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COVER: "A Broken Belt—All Hands Idle—Moral: Buy the Best Belt." From *Asher & Adams' Pictorial Album of American Industry* (New York: Rutledge Books, 1876, reprinted in 1976), p. 172. See William Worthington, Jr., "Belting Archeology," pp. 63-64.

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A Narrow Window of Opportunity: The Rise and Fall of the Fixed Steel Dam

Terry S. Reynolds

Between 1890 and 1910 a few dam designers seriously considered steel as an alternative to such traditional dam-building materials as masonry, earth, rock, and concrete. Three fixed steel dams were constructed; two still survive. Using evidence from the two surviving structures, especially the steel dam at Redridge, Michigan, as well as written records, this article challenges previous explanations for the demise of the steel dam and suggests that the neglect of steel construction is better explained by perception and personal factors than by objective, scientific factors.

"Steel dams? Dams are made of earth, or rock, or masonry, or concrete—not steel!" Such is the typical reaction to the mention of steel dams. Yet two fixed steel dams stand in the United States: one in the northern Arizona desert, the other near Lake Superior on Michigan's sparsely populated Upper Peninsula. Moreover, even though they are now largely forgotten,[1] the fixed steel dam once attracted considerable attention as a viable alternative to conventional dam forms (see figure 1). Using both written records and a surviving steel dam in Michigan, this article seeks to answer two questions: Why did steel attract attention as a dam-building material between 1890 and 1910? And why did interest in steel dams cease?

The Steel Dam, 1890-1910

At the turn of the century, a handful of civil engineers argued that steel had numerous advantages over more conventional dam-building materials. They believed that the joints between steel plates could be made, as in boilers, almost perfectly watertight—more watertight than masonry, earth, or concrete embankments. Dams made of steel, they argued, could be built for less than comparable structures, with a price advantage that increased with the dam's height. Calculations could be made more accurately for steel structures than for concrete, earth-fill, masonry, or rock-fill structures, and the uniformity and quality of materials were much more certain because steel was fabricated under shop conditions. Finally, steel dams offered easier accessibility for inspection, maintenance, and repairs, faster construction,

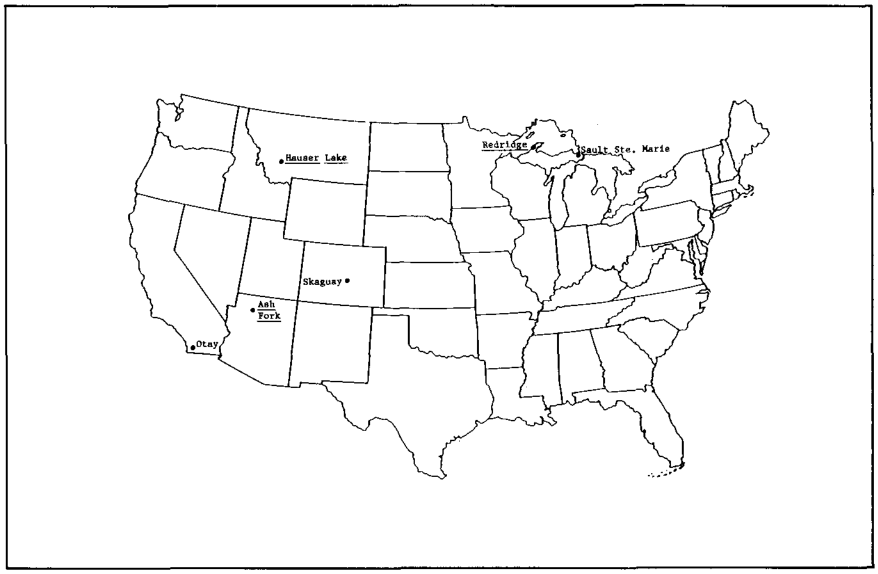

Figure 1. *Location of fixed steel dams (underlined) and other early U.S. dams with substantial steel component (1890-1910).*

and (compared to concrete) greater ability to handle thermal expansion and contraction and uneven settling.[2]

These arguments were generally valid and made steel a realistic contender as a dam-building material. In 1893, for instance, the commission reviewing the Quaker Bridge dam in the New York water-supply system considered a steel dam, noting that it could be both economical and safe.[3] That same year F. H. Bainbridge, of the Chicago & North Western railroad, made estimates on constructing steel dams, concluding that they were economically feasible. In 1894 Bainbridge went further and prepared preliminary plans and estimates for a 210-foot-tall steel dam across the Santa Ana River in California.[4] The dam was never built, but Bainbridge patented his design in 1895.[5]

In 1897 Henry Goldmark, future designer of the ship canal locks for Panama and New Orleans, then at the beginning of a distinguished career as a consulting engineer,[6] studied the use of a steel superstructure for a dam near Ogden, Utah. Goldmark published several designs for structural steel dams, which "attracted considerable attention," even though they were not adopted.[7]

In 1897 the Santa Fe Railroad built the first American fixed steel dam near Ash Fork, in the arid northern Arizona desert. To secure a reliable water supply for its steam-powered locomotives, the Santa Fe began constructing a system of dams and storage reservoirs there in 1894. The first three dams were conventional masonry structures. In 1897, however, Bainbridge proposed steel. His proposal was accepted—probably because the site of the fourth Ash Fork dam was not easily accessible. Steel beams and plates could be moved there easier than building stone.[8]

Bainbridge designed the Ash Fork steel dam in collaboration with James Dun, the Santa Fe's chief engineer. They used conventional masonry construction for the shallow wings of the 300-foot-long overflow structure. But they installed steel plate for the deeper 184-foot-long central section. Twenty-four triangular bents, or frames, made from I-beams and spaced on eight-foot centers, supported ⅜-inch thick steel plates at a 45° angle. The plates were curved to permit expansion and contraction without affecting the joints between plates and bents and were riveted to the bents with their concave portions facing upstream. Because of very hard igneous rock at the site, Bainbridge and Dun anchored the steel bents and the toe of the dam directly to bedrock, although some concrete was used as a sealant.[9] In brief, the Ash Fork dam was a buttress dam with an inclined upstream face, similar in form to some dams built using wood frames earlier in the 19th century.[10] Santa Fe crews began work at Ash Fork in October 1897; they completed the dam in March 1898. (see figure 2).

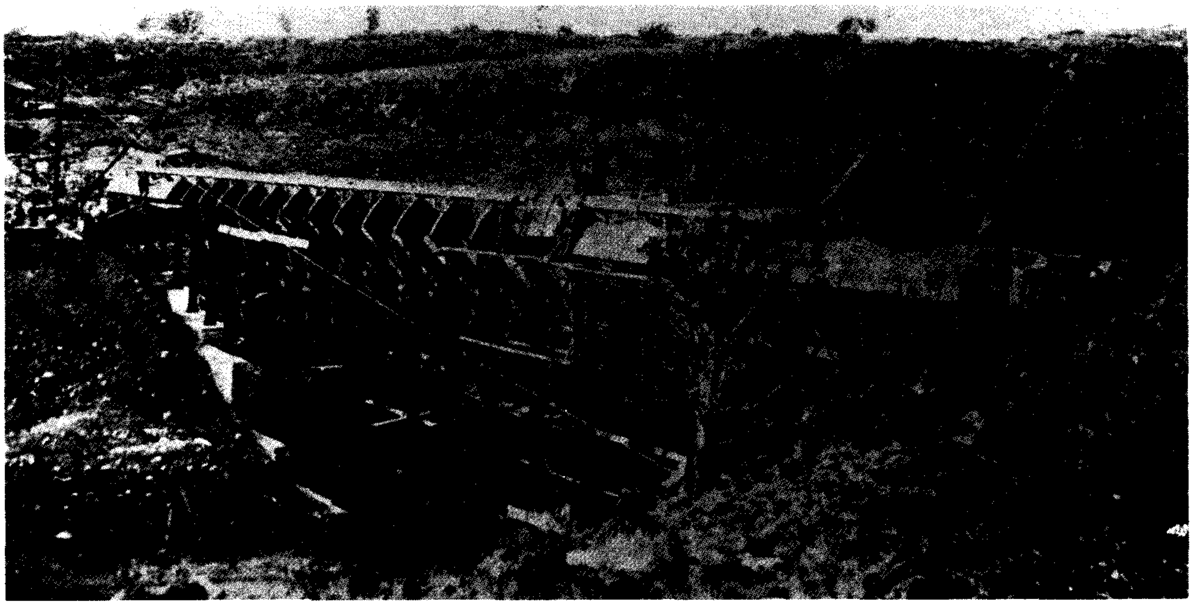

Figure 2. *Downstream view of the Ash Fork, Arizona, steel dam during closing phases of construction, 1898. Note the steel bents used to support the curved steel plates facing upstream.* From *Engineering Record* 37 (April 9, 1898): 507.

The second fixed steel dam appeared shortly after in a completely different climatic zone—at Redridge on Lake Superior in the copper-mining region of Michigan's Upper Peninsula. In 1894 the Atlantic Mining Company built a stamp mill where the small Salmon Trout River flows into Lake Superior. The lakeside location gave the company an unlimited dump for its stamp sand, while the nearby river offered a gravity-fed water supply for stamping operations. To develop this supply Atlantic erected a timber crib dam across the Salmon Trout. In 1901 the Baltic Mining Company, another copper company and one whose board of directors interlocked with Atlantic's board, built a stamp mill on the opposite side of the river. Since the timber dam provided insufficient water for both mills and needed repair, the two companies agreed to jointly construct a new and larger dam (see figure 3).[11]

The Redridge site posed several problems. First, the immediate area had insufficient conventional dam-building materials. It had no good building stone for a masonry dam and too little topsoil for an earth-fill dam. Second, swift construction was essential. The rapid expansion of the electrical industry had driven up copper prices, so neither company wished to suspend stamping operations for long. Moreover, the severe climate of the region shortened the building season, making the slow pace of construction of conventional dams troublesome. These problems prepared the mining companies to consider the unconventional. In 1899 or 1900 J. F. Jackson, the Wisconsin Bridge and Iron Company's engineer in the region, proposed a steel dam as a solution to these problems. Wisconsin Bridge and Iron had supplied the steel for the Ash Fork steel dam, and Jackson had been responsible for its erection.[12] The companies accepted.

The Redridge steel dam is 1,006 feet long, including concrete-core, earthen embankments on both wings. The central steel section is 464 feet long and 74 feet high at its deepest point. In appearance it is similar to Ash Fork: bents of steel I-beams on eight-foot centers support an inclined layer of ⅜-inch curved steel plates. Redridge differs, however, in several respects. First, Redridge is not a structural dam. At Ash Fork inclined bents carry the lateral thrust of the impounded water directly to bedrock. The weight of the

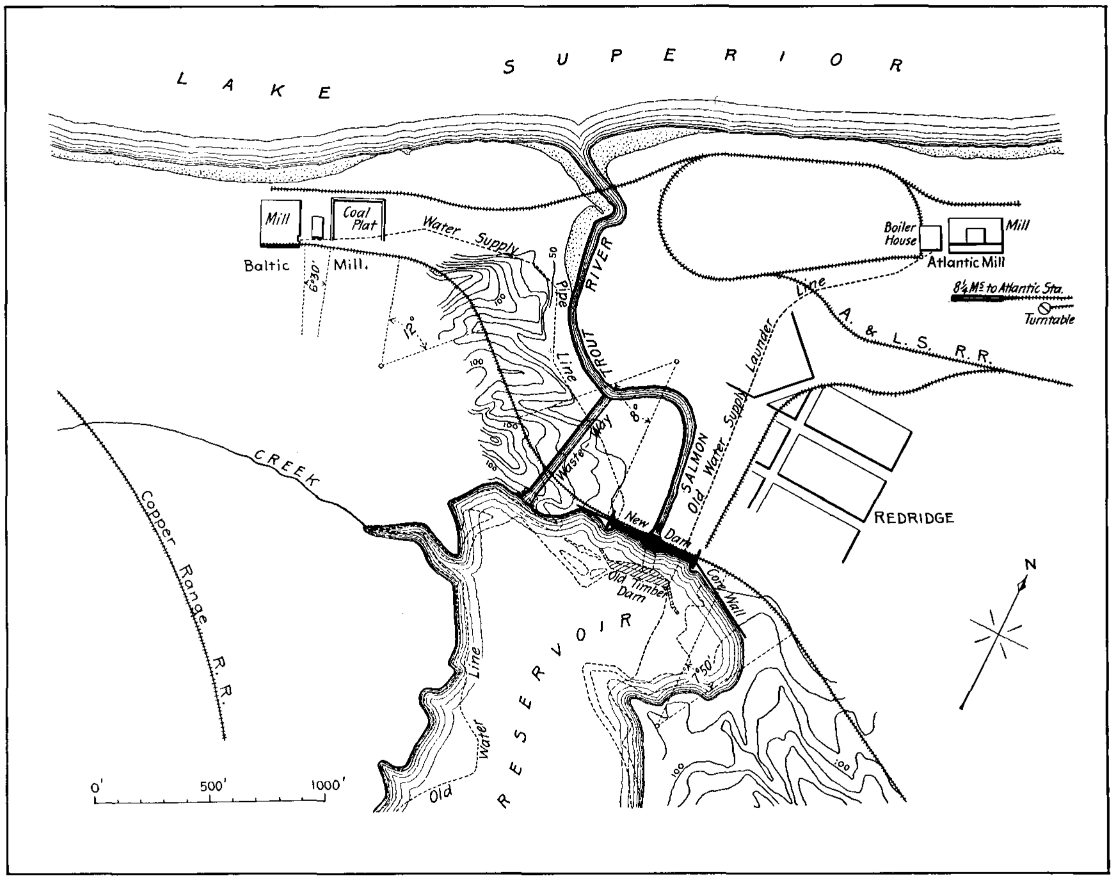

Figure 3. *Site plan of the steel dam at Redridge, Michigan, 1901.* From *Engineering News* 46 (August 15, 1901): plate following p. 101.

impounded water, not that of the dam, provides the resistance to uplift and lateral thrust. This approach could not be used at Redridge—the bedrock there was weak sandstone. Thus Jackson had to build a reliable foundation for his steel superstructure. He took advantage of sand from the nearby stamping operations and rock aggregate from mining to erect a large concrete base (8,000 cubic yards). This base, not the arrangement of steelwork and impounded water (as at Ash Fork), provides the force needed to resist uplift and sliding.

The use of the large concrete base sacrificed some of the vaunted economy of steel dams, but Jackson regained part of that cost. The water face on the Ash Fork dam was inclined 45°, so that the weight of the water on the plates could substantially contribute to the dam's resistance to sliding. The heavy concrete base performed this function at Redridge, so Jackson placed the steel plates closer to the vertical—around 55°. Less steel plate was required at that angle. In addition, the heavy concrete base gave the Baltic Mining Company a ready-made foundation for its trestle across the Salmon Trout River. The company placed the trestle's supports on the dam's base amid, but not connected to, the steelwork of the dam (see figure 4).

Another difference between the two dams lies in their water discharge systems. Bainbridge designed Ash Fork as a weir, or overflow, dam. Jackson and Foster Crowell, his consultant on hydraulic matters, designed the Redridge dam otherwise. Excess water at Redridge flowed out either through four large valve-controlled pipes in the concrete base of the dam or through a large waste-channel at the west end of the structure.[13]

Crews began construction at Redridge in May 1900 and completed it in November 1901.[14] The finished structure created a lake of 150 acres, submerging the old timber crib dam under 20 feet of water (see figure 5).

The completion of Ash Fork and Redridge stimulated further interest in the use of steel. In 1903 Charles Steiner, an engineer in the U.S. Reclamation Service, described a steel dam "under consideration" by the office of the Chief of the Hydrographic Bureau of the U.S. Geological Survey "in connection with the extensive construction of future storage reservoirs for irrigation." Steiner estimated that steel dams could be built for half the cost of masonry dams. His description, published in *Engineering News,* prompted a number of letters to that journal on steel dams.[15]

Shortly after, Jackson, the engineer who had erected the steelwork at Ash Fork and designed the steel gravity dam at Redridge, persuaded the Helena Power and Transmission Company to erect a steel dam on the Missouri River, 16 miles from Helena, Montana, to provide hydroelectric power to nearby copper mines, smelters, and urban areas.

The Hauser Lake dam was the third American fixed steel dam. It resembled the earlier ones in general design: steel bents carried an inclined face of curved steel plates. But there were important differences, especially in the foundations. At Ash Fork the steelwork rested directly on bedrock; at Redridge it rested on a large block of concrete, which, in turn, rested on bedrock. At Hauser Lake, however, the steelwork rested on longitudinal footings placed in a bed of water-bearing gravel, because bedrock, which lay 40 to 60 feet deeper, would have been difficult to reach. The leading, or lower, edge of the steel plates rested on a triangular concrete footing, or toe, which also extended the length of the dam. To prevent water from undermining the footings, Jackson used steel sheet piling. This piling, driven down 35 to 40 feet, extended the length of the dam and was anchored to the toe (see figure 6).

To provide increased stability for a structural dam not anchored in bedrock, Jackson gave the Hauser Lake dam a low angle of inclination—around 35° from horizontal, versus around 45° at Ash Fork and 55° at Redridge. This permitted him to use more of the weight of the water for stability against sliding.

Begun in 1905 and completed in March 1907, the Hauser Lake steel dam was around 670 feet long by 81 feet high. It was an overflow structure, for Jackson provided a spillway 500 feet long and 13 feet deep at the center of its 630-foot-long steel section. When placed in operation the Hauser Lake steel dam was both longer and higher than its sister dams at Ash Fork and Redridge (see table 1 and figure 7).[16]

The contemporary use of steel in association with other dam-building materials provides further evidence of widespread interest in steel as a dam-construction material between 1890 and 1910. For example, the Lower Otay dam in California, completed in 1898, used a vertical steel plate curtain in the center of a rock-fill embankment to prevent seepage.[17] The Skaguay dam in Colorado, built between 1901 and 1903, used steel plates to face a rock-fill dam.[18] And the combination hydroelectric dam and powerhouse erected between 1898 and 1902 at Sault Ste. Marie, Michigan, used curved steel plates anchored to reinforced concrete turbine chamber walls to restrain a 20-foot head of water.[19]

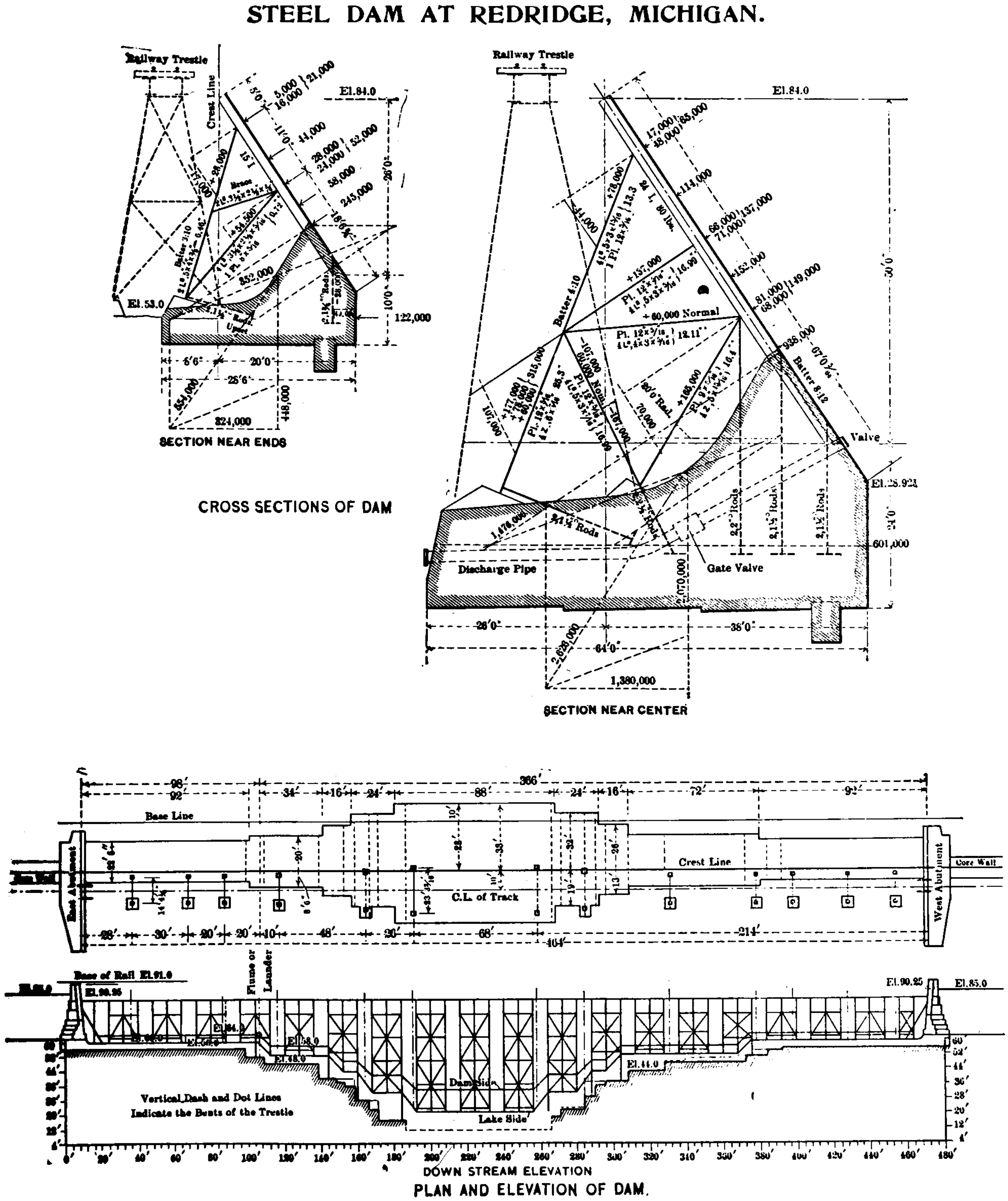

Figure 4. *Section, plan, and elevation of the Redridge, Michigan, steel dam. Note on upper right sectional view the outline of the railroad trestle which used the same foundation as the dam. Note also the size of the dam's concrete foundation.* From *Engineering News* 46 (August 15, 1901): plate following p. 101.

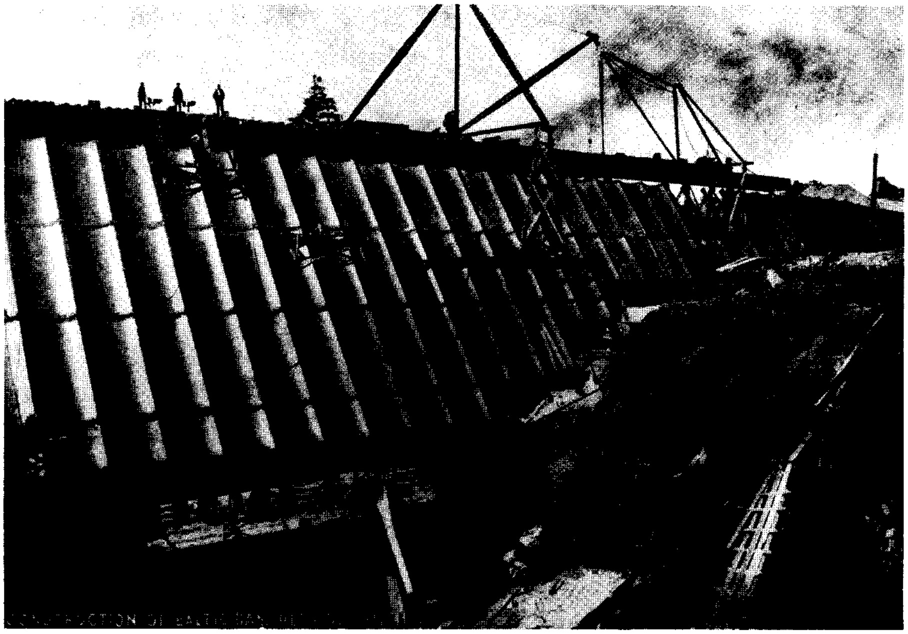

Figure 5. *View of upstream, or water face, of the Redridge steel dam as it neared completion in 1901. Figures in upper left background are standing on the railroad trestle which was placed on the same foundation as the dam but was not linked directly to the dam. The three pipes on the lower left were part of the dam's wastewater system.* From *Proceedings of the Lake Superior Mining Institute* 7 (1901): frontispiece.

Steel thus attracted widespread interest as a dam-construction material near the turn of the century. By 1910, however, this interest had vanished.

What Happened to the Fixed Steel Dam?

Why was this? The abrupt termination of interest in steel dams shortly before 1910 seems paradoxical in light of the numerous advantages that steel dams seemed to have over comparable concrete, masonry, rock-fill, and earth-fill structures. If steel dams enjoyed notable technical and economic advantages, and if three were actually constructed, demonstrating their feasibility, what happened? Why did steel dams abruptly enter a long period of near-total neglect around 1910?

In the limited published literature that discusses steel dams, five explanations, offered singly or in combination, commonly have been given for the demise of the fixed steel dam: higher maintenance expenses, leakage problems, the failure of the Hauser Lake dam, impermanence (especially due to corrosion), and "force of habit," or, in the jargon of historians of technology, the "technological momentum" enjoyed by more traditional forms of dam construction. I will review these explanations individually to determine whether artifactual and documentary evidence support them, and suggest other possible contributing factors.

Higher Maintenance

Creager's classic *Engineering for Dams* (1945) and Golze's more recent *Handbook of Dam Engineering* (1977) suggest that steel dams require greater and more constant maintenance than those made of other materials and that this was a factor in their disappearance.[20] But this explanation has problems. Reports published in 1916, in the 1930s, and in the 1950s on the Ash Fork dam indicate that maintenance costs were minimal. Ash Fork was painted only every seven to nine years and required little additional care.[21] Redridge was even less regularly maintained. When Jackson visited the site in 1930, he reported that it had been repainted only once—in 1913. Nonetheless, he noted: ". . .a hundred dollars or so would put everything, both steel and concrete, in perfect condition."[22] In 1935 A. L. Engels, Superintendent of the Copper Range Company (then owner of the dam), reported that Redridge had little rust even though it had last been painted in 1913. "To my knowledge," he added, "no repairs or replacements have been made to any of its steel work. . . .Its maintenance cost has been negligible."[23] A 1986 interview I conducted with Ray Franz, a former official with the Copper Range Company, revealed similar informa-

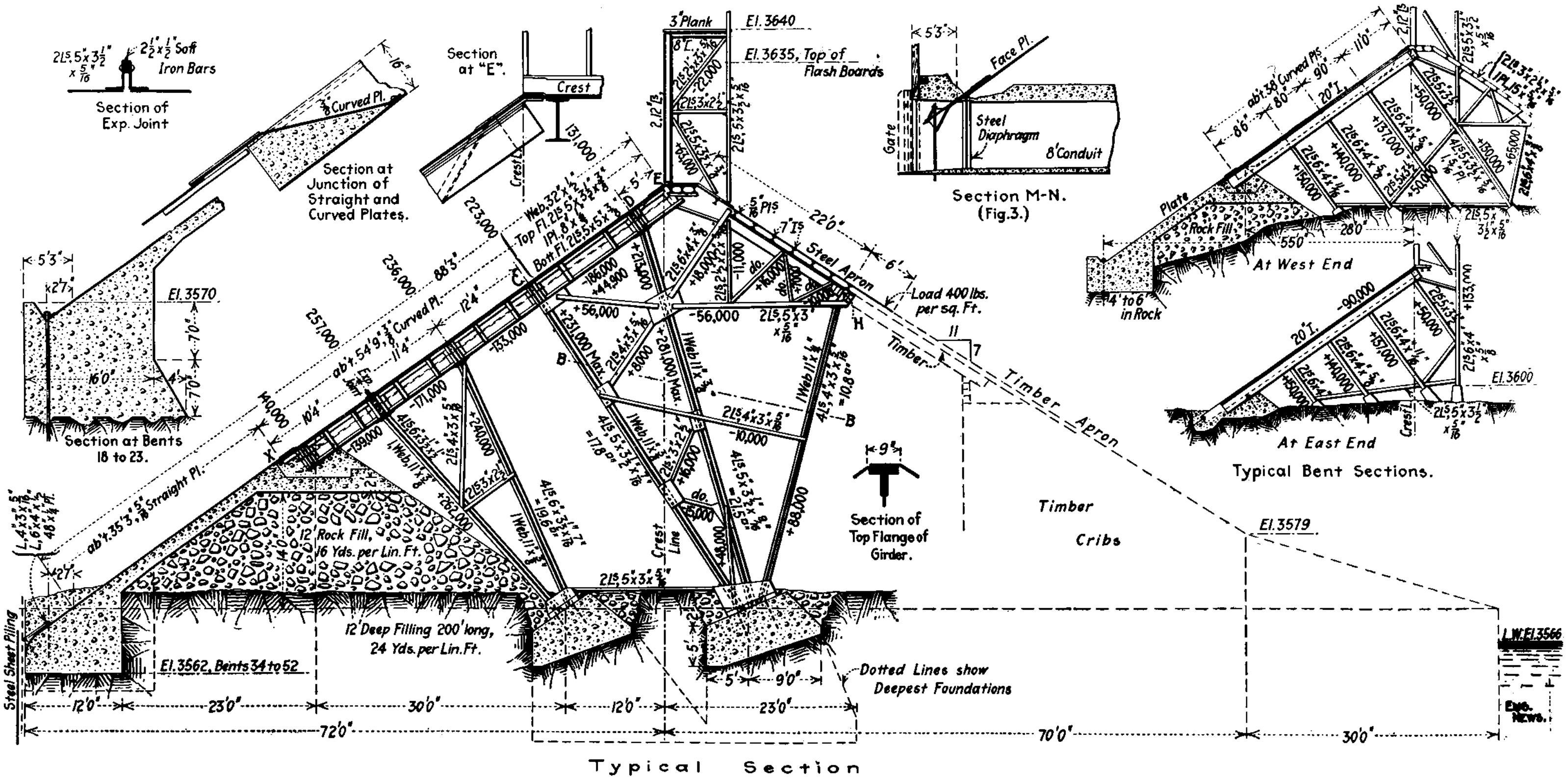

Figure 6. *Cross-section of the Hauser Lake, Montana, steel dam, 1907. The footings on which the steel bents rested were embedded in water-bearing gravel since bedrock was 40 to 60 feet deep at the dam site. The steel sheet piling driven in front of the dam (far left) was intended to prevent water from seeping under the dam and undermining the footings and hence the steelwork.* From *Engineering News* 58 (November 14, 1907): 508.

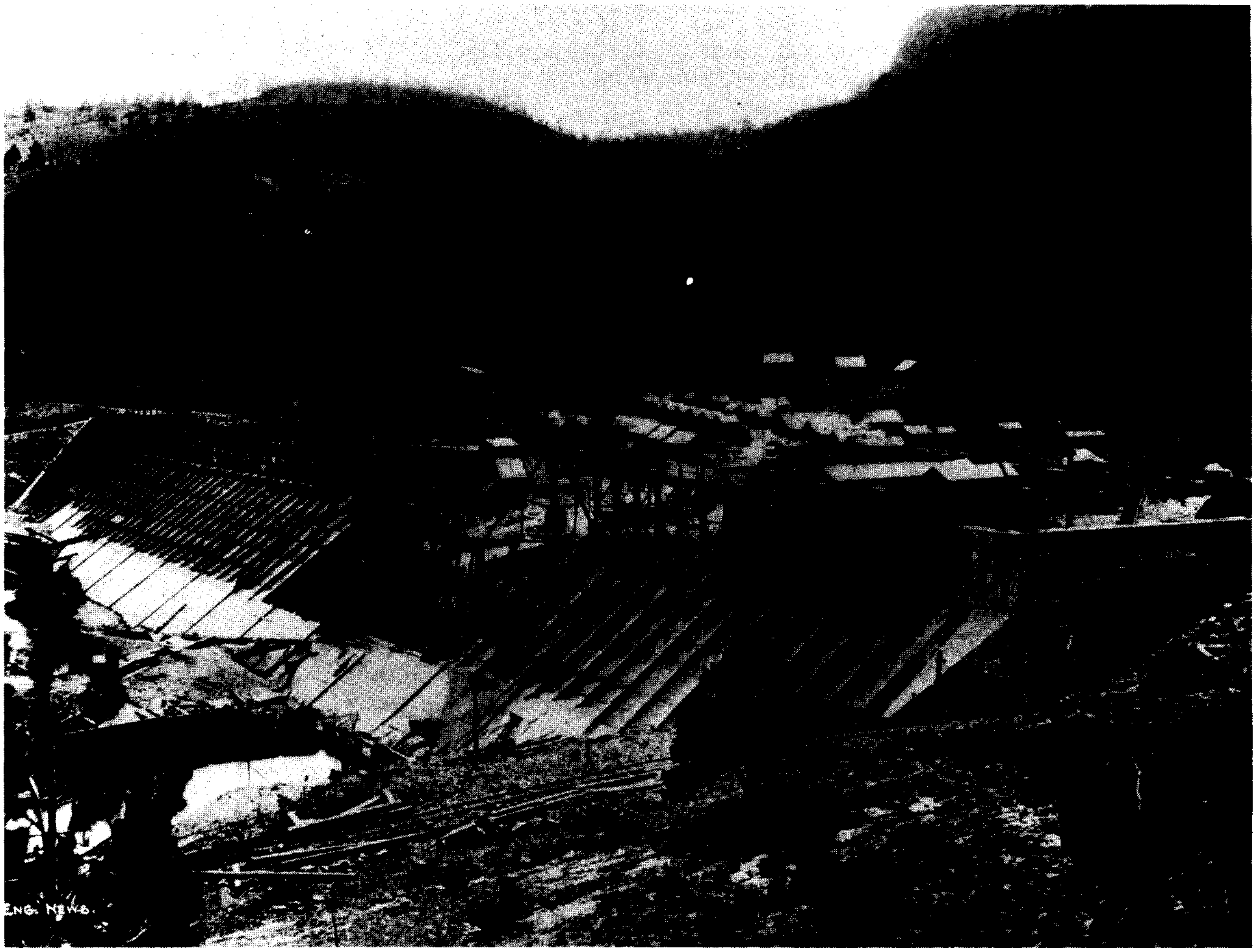

Figure 7. *The Hauser Lake dam under construction, 1907. View from upstream, or water face.* From *Engineering News* 58 (November 14, 1907): 507.

Table 1
Comparison of the Three American Fixed Steel Dams

Dam	Total Length	Length (steel portion)	Maximum Height (steel portion)	Angle (from horizontal)	Storage Capacity (millions of gallons)
Ash Fork (1897-98)	300 ft.	184 ft.	46 ft.	45°	36
Redridge (1900-01)	1,006 ft.	464 ft.	74 ft.	55°	600
Hauser Lake (1905-07)	670(?) ft.	630 ft.	81 ft.	35°	?

tion—the steel portion of the dam had never posed serious maintenance problems.[24] An interview with Bill Brinkman, a longtime resident of the community that adjoins the dam, confirmed this: the dam had been painted, at best, only every 20 years or so.[25] Clearly, maintenance costs were not a serious factor in the demise of the steel dam.

Leakage Problems

As early as 1901 James Dix Schuyler, a prominent turn-of-the-century dam engineer, noted that the Ash Fork experiment was not likely to be repeated because: "It has been found difficult, and in fact impossible, to make a tight joint between the steel and masonry work."[26] In 1905 Lyman Cooley, a prominent Chicago consulting engineer and a prolific writer on waterways, cited the "extraordinary care" required in the junction of the steelwork of steel dams with the bottom and sides of the dam site as a key reason for opposing steel dams.[27] Schuyler and Cooley were supported by others in viewing leakage as the Achilles' heel of the steel dam. H. M. Hadley, a regional representative of the Portland Cement Association, asserted in 1933 that one of the principal problems with steel dams, and presumably one of the principal reasons for their demise, was the difficulty of linking, without leakage, the steel superstructure to the substructure (concrete or bedrock).[28]

The surviving artifacts, however, undermine this explanation as well. On the two surviving steel structures, leakage between the steelwork and the foundation materials—bedrock at Ash Fork, concrete at Redridge—does not appear to have been a serious or insoluble problem. Bainbridge, the engineer who designed the Ash Fork dam, admitted some early problems with leakage at the base, but noted that a coat of asphalt placed in 1900 on the concrete used to seal the footing had completely eliminated it.[29] His testimony has been subsequently supported by other observers.[30]

At Redridge, leakage between the concrete foundation and steel superstructure was *never* a problem. In 1903 Jackson was specifically asked about leakage at that junction and reported no problems. The only leakage in the entire dam was minor seepage through disintegrated sandstone beneath the concrete foundations, with no relationship to the questionable joints.[31] Later, in 1930, Jackson reported that the steel portion of the dam was "tight as a bottle."[32]

Personal inspection confirms Jackson's statements. If water had leaked between the steelwork and the concrete foundation at Redridge, evidence would still be visible in the form of rust stains on the concrete. Close personal inspection of the dam in the fall of 1987 and the spring of 1988 revealed no evidence of such stains. The only indication of leakage, past or present, was some slight seepage through the concrete base itself, not at the joint between steel and concrete. Interviews with a former Copper Range Company official and a long-term Redridge resident provided further confirmation. Neither was aware of any problem with leakage at the dam.[33] Leakage, like maintenance expenses, was not a key factor in the steel dam's disappearance.

The Hauser Lake Dam Failure

In 1908, after a year's service, the steel dam at Hauser Lake failed. Published accounts suggest that the key problem was the dam's unusual foundation, not its steelwork. As noted previously, the Hauser Lake dam, unlike those at Ash Fork and Redridge, was built on water-bearing gravel instead of bedrock. It used sheet piling to prevent water from undermining the concrete footings that supported the steelwork. Water, however, apparently seeped under the sheet piling or, according to others, seeped between the steel piling and the concrete footing at the toe of the dam, and washed the gravel from beneath the footings. This caused the central portion of the dam to collapse (see figure 8), with damages estimated at $250,000 to $300,000.[34] The dam was replaced between 1909 and 1911 with a more conventional concrete gravity structure.[35]

No fixed steel dam was built after the Hauser Lake disaster. This coincidence has provided several authors with a seemingly open-and-shut explanation for the disappearance of steel dams. For example, Jackson, the engineer involved in the construction of all three fixed steel dams, accepted this explanation. He noted in 1930 that after Hauser Lake "there seems to have been little if anything said or published in reference to this very special type of dam. . . ," implying a cause-and-effect relationship.[36] Similarly, C. E. Grunsky in 1910 and H. M. Hadley in 1933 cited Hauser Lake, and the problem of sealing between steel skin and concrete foundations, as critical reasons for abandoning steel dams.[37]

Yet the failure of Hauser Lake is not a sufficient, or even a good, explanation. In 1903 Nils F. Ambursen introduced a reinforced-concrete flat slab dam. Several of these dams failed, one in 1909 near Pittsfield, Massachusetts, for example.[38] This attracted as much attention as the Hauser Lake failure. But hundreds of Ambursen flat slab dams were built *after* the failure of the Pittsfield dam.[39] Similarly, a multiple-arch dam collapsed in northern Italy in December 1923.[40] While the failure had an impact, the construction of multiple-

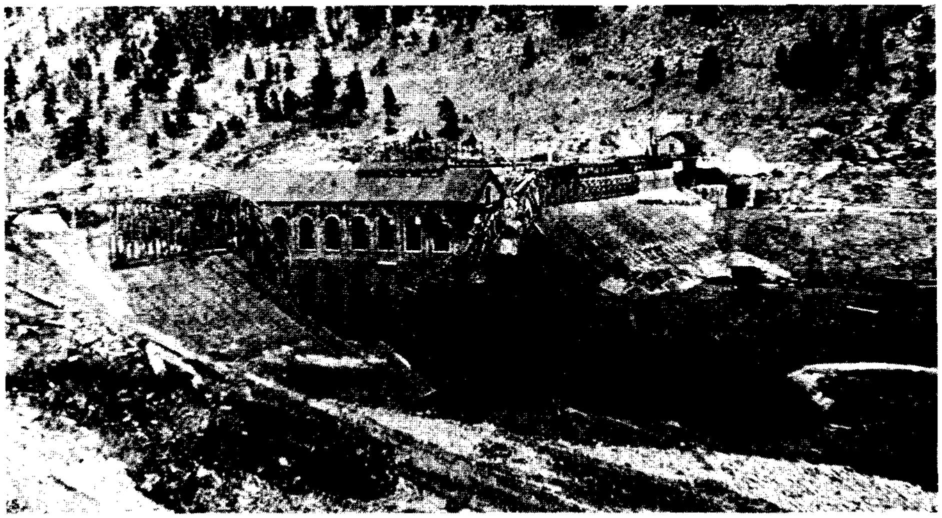

Figure 8. *The Hauser Lake dam after April 1908 failure.* From *Engineering News* 59 (April 30, 1908): 491.

arch dams did not come to an abrupt halt following it.[41] Finally, literally dozens upon dozens of masonry dams and earth- and rock-fill dams have failed, some doing far more damage than the Hauser Lake catastrophe. But these dam types continued to be built.[42] A single dam failure, in and of itself, cannot explain why steel dams have been neglected.

Impermanence

Probably the most frequently cited explanation for the demise of steel dams, and the one that likely comes to mind to *IA* readers, is impermanence. For example, *Engineering News* in 1916 noted that one "pronounced objection" to the steel dam was the great possibility of corrosion: "It seemed probable that the constant wetting to which the dam is subjected would hasten its rusting and early failure."[43] In 1932 C. M. Stanley, attempting to analyze why steel dams had not been more frequently used, noted that "the question of the permanence of steel dams has in all probability been one of the principal objections to the adoption of such construction."[44] And Hovey in a treatise on steel dams in 1937 cited "lack of confidence in its durability" as the "principal reason" for the death of the steel dam.[45]

Were steel dams impermanent? Did they seriously suffer from corrosion? The artifacts suggest that the answer is no. Consider Ash Fork: As early as 1916 a report on Ash Fork indicated that corrosion had *not* been a problem on the then-18-year-old structure.[46] Additional reports published in the 1930s and 1950s found that corrosion remained negligible. Moreover, the 1950s report pointed out that there was *less* deterioration in the steel portion of the dam than in its adjacent masonry abutments.[47] When T. Lindsay Baker inspected Ash Fork in the early 1970s he reported it in a "very good state of preservation." The upstream face had a coat of rust, but the dam's air face was "so well preserved that the date 1897 can still be clearly read on some of the curved steel sheets that form the face."[48]

The primary form of corrosion at Ash Fork was not general rust but pitting.[49] In 1916 Ash Fork's steelwork had 50 to 75 pits of 0.031-inch average depth and 0.062-inch average diameter per square foot. On steel plates 0.375 inches thick this was not much. Portions of the steel dam might look as if they had had smallpox, but there was little appreciable loss of section, and later reports on Ash Fork did not indicate that the pitting had become a serious problem.[50]

The Redridge dam also suggests that the "impermanency" explanation for the demise of the steel dam requires qualification. In 1930 Jackson visited the site after a long absence. He reported the plates in "first-class" condition, covered (and thus protected) by a light layer of slime on the water side and "entirely dry" and "in perfect condition" on the under, or air, side.[51] In 1935 A. L. Engels, Superintendent of the Copper Range Company, which by then owned the structure, reported that Redridge had "very little rust exposed," even though it had not been painted since 1913 (see figure 9).[52]

My personal inspection of the Redridge dam in the summer and fall of 1987 revealed that the structure remained in reasonably good condition despite almost total neglect for many decades and total exposure of the steelwork on the water face to air for the past eight years.

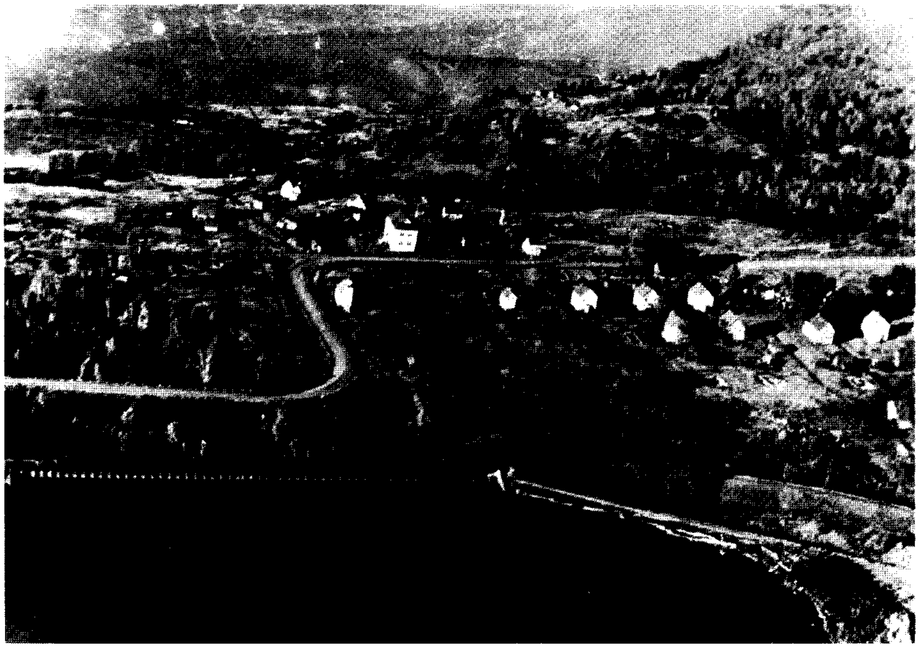

Figure 9. *Aerial view of the Redridge steel dam around 1947. The small former milling town of Redridge is in the background.* Photo by Bill Brinkman, from Bill Brinkman Collection, Copper Country Archives, Michigan Technology University, Houghton, Michigan.

Micrometer measurements (see table 2) that I made on the steel plates at Redridge revealed several things. First, although all published accounts indicate that the steel plates were ⅜ (0.375) inches thick, the plates actually installed were thicker. Measurements made near the top of the structure, where practically no corrosion was evident, suggest that the plates were not precisely rolled and probably had originally thicknesses varying between 27⁄64 (0.422) and 7⁄16 (0.438) inches. Second, corrosion had not measurably diminished the thickness of the steel plate in many sections. And third, as at Ash Fork, pitting, not uniform rust, was the primary form of corrosion, especially in sections periodically exposed to both water and air.

This last point requires further elucidation. Pitting is evident on large areas at Redridge, but this pitting does not seem, despite many years of non-maintenance, to have seriously undermined the dam's integrity. In 1979 the Copper Range Company cut four large openings in the bottom of the steel section of the dam. These openings permitted me to take micrometer readings of the steel's thickness just above the dam's foundations at a point where pitting was evident. Table 2 provides the results of those readings, taken at six-inch intervals, one inch above two of the openings. Seventeen of the measurement points fell on portions of the steel plate which had not been pitted. These points averaged 0.416 inches thick, only 0.014 inches below the probable average original thickness of the two plates. Fifteen of the measurement points fell in points that were clearly pitted. The average thickness at these points was 0.329 inches, or 0.101 inches below probable average original thickness.

This diminution of cross-section was minor and did not seriously weaken the dam. In addition, I found a half-dozen pits near the very top of the dam that had completely penetrated the steel plate, but these pits were nothing more than pinpricks and could very easily have been spot-welded closed.

In brief, my inspection of corrosion and steel plate thickness at Redridge indicates that rust has *not* seriously undermined the Redridge dam, 87 years after construction and after many decades of near-total neglect.

In addition to corrosion, steel dams may have been considered impermanent due to their flimsy appearance when compared to the more massive concrete, earth, and rock gravity dams. But the Redridge dam's performance in flooding suggests that this form of the impermanence explanation also needs qualification. Unlike Ash Fork and Hauser Lake, which were overflow structures, the Redridge dam was *not* designed as an overflow dam. Due to inadequacies in the valves and waste way and the need of the stamp mills for a maximum head of water, the Redridge dam was subjected to the most severe test of a dam's stability—overtopping—on a number of occasions. The most severe test came at Easter in 1941 when a combination of snow melt (the area receives over 200 inches of snowfall annually), heavy rains, and the

Table 2
Thickness of Steel Plate at Redridge Dam

Measurements taken in September 1987 from the center two of four openings cut in 1979 in the steel plates just above the concrete foundations. Measurements taken one inch from top of opening at six-inch intervals, east-to-west.

Specification Thickness: ⅜″ = 0.375

Plate No. 1

Reading no. 1	0.359 inch	9	0.417 inch
2	0.310	10	0.414
3	0.374	11	0.414
4	0.395	12	0.409
5	0.402	13	0.402
6	0.328	14	0.398
7	0.412	15	0.285
8	0.411	16	0.270

Average: 0.375
High: 0.417
Low: 0.270
Average of 9 readings where no clear pitting evident: 0.408
Average of 7 readings taken in clearly pitted areas: 0.332

Plate No. 2

Reading no. 1	0.402	9	0.432
2	0.394	10	0.437
3	0.309	11	0.424
4	0.369	12	0.327
5	0.332	13	0.417
6	0.426	14	0.315
7	0.428	15	0.311
8	0.434	16	0.257

Average: 0.376
High: 0.437
Low: 0.257
Average of 8 readings where no clear pitting evident: 0.425
Average of 8 readings taken in clearly pitted areas: 0.326

collapse of beaver dams upstream led to a rush of water and debris that totally destroyed the dam's waste way after clogging it with floating timber, and that battered at and overtopped the dam for hours. The dam withstood the test with no measurable damage.[53]

The Ash Fork steel dam has survived more than 90 years; the Redridge dam nearly as long. In 1976, when the Redridge dam was approaching 75 years of age, a Copper Range Company official noted that the structure "could last another 75 years."[54] One-hundred-fifty years of life for a structure that has received practically no maintenance is commendable. In other words, the record of steel dams suggests that, especially if properly maintained and perhaps even if not, they have a life potentially as long as dams constructed of rival materials.

So, the impermanence explanation for the steel dam's demise has to be qualified. The two surviving dams indicate that steel structures were durable, and that, objectively, fixed steel dams should not have been neglected because of impermanency. But the frequency with which impermanency has been offered as an explanation suggests, I think, that it *was* a factor, albeit indirectly. Engineers may have rejected steel dams not because of solid, empirical evidence that they were impermanent, but because of a non-rational, intuitive belief that steel did not or could not offer security, or because of a fear that the general public would react to steel dams in that way. In other words, perception, or perception of others' perceptions, may have played a more important role than reality in the neglect of steel dams within the supposedly scientific and rational engineering community.[55]

The concern expressed by prominent engineers over the fragile appearance of the steel dam and the surprise expressed by others on discovering its durability support this contention. For example, the committee investigating the possibility of a steel dam at the Quaker Bridge site in 1893 rejected it because they *felt* that a steel dam did "not give *the idea of permanence* which should attach to the water supply of a great city like New York."[56] In 1903 H. M. Wilson of the U.S. Geological Survey referred to steel dams as "evidently ephemeral" and urged adoption of more permanent structures.[57] Lyman Cooley, prime mover behind the Chicago Ship and Sanitary Canal, and a leading figure in American hydraulic engineering, argued in 1905 that "frail or perishable structures" might be acceptable for temporary services in isolated regions, but added: "I. . . do not sympathize with the present tendency toward bric-a-brac structures. . . I regard steel as one of the most perishable materials for hydraulic work requiring. . . constant solicitude in maintenance. Timber is more satisfactory. . . ."[58] In a similar vein, in 1932 James B. Girand, a consulting engineer and an advocate of rock-fill dams, was "surprised at the state of preservation" when he visited the Ash Fork dam, probably because he did not expect it to be so well preserved.[59] Finally, a recent authority on dams, James Sherard, noted "the *fears* which have existed" about steel plate's corrosion.[60]

The large role that perceptions and intuitive fears can play on occasion in engineering decision-making may also partially explain why high maintenance expenses and the Hauser Lake failure have been seen as causes for the demise of the steel dam. As noted above, neither of these explanations can be supported on objective grounds. Maintenance expenses were very low, and single dam failures do not, in and of themselves, abruptly halt dam-building technologies. Yet the intuitive, unsupported *perception* that steel would have high maintenance expenses in hydraulic structures may have been more important than the contrary evidence quickly offered by Ash Fork and Redridge. And the *perception* that steel structures could not provide stability and safety may have led many in the engineering community to regard the Hauser Lake failure as a steel failure rather than what it was—a collapse due to faulty foundations that had nothing to do with the steel design.

The steel dam was not the only novel and light dam type to suffer from erroneous perceptions in the early 20th century—John Eastwood's multiple-arch concrete dams encountered similar reactions. His Big Meadows dam in California was abandoned before completion in large part because of "psychological" objections offered by prominent eastern civil engineers John R. Freeman and Alfred Noble. Freeman, for example, noted that "the psychology of these airy arches and the lace curtain effect of [Eastwood's] stiffening props is not well suited to inspire confidence."[61] Such a statement, modified to refer to thin steel sheets and airy steel frames, would likely describe Freeman's reaction to steel dams.

Force of Habit or Technological Momentum

Related to the "perception" of impermanency as an explanation for the demise of the steel dam is force of habit or the tendency to follow precedent. An *Engineering News-Record* editorial offered such an explanation in 1932.[62] What that editorial called "force of habit" is, in a sense, what historians of technology have termed "technological momentum": the power of an old, established technology to turn back challenges from technically superior solutions and survive, even after the factors that stimulated its emergence have disappeared.

Thomas Hughes introduced the concept of technological momentum in his account of work on hydrogenation in Germany between 1898 and 1933. He pointed out how World War I produced a body of engineers, chemists, and managers experienced in high-pressure hydrogenation processes and corporations that had invested heavily in such processes. After the war these groups successfully sought to continue development in the area, even after the need for and economic viability of hydrogenation processes had vanished.[63]

The analog to hydrogenation in dam building in the early 20th century was the massive gravity dam constructed with traditional materials–earth, rock, and masonry. That tradition negatively influenced the reception of steel dams in several ways. First, the tradition provided engineers and the general public with a paradigm of what a dam should look like–a massive, solid structure. Steel dams, by comparison, were bound to appear flimsy and unsound, no matter what calculations indicated; hence the comments, cited above, about steel dams being "evidently ephemeral" and "bric-a-brac structures." Second, the technological momentum of the gravity dam tradition meant that many prominent engineers had a ready-made interest in preserving its dominance. Massive gravity dams had emerged in an era when the lack of theoretical understanding made them the only safe structures to build. By 1900 there was a body of prominent engineers trained and experienced in their design and construction.[64] They were prepared to defend the traditional construction against other forms because it retained some advantages over its challengers, because intuitively it seemed safer and more permanent, and because they had experience with it. Economic reasons may also have intruded. Lighter, more economical dam designs could have eaten into incomes. Dam designers were traditionally paid a percentage of the total cost of construction. This created a built-in bias against economy and toward bulky, expensive, overly safe designs.

The steel dam was not the only dam form affected by the technological momentum of the traditional massive gravity dam. Donald C. Jackson, in a solid dissertation on John Eastwood and the multiple-arch dam, sees this as one of the factors behind the limited application of the economical multiple-arch structure. In considerable detail, he shows how eastern engineers in prominent positions who had long built in the massive gravity tradition undermined Eastwood, who sought to promote the more economical multiple-arch configuration.[65]

Comments made by engineers opposing the use of steel in dams lend support to the argument that attachment to the massive dam-building paradigm undermined the steel dam, just as it undermined Eastwood's multiple-arch design. Burr Bassell, resident engineer for the Kern River Company, commented in 1903 that he failed "to appreciate the necessity of resorting to purely metal construction" when earth or rock were nearly always available.[66] That same year, H. M. Wilson of the Geological Survey urged Reclamation Service engineers, who were considering the use of steel dams, to realize "the necessity for the most conservative design and most permanent construction in government works" and not to consider things as "untried" as steel.[67] Lyman Cooley, mentioned already as one suspecting the permanency of steel dams, provides an even better example of the attitude of the dam "establishment." In 1905 Cooley argued that dams were the most important and responsible class of structures engineers could be called on to design or construct and that therefore they should "have all the elements of permanence and safety which the engineering art will permit." To Cooley, permanence and safety implied massive gravity structures. He made it clear that steel structures, in particular, did not fit the bill.[68] Similarly, M. M. O'Shaughnessy, for two decades San Francisco's city engineer, responded to the *Engineering News-Record*'s 1932 editorial by asking: "Why experiment with steel when successful dams of the rock-fill type have been built and faced with concrete. . . ." He argued that engineers "should . . . adhere to successful materials and practice rather than experiment with novel types."[69] Finally, H. M. Hadley, a west coast engineer, commented in 1933 that he found "it very difficult to believe that any other type of dam was superior in respect to safety, security and service to the gravity dam."[70]

Thus the technological momentum possessed by the massive gravity dam-building paradigm, along with the associated perception of steel's impermanency, help explain the steel dam's demise. I believe, however, that two additional factors, not generally cited in the literature on steel dams, also contributed to the disappearance of the steel dam-building tradition: lack of a product champion and diminishing cost advantages.

Lack of a Product Champion

While there were multiple-arch dam and Ambursen slab dam failures, both traditions enjoyed a longer and fuller life than the steel dam, even if they did not displace the massive gravity tradition. While the fixed steel dam died an abrupt and complete death, these other dam types survived and continued for some decades to be built at least occasionally, partly because of their product champions.[71] Both the flat slab and multiple-arch dams had advocates who devoted their careers to proclaiming their advantages and encouraging their construction. The multiple-arch dam's great proponent was John Eastwood, who for two decades enthusiastically argued the merits of this design against significant opposition from prominent eastern engineers.[72] Ambursen played a similar role for the flat slab dam. The steel dam had no such product champion. One of the candidates for such a role should have been F. H. Bainbridge, who patented the steel dam in 1895 and constructed the dam at Ash Fork. But after Ash Fork, Bainbridge apparantly withdrew from dam building. He wrote an article advocating structural steel dams in 1905,[73] but he played no observable role in either the Redridge or Hauser Lake dams. After 1905 little is heard from him.

A more serious candidate for product champion was J. F. Jackson. Jackson played a role in all three fixed steel dams. He was in charge of steel erection at Ash Fork and designed the Redridge and Hauser Lake dams. But after Hauser Lake, Jackson ceased active promotion of the steel dam, with the exception of a 1909 article proposing a new steel dam design and a short 1930 article discussing a long-dead dam-building tradition.[74] Perhaps the disappointment of the Hauser Lake collapse discouraged Jackson and his company, Wisconsin Bridge and Iron, from further promoting this use of steel. After Hauser Lake, Jackson continued to be very active as a structural engineer, designing or supervising construction of several large bridges and docks and designing ore-crushing plants and concentrating mills. He became a respected advocate of steel in mining and milling structures and a pioneer in the area.[75] But neither he nor his company was ever again intimately involved in dam design or construction.

Without an active product champion, without a technological enthusiast to push the new technology, steel dams had no one to demonstrate that the greater engineering community's perceptions about steel were false. Steel dams thus had little chance of derailing the technological momentum enjoyed by the massive gravity dam tradition.

Declining Cost Advantages

Economic factors also clearly played a role in the rise and fall of the fixed steel dam. They are particularly important, I believe, in explaining why interest in steel dams emerged when it did—in the mid-1890s.

The achievement of integrated, large-scale production in steel in the 1880s, the low demand and depressed market for steel following the panic of 1893, and the price wars between Carnegie and other steel manufacturers later in the decade brought steel prices to an all-time low in the mid- to late 1890s.[76] Steel billets, for example, averaged $31.03 a ton between 1884 and 1888. Following the economic collapse of 1893, they dropped to an average of $16.73 a ton between 1894 and 1898. The first serious proposals for steel dams appeared at this time, when steel prices were at an all-time low.[77]

After 1898 the price of steel rose, perhaps reflecting the consolidation of the American steel industry around U.S. Steel and increased demand. The average price for steel billets between 1904 and 1908, for instance, was $25.82 a ton, 54 percent higher than between 1894 and 1898, though still less than in the 1880s. Because of the technical advantages of steel construction in dams, the rising price of steel might not, by itself, have proven fatal to the steel dam or to the broader use of steel in hydraulic structures, if the prices of alternate materials for dam construction had also risen. But they did not. The prices of alternate materials, particularly concrete, steadily dropped, even after steel prices rose (see table 3).

Table 3
Comparison of Cost of Portland Cement and Steel Billets at 5-Year Intervals, 1889-1918

Average 1889-1893 price = 1.00 for index

	Portland Cement 376-lb. barrel		**Steel Billets** gross ton	
Interval	**Average Price**	**Index**	**Average Price**	**Index**
1889-93	$1.99	1.00	$25.73	1.00
1894-98	1.63	0.82	16.73	0.65
1899-03	1.20	0.60	27.46	1.07
1904-08	0.98	0.49	25.82	1.00
1909-13	0.87	0.44	23.83	0.93
1914-18	1.17	0.59	41.05	1.60

Sources:

Portland Cement: United States Bureau of the Census, *Historical Statistics of the United States* (Washington, D.C.: Government Printing Office, 1976), pp. 597-598.

Steel Billets: *Metal Statistics 1940* (New York: American Metal Market, 1940), p. 90, and Peter Temin, *Iron and Steel in Nineteenth-Century America: An Economic Inquiry* (Cambridge, Mass.: MIT Press, 1964), p. 284.

In contrast to steel, portland cement prices were relatively high in the early 1890s but were just at the beginning of a long decline due to the introduction of new production technologies like the rotary kiln.[78] Between 1889 and 1893 a 376-pound barrel of portland cement was sold f.o.b. at the mill for $1.99. Between 1904 and 1908 the same barrel cost only $0.98, or 51 percent less. Between 1909 and 1913 the average price dropped even lower, to $0.87, or 56 percent less than in the early 1890s. Thus, between the early 1890s and the middle of the first decade of the 20th century the price of steel rose 54 percent, while the price of cement fell by approximately the same percentage.[79]

What the comparative prices of cement and steel suggest is that steel dams enjoyed a brief "window of opportunity" from around 1893 to some point very early in the 20th century. In this period steel enjoyed cost advantages over concrete and had an opportunity to demonstrate its non-cost advantages, such as speed of construction and resistance to cracking from expansion or contraction. But this window closed in the early 20th century with declining cement prices.

Conclusion

Economic factors provide the best explanation for the sudden burst of interest in steel as a dam construction material in the mid-1890s and *help* explain its disappearance toward 1910. But they do not provide a sufficient explanation for the near-complete disappearance of steel from dam construction. Steel's cost advantage declined after 1900 but not for all situations. Moreover, steel continued to have economic advantages as a supplementary material, for example, to provide a watertight membrane over rock fill. Yet after 1910 steel ceased to be used, even in a supplementary role. So the causes of the demise of the fixed steel dam are also non-economic.

Most of the non-economic explanations offered, however, have focused on supposed technical shortcomings — leakage between steel and foundation, the need to protect steel from the elements with high maintenance expenses, and steel's impermanency. This is perhaps to be expected, since the ideology of engineering assumes that engineers always make technical decisions based on objective, measurable, scientific criteria. But the surviving artifacts and the literature on steel dams suggest that these technical shortcomings were not really evaluated by the engineering community in an objective manner, based on quantitative evidence. If they had been, the supposed leakage, maintenance, and impermanency problems and the failure of the Hauser Lake dam would *not* have led to the abandonment of steel dam construction.

What this study of the fixed steel dam suggests is that non-rational, non-measurable factors–particularly intuitive perceptions, some of which may be false–play a far greater role than is usually presumed in the supposedly objective and rational decision-making of the engineering community. The steel dam did not die because of measurable leakage, maintenance, or impermanency problems or because of the Hauser Lake failure. Steel dams died because of the *perception* that these should be problems with steel in hydraulic structures and the *perception* that steel dams were inherently unsafe. These perceptions, although false, were no doubt reinforced by the "force of habit," or technological momentum, enjoyed by the traditional massive gravity dam. Finally, the absence of a long-term product champion, an individual willing to stake reputation and career on promoting a new technological idea, enabled the false perceptions to prevail.

Engineering practice is often discerned by the engineering community and by the general public as a very rational, scientific endeavor, where technologies live or die for sound, objective, technical reasons. The case of the fixed steel dam implies that intuitive perceptions and personal factors can play a more important role than objective technical and economic considerations in engineering decisions.

Postscript

The steel dam at Ash Fork is likely to continue in use for some time. Isolated and still useful for stock watering, it seems in no danger of destruction.

It is less certain how much longer the Redridge steel dam will continue to stand. It is no longer a useful structure. The two stamp mills that it supplied with water are long gone; one closed in 1912 and the other in 1922. In the early 1950s the dam's owner, the Copper Range Company, considered dismantling it because it no longer had utility and had become a potential liability hazard.[80] Before pursuing demolition the company offered the structure to the Michigan Department of Conservation, hoping it would maintain the dam and reservoir for public use, but the department refused the offer.[81] Copper Range then tried to interest Houghton County, the Houghton County Road Commission, and Stanton Township in taking possession of the structure and its reservoir and using them as a public park. All three refused.[82] However, the Redridge dam escaped demolition, apparently because this would have compelled Copper Range to make extensive modifications to the roadway located below the dam and because estimates of the return from salvage were disappointing.[83]

In 1976 the Copper Range Company again considered dismantling the Redridge dam, fearing that spring flooding, the abandonment and overgrowth of the lateral discharge channel, the blockage of several of the discharge pipes, and general neglect of the structure might someday lead to dam collapse.[84] But the company found a more economical alternative. To relieve water pressure on the dam, in 1979 Copper Range cut four four-by-eight-foot openings in the steel plates just above the dam's concrete foundation.[85] These large openings drained most of the reservoir behind the dam, eliminating the water load on the steelwork. They have also completely exposed the steel on the dam's water face to the elements and have probably accelerated the dam's aging (see figures 10 and 11).

Presently the fixed steel dam is a dead technology, despite the two surviving examples. But the idea of using steel plate to supplement other dam-building materials, an idea that

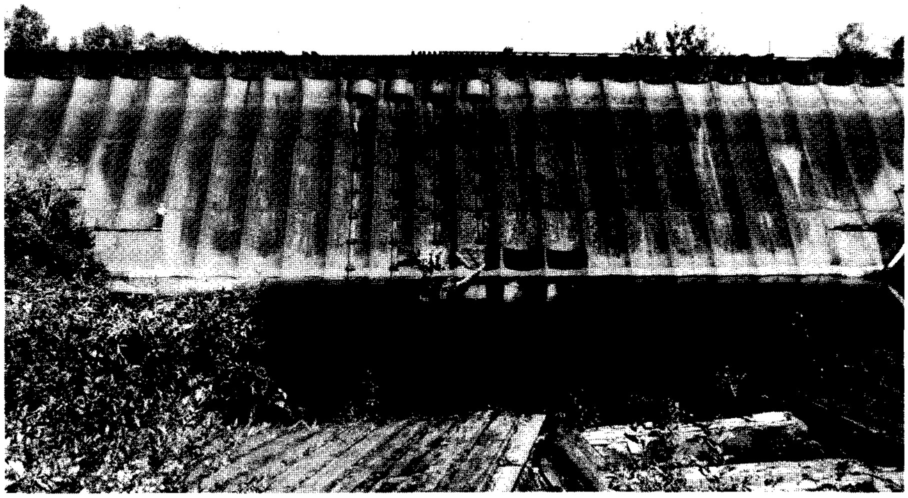

Figure 10. *Water face of Redridge steel dam, 1988. View from the south taken from remnants of 1894 timber crib dam (foreground). Note sections of steel plate removed just above waterline (center of photo). These were cut out in 1979 to reduce water load on the dam. The railroad trestle which shares the concrete foundation of the dam is visible above the dam.* Photo by Author.

emerged with the fixed steel dam and apparently died with it, revived in the 1930s. Since then engineers have constructed a number of rock- and earth-fill dams faced with steel plates, both in the United States and abroad.[86]

Acknowledgments

This paper was presented in preliminary form at the 1987 Troy meeting of the Society for Industrial Archeology. Charles Hyde provided me with information on the Redridge dam early in the course of my research. Donald Jackson furnished me with several key ideas, with literature references, and with a host of detailed suggestions in a number of conversations in which we discussed the similarities between the fate of the fixed steel dam and the multiple-arch dam. Bruce Seely, my colleague at Michigan Tech, provided several valuable suggestions on organizing my argument. Finally, Laurence Gross, my session leader at Troy and one of my not-so-anonymous referees, forced me, through his suggestions, to rethink the organization and emphasis of the paper. All of them have made this a better article than it otherwise would have been.

Notes

1. Steel dams, for example, are not mentioned in Carl W. Condit, *American Building* (Chicago: University of Chicago Press, 1968), or Norman Smith, *A History of Dams* (Secaucus, N. J: The Citadel Press, 1972). Movable dams made of steel, though often not recognized as dams in the conventional sense, are more common than fixed steel dams. The steel gates on canal locks, for instance, can be considered movable steel dams. Other forms of movable steel

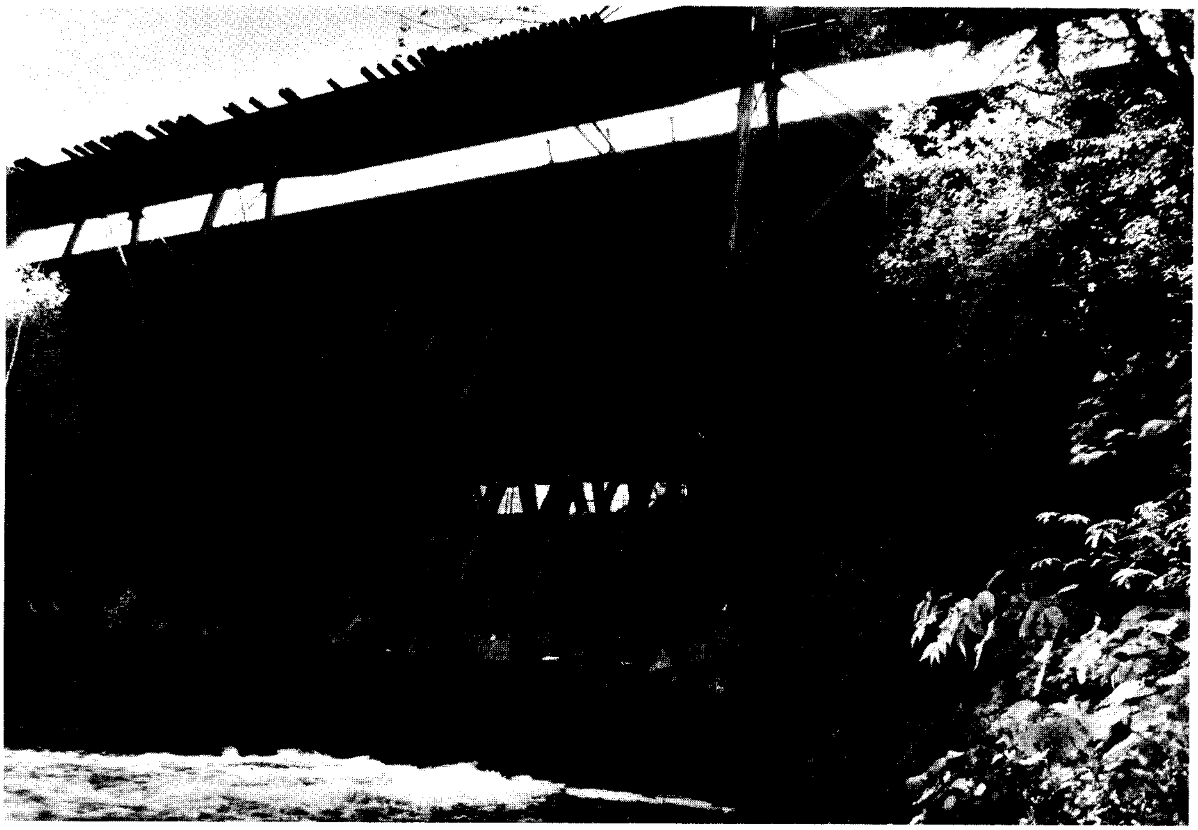

Figure 11. *Airface of Redridge steel dam, 1988. View from the north. Railroad trestle built on the same foundation as the dam projects above rim of dam. Openings cut in steelwork of the dam just above concrete foundation are visible in center.* Photo by Author.

dams are reviewed in Leland R. Johnson, *The Davis Island Lock and Dam, 1870-1922* (Pittsburgh: U.S. Army Corps of Engineers, 1985), pp. 34-41.

2. The advantages of steel dams are discussed by numerous authors, including: Charles R. Steiner, "Proposed Steel Dam, Irrigation Reclamation Service, U.S. Geological Survey," *Engineering News* 49 (June 11, 1903):526-527, and "Steel Dams for Storage Reservoirs" (Letter to Editor), *Engineering News* 50 (August 6, 1903): 123; F. H. Bainbridge, "Structural Steel Dams," *Engineering News* 54 (September 28, 1905: 323-324; J. F. Jackson, "Four Steel Dams—Their Design and History," *Engineering News-Record* 104 (February 13, 1930): 281; C. Maxwell Stanley, "Why Not Steel Dams?" *Engineering News-Record* 109 (December 1, 1932):653-654; Otis E. Hovey, *Steel Dams* (New York: American Institute of Steel Construction, 1935), pp. 12-13, and "Principal Considerations in the Design of Steel Dams," *The Canadian Engineer* 73 (August 24, 1937):6; and William P. Creager, Joel D. Justin, and Julian Hinds, *Engineering for Dams*, vol. 3 (New York: John Wiley & Sons, 1945), p. 834.
3. Bainbridge, "Structural Steel Dams" (n. 2 above), p. 323. This article was printed in a slightly more extended form with additional illustrations and discussion in *Journal of the Western Society of Engineers* 10 (1905): 615-637. Since *Engineering News* is more widely available, all subsequent citations to Bainbridge's article will refer to the *Engineering News* article unless otherwise noted.
4. Ibid., p. 323.
5. U.S. Patent no. 537,520.
6. For a biographical sketch, see "Henry Goldmark," *Transactions of the American Society of Civil Engineers* 106 (1941):1588-1593.
7. Henry Goldmark, "The Power Plant, Pipe Line and Dam of the Pioneer Electric Power Company at Ogden, Utah," *Transactions of the American Society of Civil Engineers* 38 (December 1897):246-314. The discussion of possible steel construction appears on p. 293. See also Appendix B: "Designs for a Structural Steel Dam," pp. 302-305. The notice that Goldmark's consideration of steel "attracted considerable attention" comes from "Steel Weir, Ash Fork, Ariz.," *Engineering Record* 37 (April 9, 1898):404. Goldmark had some interest in steel dams as late as 1929, when he mentioned them briefly in a professional meeting: "Steel Fabricators Hold Record Meeting," *Engineering News-Record* 103 (November 21, 1929):811.
8. For the background of the Ash Fork dam, see: "Steel Weir, Ash Fork, Ariz." (n. 7 above); "Steel Dam at Ash Fork, Arizona; A., T. & S.F. Ry.," *Engineering News* 39 (May 12, 1898):299; James Dix Schuyler, *Reservoirs for Irrigation, Water-Power, and Domestic Water-Supply* (New York: John Wiley & Sons, 1901), pp. 214-215; and Hovey, *Steel Dams* (n. 2 above), p. 44.
9. For the technical details of the Ash Fork steel dam, see: Bainbridge, "Structural Steel Dams" (n. 2 above), pp. 323-324; Schuyler, *Reservoirs for Irrigation* (n. 8 above), pp. 222-224; "Steel Dam at Ash Fork" (n. 8 above), pp. 299-300; "Steel Weir" (n. 8 above), pp. 404-405; Edward Wegman, *The Design and Construction of Dams*, 7th ed. (New York: John Wiley & Sons, 1922), pp. 294-297; and Hovey, *Steel Dams* (n. 2 above), pp. 44-51.
10. See James Leffel, *Leffel's Construction of Mill Dams* (Springfield, Ohio: by the author, 1881), pp. 16-19, for similar timber buttress dams.
11. For the background of the Redridge steel dam, see Atlantic Mining Company, *Report of the Directors to the Stockholders*, for the years ending December 31st 1890 to 1900, esp. 1900, pp. 6-7. See also Baltic Mining Company, *Report of the Directors to the Stockholders for the Year Ending December 31st, 1900*, pp. 18-19. On the earlier timber crib dam, see "Michigan. Copper. Atlantic Mining Company," *Engineering and Mining Journal* 57 (May 16, 1894):494; "Atlantic Mining Company, Michigan," ibid. 59 (March 16, 1895):246; and Charles K. Hyde, *The Upper Peninsula of Michigan: An Inventory of Historic Engineering and Industrial Sites* (Washington, D.C.: Historic American Engineering Record, 1978), pp. 207-208.
12. Bainbridge, "Structural Steel Dams" (n. 2 above), p. 324.
13. For technical details on the Redridge dam, see: "The Redridge Dam," *Engineering News* 46 (August 15, 1901): 101-102; Schuyler, *Reservoirs for Irrigation* (n. 8 above), pp. 456-459; Horace J. Stevens, comp., *The Copper Handbook*, 1st ed. (Houghton, Mich.: Horace J. Stevens, 1900), pp. 254-256 (or 4th ed., 1904, pp. 209-210); Bainbridge, "Structural Steel Dams" (n. 2 above), p. 324; Wegman, *Design and Construction of Dams* (n. 9 above), p. 297; "The Redridge Dam," *Mining and Scientific Press* 83 (August 31, 1901):88-89; and Hovey, *Steel Dams* (n. 2 above), pp. 54-62.
14. Construction progress is outlined in: Baltic Mining Company, *Report*, 1900, pp. 15, 18-19; 1901, pp. 7, 16, 19; Atlantic Mining Company, *Report*, 1900, p. 14; 1901, pp. 6, 16; *Daily Mining Gazette* (Houghton, Michigan), August 24, 1900.
15. Steiner, "Proposed Steel Dam" (n. 2 above), pp. 526-527. For the letters, see *Engineering News* 50 (July 2, 1903): 13; (July 16, 1903): 59; and (August 6, 1903):123.
16. For technical details on the Hauser Lake dam, see: "The Hauser Lake Steel Dam in the Missouri River Near Helena, Mont.," *Engineering News* 58 (November 14, 1907):507-509; and Wegman, *Design and Construction of Dams* (n. 9 above), p. 298.
17. W. S. Russell, "A Rock-Fill Dam with a Steel Heartwall at Otay, Cal.," *Engineering News* 39 (March 10, 1898):157-158.
18. W. P. Hardesty, "The Water and Electric Power System of the Pike's Peak Power Co., Colorado," *Engineering News* 49 (January 1, 1903): 2-5. A later report on the excellent condition of this structure is J. R. Wemlinger, "Facing Dam with Steel Plates," *Engineering News-Record* 109 (August 25, 1932):233.
19. Terry S. Reynolds, "The Soo Hydro: A Case Study of the Influence of Managerial and Topographical Constraints on Engineering Design," *IA* 8,1 (1982): 37-56, or *Sault Ste. Marie: A Project Report* (Washington, D.C.: Government Printing Office, 1982).
20. Creager, *Engineering for Dams* (n. 2 above), p. 834; also Alfred R. Golze, ed., *Handbook of Dam Engineering* (New York: Van Nostrand Reinhold, 1977), p. 338.
21. George W. Lamb, "Steel Dam in Good Shape after 50 Years," *Steel Construction Digest* 7, 2 (April 1950): 14.
22. J. F. Jackson, "Four Steel Dams" (n. 2 above), p. 281.
23. Hovey, *Steel Dams* (n. 2 above), p. 60, citing a report of January 1935 from A. L. Engels, Superintendent, to W. H. Schact, President of the Copper Range Company.
24. Interview with Ray Franz, June 27, 1986. Franz is a former official, now retired, of the Copper Range Company, which owned the dam from 1905 until recently.
25. Interview with William Brinkman, May 11, 1987.
26. Schuyler, *Reservoirs for Irrigation* (n. 8 above), p. 223.
27. In discussion of Bainbridge, "Structural Steel Dams," *Journal of the Western Society of Engineers* (n. 3 above), p. 636.
28. H. M. Hadley, "In Favor of Gravity Dams" (Letter to the Editor), *Engineering News-Record* 110 (March 30, 1933): 415.
29. Bainbridge, "Structural Steel Dams" (n. 2 above), p. 324.
30. "Steel Dam Eighteen Years Old Still Well Preserved," *Engineering News* 75 (June 1, 1916): 1035; Hovey, *Steel Dams* (n. 2 above), pp. 47-53.
31. J. F. Jackson, "Copper Mining in Upper Michigan," *Journal of the Western Society of Engineers* 8 (February 1903): 20-21.

32. J. F. Jackson, "Four Steel Dams" (n. 2 above), p. 281.
33. Interview with Ray Franz, June 27, 1986, and with William Brinkman, May 11, 1987.
34. F. L. Sizer, "The Break in the Hauser Lake Dam, Montana," *Engineering News* 59 (April 30, 1908):491-492.
35. Barrett Smith, "The Construction of the New Hauserlake [*sic*] Dam," *Engineering News* 66 (August 10, 1911):162-164; George A. McKay, "Difficult Deep Foundation Work at the Hauserlake [*sic*] Dam, Montana," ibid. 65 (June 22, 1911):743-747.
36. J. F. Jackson, "Four Steel Dams" (n. 2 above), p. 281.
37. C. E. Grunsky in discussion on John S. Eastwood, "The Hume Lake Multiple-Arch Dam, *California Journal of Technology* 15, 3 (March 1910): 27 (which blames the Hauser Lake failure on difficulties of linking the steel skin with the foundations); Hadley, "In Favor of Gravity Dams" (n. 28 above), p. 415; J. F. Jackson, "Four Steel Dams" (n. 2 above), p. 281; Hovey, "Principal Considerations" (n. 2 above), p. 5; Stanley, "Why Not Steel Dams?" (n. 2 above), p. 652; and Donald Jackson, "A History of Water in the American West: John S. Eastwood and 'The Ultimate Dam'," Ph.D. diss. (University of Pennsylvania, 1986), p. 114.
38. "The Undermining of a Reinforced-Concrete Dam at Pittsfield, Mass.," *Engineering News* 61 (April 1, 1909):345-347. A second Ambursen dam failed in 1914: F. W. Scheidenhelm, "The Reconstruction of the Stony River Dam," *Transactions of the American Society of Civil Engineers* 81 (1917):907-1024.
39. D. Jackson, "Eastwood and 'The Ultimate Dam'" (n. 37 above), pp. 114, 115.
40. "Official Report on the Collapse of Gleno Dam," *Engineering News-Record* 93 (August 7, 1924): 213-215. D. Jackson, "Eastwood and 'The Ultimate Dam'" (n. 37 above), pp. 695-698, points out that the failure here was not due to the multiple-arch design, but to other circumstances such as foundations and poor-quality masonry. The same was the case, of course, with the Hauser Lake steel dam.
41. D. Jackson, "Eastwood and 'The Ultimate Dam'" (n. 37 above), pp. 747, 760.
42. American Society of Civil Engineers, *Lessons from Dam Incidents USA* (New York: American Society of Civil Engineers, 1975).
43. "Steel Dam Still Well Preserved" (n. 30 above), p. 1035. Among others who have cited corrosion as a major objection against steel dams or as a factor contributing to their failure to catch on are: D. Jackson, "Eastwood and 'The Ultimate Dam'" (n. 37 above), p. 114; John S. Fielding, "The Use of Steel in the Construction of Dams and Reservoirs," *The Canadian Architect and Builder* 10 (August 1897):148; Hovey, "Principal Considerations" (n. 2 above), p. 5, and *Steel Dams* (n. 2 above), p. 51 ("the principal objection"); Creager, *Engineering for Dams* (n. 2 above), p. 834; and Golze, *Handbook of Dam Engineering* (n. 20 above), p. 338.
44. Stanley, "Why Not Steel Dams?" (n. 2 above), p. 653.
45. Hovey, "Principal Considerations" (n. 2 above), p. 5.
46. "Steel Dam Still Well Preserved" (n. 30 above), p. 1035, and Bainbridge, "Structural Steel Dams," *Journal of the Western Society of Engineers* (n. 3 above), pp. 629-630. Bainbridge quotes from a letter written by A. F. Robinson, Bridge Engineer of the AT&SF system, noting that after the joint between steel and masonry at Ash Fork had been treated in the second season with asphalt at a cost of $150, "there has not been the slightest indication of leaks of any kind in or around the dam."
47. J. F. Jackson, "Four Steel Dams" (n. 2 above), p. 281; James B. Girand and W. B. Storey, "Steel-Faced and All-Steel Dams" (Letters to the Editor), *Engineering News-Record* 109 (October 27, 1932): 505-506; Lamb, "Steel Dam in Good Shape" (n. 21 above), pp. 13-14, and "Steel Dam in Good Shape after 50 Years," *Engineering News-Record* 144 (January 12, 1950): 36-37. For the comment on less deterioration in steel portion than masonry portion, see Lamb, "Steel Dam in Good Shape" (n. 21 above), p. 37.
48. T. Lindsay Baker, Steven R. Rae, Joseph E. Minor, and Seymour V. Connor, *Water for the Southwest: Historical Survey and Guide to Historic Sites* (New York: American Society of Civil Engineers, Historical Publication no. 3, 1973), p. 33.
49. The pitting is probably due either to ice action against the face of the steel or to air dissolved in the water at low temperatures. Generally, however, the light slime which covers the steel on a steel dam prevents entrained air from reaching the steel to cause rust.
50. Lamb, "Steel Dam in Good Shape after 50 Years," *Engineering News-Record* (n. 47 above), p. 37.
51. J. F. Jackson, "Four Steel Dams" (n. 2 above), p. 281.
52. In Hovey, *Steel Dams* (n. 2 above), p. 60.
53. An account of the 1941 flood with an illustration of the water overtopping the Redridge dam can be found in *Daily Mining Gazette* (Houghton, Michigan), March 22 and April 9, 1982. Also: interview with William Brinkman, May 11, 1987. Brinkman has lived in Redridge near the dam for most of his 81 years.
54. Raymond A. Kenney to Edward R. Bingham, October 22, 1976 (Copper Range Company records). Copper Range Company records relating to the Redridge dam apparently date back only to 1951. The surviving records were kindly loaned to me by John Lasio of Laurium, Michigan, who is currently engaged in co-authoring a history of the Copper Range Company. The Copper Range Company contacted Wisconsin Bridge and Iron Company about surviving records on the Redridge dam in 1951 (H. A. Kiesow to William Nicholls, July 10, 1951) but was informed that the contract files on the dam had either been lost or destroyed.
55. Fielding, "The Use of Steel in Dams" (n. 43 above), p. 148, pointed out that rationally there was not much in the argument that water in contact with steel would create a major corrosion problem. If this were so, he pointed out, ". . . why use iron water mains or steel bridge piers or even steel ships, steel lighthouses, steel piles, . . ."
56. Bainbridge, "Structural Steel Dams" (n. 2 above), p. 323, emphasis added. See also Cooley's comments on Bainbridge's paper in the version in the *Journal of the Western Society of Engineers* (n. 3 above), p. 635.
57. H. M. Wilson, "Steel Dams and Concrete-Steel Diaphragms for Earth or Rock-Fill Dams" (Letter to Editor), *Engineering News* 50 (July 16, 1903):59.
58. Comment by Lyman E. Cooley on Bainbridge, "Structural Steel Dams," *Journal of the Western Society of Engineers* (n. 3 above), p. 636.
59. James B. Girand to M. N. Baker, August 22, 1932, letter published in M. N. Baker, "Steel-Faced and All-Steel Dams," *Engineering News-Record* 109 (October 27, 1932): 505-506.
60. James L. Sherard et al., *Earth-Rock Dams: Engineering Problems of Design and Construction* (New York: John Wiley, 1963), p. 480, emphasis added. Sherard's work notes that experience with steel plate membranes indicates that steel plates have approximately the same life as reinforced concrete, that corrosion of the plates has never been a serious problem, and that maintenance costs on steel dams have been very low.
61. D. Jackson, "Eastwood and 'The Ultimate Dam'" (n. 37 above), pp. 368-379.
62. "Force of Habit," *Engineering News-Record* 109 (December 1, 1932): 658.
63. Thomas P. Hughes, "Technological Momentum in History: Hydroge-

nation in Germany 1898-1933," *Past and Present* 44 (August 1969): 106-132.

64. Smith, *History of Dams* (n. 1 above) is practically the only survey history of dams.
65. D. Jackson, "Eastwood and 'The Ultimate Dam'" (n. 37 above), esp. chap. 8, pp. 747-823. Eastwood's position was further undermined by two other developments that reinforced the technological momentum already possessed by the massive gravity dam tradition: (1) the cautious nature of the emerging state regulatory bureaucracies, often dominated by more traditional dam designers, which placed safety far above economy, and (2) the replacement of private industry, with its emphasis on economy, by the federal government as the major builder of dams.
66. Burr Bassell, "The Type of Steel Dam Proposed by the U.S. Irrigation Reclamation Service," *Engineering News* 50 (July 2, 1903): 13.
67. Wilson, "Steel Dams and Concrete-Steel Diaphragms" (n. 57 above).
68. Comment by Cooley on Bainbridge, "Structural Steel Dams," *Journal of the Western Society of Engineers* (n. 3 above), p. 636.
69. M. M. O'Shaughnessy, "Steel-Faced Dams," *Engineering News-Record* (July 28, 1932): 113.
70. Hadley, "In Favor of Gravity Dams" (n. 28 above).
71. A product champion is an individual or company willing to invest heavily in time, money, or reputation to support a particular product or concept. The concept was used, for example, in J. Langrish, M. Gibbons, W. G. Evans, and F. R. Jevons, *Wealth from Knowledge* (London: Macmillan, 1972).
72. D. Jackson, "Eastwood and 'The Ultimate Dam'" (n. 37 above), provides an excellent overview of Eastwood's career-long promotion of the multiple-arch dam.
73. Bainbridge, "Structural Steel Dams" (n. 2 above), pp. 323-324.
74. J. F. Jackson, "Some Observations on the Stability of Dams," *Engineering News* 62 (July 29, 1909): 120-121, and "Four Steel Dams" (n. 2 above).
75. Raleigh W. Gamble, "John Franklin Jackson," *Transactions of the American Society of Civil Engineers* 104 (1939): 2042-2043.
76. See Peter Temin, *Iron and Steel in Nineteenth-Century America: An Economic Inquiry* (Cambridge, Mass.: MIT Press, 1964), pp. 188, 208; and W. David Lewis, *Iron and Steel in America* (Greenville, Del.: Hagley Museum, 1976), pp. 50-51.
77. During the Great Depression of the 1930s, steel prices again dropped sharply. As a result, the steel industry began to seek new markets for its product and attempted to revive the fixed steel dam. This explains the American Institute of Steel Construction's sponsorship of Hovey's *Steel Dams* (n. 2 above) in 1935.
78. On the importance of the rotary kiln in the manufacture of concrete, see, for example, Jasper O. Draffin, *A Brief History of Lime, Cement, Concrete, and Reinforced Concrete* (Urbana, Ill.: University of Illinois, Bulletin 40, June 29, 1943), p. 12; A. W. Skempton, "Portland Cements, 1843-1887," *Transactions of the Newcomen Society* 35 (1962-1963): 149; and P. Gooding and P. E. Halstead, "The Early History of Cement in England," *Proceedings of the Third International Symposium on the Chemistry of Cement, 1952* (London: Cement and Concrete Association, 1954), p. 26.
79. Bainbridge, "Structural Steel Dams" (n. 2 above), p. 323, is the only author to have pointed to the changing prices of steel and concrete. He noted that structural steel was as low as one cent per pound in 1894, but in 1905 was 75 percent higher. On the other hand, he pointed out, portland cement's price was about ⅓ of what it had been in 1894. He concluded: "Had the relative values of steel and Portland cement in 1894 been maintained, the subject of steel dams would have received far greater attention than has been the case." Low prices definitely encouraged the use of steel. J. F. Jackson, "Copper Mining in Upper Michigan" (n. 31 above), p. 21, noted: "It was believed, at the time the work was under way [on the Redridge Dam], that a steel dam was considerably cheaper than a dam of masonry or entirely concrete."
80. William P. Nicholls, Manager, Lands and Forestry Division, Copper Range Company, to F. P. Strusaker, Secretary, Michigan Department of Conservation, August 7, 1951 (Copper Range Company records, n. 54 above).
81. Ibid., and Strusaker to Nicholls, September 28, 1951 (Copper Range Company records, n. 54 above).
82. P. F. Beaudin, Vice President, Copper Range Company, to W. E. Romig, General Manager, Copper Range Company, October 4, 1951; Memo, Copper Range Company, November 14, 1951 (Copper Range Company records, n. 54 above); *Daily Mining Gazette* (Houghton, Michigan), July 9, 1952.
83. William A. Waara, Superintendent, Copper Range Company, to William P. Nicholls, Manager, Lands and Forestry Division, June 30, 1952, and handwritten memo on expected salvage revenue, July 10, 1961 (Copper Range Company records, n. 54 above).
84. Memo, Coppper Range Company, February 9, 1976; Edward R. Bingham, Vice President, Copper Range Company, to Kathryn B. Eckert, Michigan History Division, March 17, 1976; and "Notes on Meeting: Redridge Dam and County Road," September 7, 1976 (Copper Range Company records, n. 54 above).
85. *Daily Mining Gazette* (Houghton, Michigan), April 23, 1979, and April 9, 1982.
86. For later use of steel as a facing on earth- and rock-fill dams, see, for example, H. I. Reid, "Steel Plates with Welded Joints Seal Rockfill Dam," *Engineering News-Record* 108 (May 26, 1932):761-763; J. D. Galloway, "The Design of Rockfill Dams," *Transactions of the American Society of Civil Engineers* 104 (1939): 21, 91; Charles P. Seger, "Steel Used Extensively in Building El Vado Dam," *Engineering News-Record* 115 (August 15, 1935):211-215; H. P. Bunger, "Constructing the First Large Steel Faced Dam for Irrigation Storage in New Mexico," *Western Construction News* 10 (February 1935): 36-41; H. P. Bunger, "Metal-Faced Gravel Dam Being Built in New Mexico," *Engineering News-Record* 111 (October 26, 1933): 504-505; "Metal-Faced Dams," ibid.: 510; Sherard, *Earth-Rock Dams* (n. 60 above), pp. 479-487. Sherard describes, in addition to the El Vado dam in New Mexico (1934), later dams such as the Alazar dam in Portugal (1948) and the Caracas Water Supply dam in Venezuela (1958).