placing portable timber caissons successively around each one to dry the work area.[58] This procedure allowed the construction to proceed at the rapid pace demanded politically and in tempo with the other design and construction work at the spillway dam, navigation lock, and powerhouse. This technique would later be used on each of the other lower Columbia and lower Snake River dams.

Power Production and the Bonneville Power Administration

Throughout the design and construction process, the question of who would gain control of marketing the power produced at Bonneville and Grand Coulee dams, and how, was a subject of contentious political debate. The issue was complicated because unlike the Tennessee Valley, where one government agency controlled the entire basin, the Bureau of Reclamation and the Corps together had jurisdiction over the Columbia River, and both agencies negotiated to retain its control. A number of prominent New Deal politicians, including Roosevelt, advocated creating a Columbia Valley Authority after the Tennessee model.[59]

Responding to political backlash against a new TVA, though, Senator

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[58] For summaries of the construction procedure, see Willingham (n. 9 above), 16, and Stevens, *A Report on Model Studies* (n. 21 above), 675. On the engineering and political challenges of construction at the Bonneville Dam site, see Willingham, 16, and "Three Big Dam Operations Begun in the Pacific Northwest," *Engineering News-Record*, 5 April 1934, 444–45.

[59] A variety of sources exist: Roy Bessey, "Resource Conservation and Development Problems and Solutions in the Columbia Basin," *Journal of Politics* 13 (1951): 418–40; Willingham, 41–43; Reed (n. 49 above), 60–66; and William E. Leuchtenburg, "Roosevelt, Norris, and 'Seven Little TVAs,'" *Journal of Politics* 14 (1952): 418–41. Leuchtenburg's essay discusses various efforts to form additional TVAs, and the significance of Roosevelt's decision not to support these efforts.

Charles McNary and President Roosevelt pushed the Bonneville Power Act through Congress in August 1937. This act allowed the Corps to continue the operation of the Bonneville facility but created a new agency, the Bonneville Power Administration, to transmit and sell the power. With the Bonneville powerhouse completed, the Bonneville Power Administration quickly became the chief power provider in the Pacific Northwest, and inexpensive power helped to transform the region.[60]

Conclusions

During the first seventy years of the twentieth century, the U.S. government built a large number of huge multipurpose concrete dams, typically either high dams with water storage for power, flood control, and irrigation, or low, run-of-the-river dams for power and navigation. Bonneville is characteristic of the second group because it consists of a navigation lock, a spillway dam, and a power plant. Among these large-scale, civil, public works projects, however, Bonneville is distinguished by its technological innovations, which resulted from fresh thinking related to all significant components of the project: the material for the concrete dam, the turbines for the powerhouse, and the shape and energy-dissipation mechanisms of the spillway, particularly the downstream apron and baffles. Even more important, it was the Corps' approach to the planning and design of the dam's structures, machines, materials, and processes that fostered these innovations. This approach, characterized by the Corps' careful use of the studies of best practice conducted for the earlier 308 Report, its judicious choice of consultants, and the manner in which it compartmentalized design decisions, allowed experts in each engineering discipline to find the best possible solution to a particular design problem, while still keeping the various aspects of the project integrated and timely.

The Bonneville project can be best understood as an integration of the four major branches of engineering: structures, machines, networks, and processes—each typical of engineering as a whole, but each governed by different principles. The spillway dam is a typical structure, an object that is static, custom-made, and permanent. The turbines are typical machines: they are dynamic, produced in quantity, and replaceable. Bonneville also required the distribution of power for a network and a new process for making the portland-pozzolan cement, which transmuted natural resources into a product quite different from the initial materials.

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[60] The legacy of the Bonneville Power Administration on the economic development of the Pacific Northwest and U.S. defense efforts in World War II has been well-documented elsewhere. See, for example, Reed, 101–4; Charles McKinley, *Uncle Sam in the Pacific Northwest: Federal Management of Natural Resources in the Columbia River Valley* (Berkeley, Calif., 1952), 173–75; and Willingham, 43.

Crucially, each of the design innovations at Bonneville was derived separately and without reference to the others. They had to be integrated into one project, but the choice of cement had no influence on the spillway shape and energy-dissipation studies or on the concrete design for the powerhouse. Similarly, the design of the turbines and their necessary concrete passageways had no influence on the material and shape of the spillway dam. The task of the Corps civil engineers was to keep the various parts on time, sufficiently coordinated, and reasonably within budget so that the project would be completed quickly and perform successfully afterward.

Two civilian engineers led the design process for the Army Corps of Engineers: Claude Grimm and George Gerdes. Grimm and Gerdes had a civilian staff and the benefit of a small group of nationally prominent consulting engineers who played a key role in significant engineering decisions. The Corps' officers played a central role in organizing the project, managing their civilian engineers, and integrating disparate aspects of the design process. This engineering process differed from that which the Corps used at Wilson Dam, where the design and construction supervision was under the direction of a private, civilian consulting engineer, Hugh Cooper.[61]

The Corps requested bids from private contractors for nearly all parts of the construction, most significantly for the supply of portland-pozzolan cement, for the construction of the spillway dam, and for the manufacturing and installation of the Kaplan turbines. It worked closely with the contractor and the consultant for the manufacture and supply of the portland-pozzolan cement, as well as the researchers who engineered the cement. For the spillway dam, the Corps and its civilian engineers worked out the concept for construction, but the actual details of the building were left to the contractor. The Corps, its consultants, and the turbine manufacturer together developed testing procedures and designed the concrete passageways essential for efficient turbine performance. Overall, this process was entirely different from that used by the TVA, which did not normally hire private contractors, but it was similar to the operation of the Bureau of Reclamation, which also had a large civilian engineering staff and had built its own major laboratories. The Corps was also unique in its creation of the integrated 308 Reports on large-scale river basins, and it demonstrated a remarkable sophistication in engineering planning and analysis in implementing the planned designs. Although the direction to conduct the reports came from Congress, the Corps took a holistic, innovative approach to the reports; moreover, these reports provided essential forethought, which led to major projects such as Bonneville and created the framework through which innovative solutions could be planned and designed. With Bonneville Dam, the U.S. Army Corps of Engineers for the first time brought together several engineering branches, each with its own techno-

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[61] See note 3 above.

logical characteristics, to create a concrete multipurpose dam that successfully challenged standard practice in its leading engineering features. As a full-scale laboratory for new technologies, it served as an exemplar for future works; future environmental critiques could not have been foreseen by designers immersed in the era of the Great Depression and the New Deal.

The history of modern technology has tended to focus on advances in mechanical and electrical engineering in which electricity, electronics, cars, and airplanes play a prominent role. As a discipline, civil engineering developed somewhat separately from the systems of production that generally fueled innovation in other fields of engineering. For this reason, the historiography of engineering innovation in the twentieth century tends to be associated with the overarching themes of mechanization and network, to the near exclusion of structures. Yet the Corps' success in the development of innovative design technologies at Bonneville Dam illustrates the central role of civil engineers as knowledge-producers in the process of planning, designing, and building major public works. Bonneville Dam and the other dams of its period are prototypical examples of structures that were designed and constructed under the supervision of civil engineers. New York's George Washington Bridge represents another prototype structure of the same era—also designed and constructed by civil engineers.[62] The principal consultants to the Corps in its three major innovations at Bonneville (Raymond Davis for materials; Leroy Harza and John Hogan for the hydraulics and turbines; and, for the spillway studies, J. C. Stevens) were all civil engineers. These men were not engineers of mechanization like Henry Ford, nor were they network builders like Thomas Edison. Yet their innovative contributions were critical to building public work projects and thus to creating the physical infrastructure that supports our modern society.

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[62] Jameson W. Doig and David P. Billington, "Ammann's First Bridge: A Study in Engineering, Politics, and Entrepreneurial Behavior," *Technology and Culture* 35 (1994): 537–70.