Journal of the
BOSTON SOCIETY
of
CIVIL ENGINEERS SECTION
AMERICAN SOCIETY
of
CIVIL ENGINEERS

1848 BOSTON SOCIETY OF CIVIL ENGINEERS

AMERICAN SOCIETY OF CIVIL ENGINEERS FOUNDED 1852

VOLUME 63 OCTOBER 1976 NUMBER 3

JOURNAL OF THE
BOSTON SOCIETY
OF
CIVIL ENGINEERS SECTION
AMERICAN SOCIETY
OF
CIVIL ENGINEERS

Volume 63 | October 1976 | Number 3

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Second-Class postage paid at Boston, Massachusetts

Published four times a year, January, April, July, and October, by the Society
230 Boylston Street, Boston, Massachusetts 02116

Subscription price $10.00 a Year (4 Copies)
$2.50 a copy
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JOURNAL OF THE
BOSTON SOCIETY OF CIVIL ENGINEERS SECTION
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Volume 63 **October 1976** **Number 3**

CONSTRUCTION OF THE HOOSAC TUNNEL 1855 to 1876

By
Gary S. Brierley[1]

Dedication

This paper is dedicated to my father, the late Harry W. Brierley, who took the author as a young boy to visit the west portal of the Hoosac Tunnel. Although we did not know it at the time, that visit represented the beginning of a fascination for me with the Hoosac Tunnel which led to the preparation of this paper.

I. Introduction

The Hoosac Tunnel is a truly great civil engineering accomplishment. Constructed through Hoosac Mountain in Northwestern Massachusetts from 1855 to 1876, the 4 and ¾-mile route has been used continuously since then as a railroad tunnel. It is currently owned and operated by the Boston & Maine Corporation.

Tunneling the "Mighty Hoosac" was significant for two principal reasons. First was the herculean efforts which were required to overcome natural obstacles such as a fault zone and large water flows. Nearly 200 construction workers lost their lives in the tunnel! Second was the substantial strides that were made in hard rock tunneling technology during construction of the tunnel. To quote Sandstrom (1963), ". . . out of the Hoosac mess would ascend the American compressed air industry which . . . took an unchallenged leadership in developing and providing the mining and construction industries with the only types of tools and machines hitherto capable of mechanized work underground."

The following paper presents a brief history of the tunnel and discusses construction methods, costs and time durations. The construction history is summarized in Chapter III and there is a discussion of contemporary tunneling technology in Chapter IV. Chapter V contains a description of specific construction activities at the Hoosac Tunnel. Other chapters provide additional general information. In the Epilogue is a discussion of how a tunnel like the Hoosac might be constructed today in accordance with modern requirements and construction methods.

[1]Project Engineer, Haley & Aldrich, Inc., Rochester, New York

II. Early History

Following the Revolutionary War, Massachusetts enjoyed a period of economic prosperity. Sailing fleets from her eastern seaports travelled the world reaping large profits for their owners. Embargoes associated with the War of 1812, however, placed severe hardships on the shippers. Then followed agricultural development in the "West" (New York and Pennsylvania) where conditions for farming were more favorable than in rocky Massachusetts. Completion of the Erie Canal in 1825 from Lake Erie to the Hudson River made New York City the busiest port on the eastern seaboard. By 1830, when Massachusetts celebrated the bicentennial year of the Massachusetts Bay Colony, it was obvious that her economic growth was lagging behind that of her northeastern neighbors (Salsbury, 1967). Hoosac Mountain in Western Massachusetts was one of the things that prevented significant commercial interaction between Boston and the country's new commercial center.

An engineering study was commissioned by the Massachusetts General Court in 1825 under the direction of Loammi Baldwin, Jr. to determine the feasibility of constructing a canal from Boston to the Hudson River. Baldwin found two possible routes: one along southern Massachusetts through Worcester, Springfield and Pittsfield, and another more northerly route through Fitchburg, Greenfield, and North Adams which included a five-mile long tunnel through Hoosac Mountain (See Figure 1). Baldwin recommended the northerly route but the Legislature discarded the entire proposal. A canal was too expensive, could not be used during the winter, would require large amounts of water which were sometimes needed for farming, and, most significant, canals began to compare unfavorably with a new mode of transportation: the railroad.

In 1826, the Massachusetts Legislature began to receive requests for possible railroad route surveys across Massachusetts. In 1831, the Boston and Worcester Railroad was chartered and subsequently constructed from Boston to Worcester, Massachusetts as a private development. By 1842, this line was extended by the Western Railroad from Worcester to Greenbush, New York on the east bank of the Hudson River directly across from Albany. A branch line in Massachusetts from Pittsfield to North Adams was constructed in 1845 and 1846. These railroads produced some trade with New York, and, just as important, induced considerable industrial expansion on the extensive interior river system of Massachusetts.

Interest never waned, however, in the possibility of a railroad across Northern Massachusetts to Troy, New York along the route originally recommended by Baldwin. Troy was jealous of the railroad connection of her southern neighbor, Albany. Massachusetts' northern residents wanted the same opportunities for development that existed along the southern route. Even Albany merchants became upset with the southern route because its steep gradients and excessive curvature sometimes resulted in long delays for shipping their produce. Lastly, Yankee pride was stung by the thought that only 4 and ¾ miles of rock stood in the way of this enterprise.

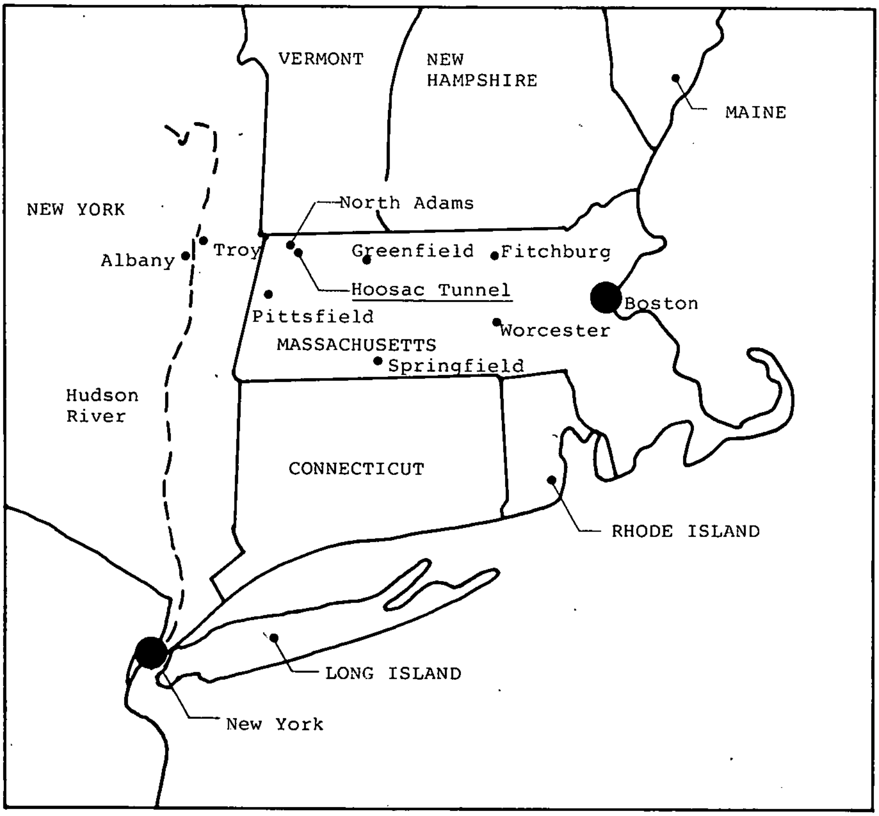


Figure 1. Hoosac tunnel project locus.

III. Construction History

A northern route was begun in the early 1840's with a railroad from Boston to Fitchburg, Massachusetts. This was extended by the Vermont and Massachusetts Railroad so that by 1848 a line was complete to Greenfield, Massachusetts. On May 10, 1848, the Massachusetts General Court chartered the Troy and Greenfield Railroad, including the Hoosac Tunnel, from Greenfield to the Massachusetts-Vermont border at Williamstown, Massachusetts. Soon thereafter, railroads were chartered in Vermont (Southern Vermont Railroad Company) and New York (Troy and Boston Railroad Company) to complete the link from Greenfield, Massachusetts to Troy, New York.

The location of the proposed Troy and Greenfield Railroad was filed in 1850 and a contract let on October 28 of that year to Gilmore and Carpenter for construction of railroad from North Adams westward to the State line. On January 7, 1851, directors of the Troy and Greenfield Railroad voted to break ground in North Adams.

As part of the early preparations for the tunnel, geologists were asked for opinions about the structure of Hoosac Mountain. The most notable of these was the State Geologist, President Edward Hitchcock of Amherst College. Professor Hitchcock had visited the mountain on numerous occasions, but never specifically to analyze the route of the proposed tunnel.

He correctly perceived that the mountain was composed of metamorphic rock (mica slate with some gneiss and occasional quartz veins) and that the mountain had been forced upward by high horizontal stresses. He was certain that no granite or trap would be found in the interior of the mountain. He had noticed some limestone "near the foot on the west side" but attached no particular significance to this observation. In general, he perceived the rock to be dipping steeply and striking nearly at right angles to the tunnel alignment, and felt that very little arching would be necessary. At a hearing before the Legislature on January 31, 1854, Hitchcock said, ". . . I do not believe that it (the tunnel) would require any more masonry for its support than would be necessary for a good sound stick of timber with an auger-hole bored through it." He even went so far as to volunteer to construct all required masonry for a few thousand dollars. Luckily, no one accepted his offer. Professor Hitchcock also had the "impression" that the tunnel would "go below where the groundwater percolated" and that it would be dry after tunneling in from the portals.

On the basis of this information, A.F. Edwards, the first Chief Engineer for the Troy and Greenfield Railroad, addressed himself to the feasibility of constructing the tunnel (since no tunnel of this size had been constructed in America) and, if feasible, to the cost and time for completion. True to his profession, he decided that the tunnel was indeed feasible. The cross-section recommended by Mr. Edwards is shown in Figure 2. If the tunnel were to be excavated manually from either portal, he estimated that it would cost $1,968,557 and that it would take 1556 working days to complete. With the use of two shafts, he estimated that the time for construction would be reduced to 1005 working days. Mr. Edwards felt that additional time reductions were possible if a tunnel boring machine then being tested at the east portal of tunnel (see Chapter IV) or various drilling machines could be made operable.

In 1854, the Massachusetts General Court agreed to loan the railroad corporation $2,000,000 to help with construction. Contracts with E.W. Serrell, Herman Haupt and others were let from 1855 to 1858 during which time the railroad from North Adams to Troy was finished and construction of the tunnel, and the railroad east of the tunnel begun. Construction continued until July 12, 1861 when W.S. Whitewell, a recently appointed chief engineer, refused to authorize an installment payment to the contractor and work ceased. The State took complete possession of the railroad on September 4, 1862 following mortgage payment default by the Troy and Greenfield Railroad.

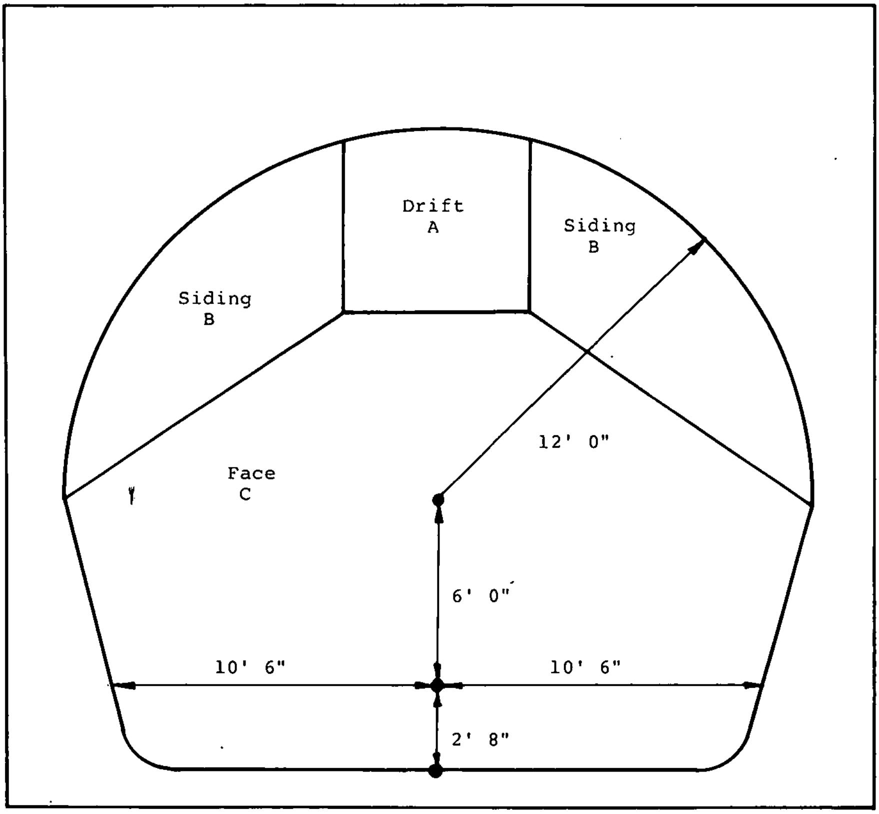


Figure 2. Tunnel cross-section recommended by A. F. Edwards, Chief Engineer, 1851.

There followed an interesting interlude in the construction of the tunnel from 1862 to 1868 when the State became the general contractor and appointed a three-man commission to oversee the project. One of the commissions' first official functions was to send Charles S. Storrow to Europe to study contemporary European tunneling methods. The commissioners also appointed Thomas Doane as their first Chief Engineer; he was responsible for many of the innovative tunneling procedures tried at the tunnel.

Work under State control proved to be very expensive; although in fairness to State officials, allowance must be made for cost escalation during the Civil War and for considerable research and development activities. During this period, a dam was constructed across the Deerfield River to provide water power for machinery, a central shaft was begun, compressed-air rock drills were introduced to the tunnel, nitroglycerine supplemented black powder as a blasting compound, electric blasting caps were used for detonation, and new surveying instruments were manufactured to improve tunnel alignment methods. The State supervised construction of the dam and machine shop near the east portal, the hoisting equipment at the central shaft, and the nitroglycerine factory and brick kiln at the west end. Toward the end of this period, successful contracts were let to B.N. Farren for open-cut excavation and brick arching along the west end of the tunnel and for construction of the railroad east of the tunnel to Greenfield. A contract for construction of the tunnel except the west end was let to Messrs. Dull, Gowan & White in 1867, but was terminated after a disastrous fire at the central shaft.

In June, 1868, Walter and Francis Shanly of Canada received a letter from Consulting Engineer Benjamin H. Latrobe, Jr. informing them that the tunnel was going out to bid and asking them to submit a proposal. This they did, and immediately became involved in the greatest undertaking of their career. It took two distinct types of courage to face the Hoosac: the first was to face the mountain itself, and the second was to face Massachusetts politicians who had shown a propensity for rough treatment of contractors associated with the project. The Shanlys overcame both obstacles with equal fortitude and energy.

The Shanlys were well pleased with the contract they had negotiated in the face of opposition. Originally it called for a lump sum deposit of $500,000 and payment of 80 percent of earned income for the duration of the project. This was a very large sum of money to commit. The Shanlys were able to change this so that instead of a $500,000 deposit, they were to perform $500,000 worth of work (which they thought they could do for $400,000). Their bid price was reduced from $4,623,069 to $4,594,268, largely on account of work performed by the State or omitted from the contract during the negotiation period. Payment was to be received by the Shanlys on a monthly basis at 80 percent of the payment schedule outlined in Table I. The Shanlys also agreed to the stringent rates of progress shown in Table II. The contract was signed December 24, 1868.

The Shanlys capitalized on the experiences of those that had come before and pushed the tunnel through to final hole-through on November 27, 1873. Although the Shanlys completed most of the tunnel excavation, they were apparently not interested in finishing the entire project. When they reached a provisional settlement of their contract on December 22, 1874, considerable tunnel enlarging and lining construction remained to be done. A great deal of open-cut excavation was also necessary west of the west portal.

On November 19, 1874, the Commonwealth of Massachusetts entered into a contract with B.N. Farren for $300,000 ". . . to do and perform all such work and furnish all necessary materials as may be required to complete enlargement and arching of the Hoosac Tunnel and the facade and stone-arch at the *eastern* portal . . .". The compensation schedule for work performed, with the usual 20 percent deduction for security deposit, is given in Table III. Payments were to be made monthly.

TABLE I
COMPENSATION SCHEDULE — SHANLY CONTRACT

East End Section	
Tunnel Enlargement	$16/cu. yd.
Heading Enlargement	$ 9/cu. yd.
Full-Size Tunnel Excavation	$11/cu. yd.
Central Drain Construction	$13/lin. ft.
Single-Track Construction	$14,000/mile
Central Section	
Fire-Proof Door Erection	$2,000
Shaft Repair	$5,830
Shaft Excavation	$395/lin. ft., or $33.62/cu. yd.
Iron Pipe Placement	$10/lin. ft.
Full-Size Tunnel Excavation	$14/cu. yd.
Central Drain Construction	$13/lin. ft.
Single-Track Construction	$14,000/mile
West End Section	
Heading Enlargement	$9.75/cu. yd.
Full-Size Tunnel Excavation	$12/cu. yd.
Brick Arch Construction	$22/1000 brick
Central Drain Excavation Only	$4.35/lin. ft.
Central Drain Construction	$13/lin. ft.
Central Drain Construction West of West Shaft	$3/lin. ft.
West End Stone Arch and Facade	$49,000
Haupt Tunnel Maintenance	$8,500
Single-Track Construction	$14,000/mile

TABLE II
RATES OF PROGRESS — SHANLY CONTRACT

	Feet/Month
East End Heading Advance and Tunnel Excavation	75
East End Full-Size Tunnel Excavation	125
Central Shaft Complete by May, 1870	---
Central Section Full-Size Tunnel Excavation	80
West End Full-Size Tunnel Excavation	100

TABLE III
COMPENSATION SCHEDULE — FARREN CONTRACT

Enlargement Excavation	$10.00/cu. yd.
Brick or Stone Masonry	$11.50/perch*
Eastern Portal Facade & Stone Arch	$25.00/cu. yd.
Foundation Masonry	$ 7.50/cu. yd.
Dry Packing Behind Arch	$ 2.75/cu. yd.
Wing Walls	$ 7.50/cu. yd.
Facing of Stone Walls	$ 0.50/sq. ft.

*1 Perch = 25 cu. ft.

The contract also provided for the use of the State's brickyard and for passage of trains through the tunnel. Farren apparently made a few extra dollars by agreeing to haul trains through the tunnel with his own locomotive. In case of controversy, the specification provided for the appointment of a three-man arbitration board, whose decisions were to be "final and conclusive."

Farren attacked the project with vigor, laying more brick and completing more lining than anyone thought possible at the time. He was greatly aided in this work by the fact that the Shanlys had intentionally overexcavated in some areas at the request of the State to allow room for lining. Farren laid more than 1,000,000 brick per month and completed 4922 ft of lining by June 30, 1876, at which time he turned the tunnel over to the State. The tunnel was officially dedicated and opened for business on July 1, 1876.

Farren was justifiably proud of the work he had done at the Hoosac; he completed all his work on or before schedule and never claimed as much as one penny in extra compensation. The Hoosac construction was exceptional in that it had three great contractors on it: Herman Haupt, Walter Shanly, and Bernard Farren.

A summary of the construction schedule is given in Table IV showing the time periods and activities of the major contractors. Additional discussion of construction activities at the four working areas of the tunnel (east end, central shaft, west shaft, west end) is given in Chapter V.

IV. Contemporary Tunneling Technology

When plans for the Hoosac Tunnel were first seriously considered around 1850, tunnel excavation procedures had not advanced very much in the preceding 200 years. Gunpowder had been known to Western man since the early 1300's and successfully applied to mining by placement in drill holes in the early 1600's in Germany. Drill holes were shallow and placed individually so that each shot would have the greatest advantage for moving the largest possible volume of rock. All drilling and mucking was done by hand. Ignition of the powder was done by a powder trail or simple fuse, preferably by someone who could run fast.

TABLE IV
SUMMARY OF CONSTRUCTION ACTIVITIES

Period	Contractor	Remarks
1850 to 1853	----------	Preliminary layout and railroad construction.
1854	----------	Commonwealth of Massachusetts loans $2 million to the Troy and Greenfield Railroad.
1855 to July 12, 1861	E.W. Serrell, Herman Haupt and others	2399 ft. of 14 x 6 ft. heading and 2129 ft. of 14 x 18 ft. full-size tunnel completed at east end, west shaft sunk to grade, 450 ft. of tunnel completed at west end (later abandoned).
1862 to 1868	Commonwealth of Massachusetts	Studied contemporary European technology, placed the tunnel on one straight line, built power dam and machine shop at east end, developed practical compressed air rock drill, introduced nitroglycerine for general heading advance, enlarged Haupt's tunnel at east end to double track dimensions and carried heading 5282 ft. from east portal, began excavation of central shaft, tunneled 1609 ft. east from west shaft, completed extensive work on west end of tunnel.
1866 to 1869	B. N. Farren	Excavated and lined 931 ft. of double track tunnel at west end under most difficult working conditions and completed drainage adit from west end to west shaft.
Aug., Sept. & Oct. 1867	Messrs. Dull, Gowan and White	Continued excavation at east end, carried central shaft to a depth of 583 ft., continued excavation eastward from west shaft with a top heading rather than the bottom heading which was used at the east end. This brief contract was voluntarily withdrawn following the central shaft fire on Oct. 19, 1867.
Dec. 24, 1868 to Dec. 22, 1874	Walter and Francis Shanly	Carried central shaft to full depth, holed through at east end on December 12, 1872, holed through at west end on November 27, 1873, firmly established the center cut system of heading advance.
1873 to 1874	Messrs. McClallan, Son & Walker	Constructed railroad from west portal to North Adams, including extensive rock excavation near west portal along abandoned Haupt tunnel.
Nov. 19, 1874 to June 30, 1876	B. N. Farren	Completed enlarging and lining of tunnel, laid track in tunnel.

Initially rock excavation at the Hoosac Tunnel was similar to the description above. Holes were drilled with a small sledge by one man striking a drill held by himself, or, if room allowed and the holes were to be advanced more than about three feet, by one, two or even three men striking a drill held by another person. Hole locations were selected individually by the foreman based on the rock mass configuration and observed geologic discontinuities.

After drilling several holes (8 to 10), the men were withdrawn behind heavy wooden parapets, the holes charged with powder, and fuses lighted. The fuse in this case was probably the Bickford Safety Fuse developed by William Bickford in 1831. It consisted of a powder thread spun in jute yarn and waterproofed with coal tar. It burned at approximately 2 to 3 feet per minute. When a blast occured, the parapet behind which the men and mules were protected was showered with rock, every lamp in the tunnel was extinguished by the air blast, and the tunnel was filled with dust and acrid smoke. During the blast, the foreman would carefully count the number of explosions to be certain that none of the fuses had been cut or that a hole was not "hanging fire". Very often the men had to stay behind the parapet until the reason for a misfire could be ascertained. Upon receiving an all-clear signal, the men returned to the face to begin loading broken rock into mule cars for removal from the tunnel and drilling more blast holes.

Initial attempts to improve the rate of progress with the techniques described above led to experiments with tunnel boring machines. For those who think tunnel boring machines are a recent idea, it will come as a surprise to learn that the first tunnel boring machine was proposed by Monsieur Mauss in 1845 for use at the Mont Cenis Tunnel (Drinker, 1878.). By 1850 his idea had been given up as impracticable.

In 1851, the Wilson Patent Stone-Cutting Machine was constructed by Richard Munn & Company of South Boston for use at the east portal of Hoosac Tunnel. The machine was designed to cut a 24-foot outside diameter, 13-inch wide groove in the rock by means of revolving cutters with a small-diameter cylindrical borehole at the center. After drilling approximately two feet, it was planned to withdraw the machine and remove the center core by blasting or wedging. During various trials, the machine actually cut rock at the rate of 14 to 24 inches per hour to a total depth of approximately 10 feet. The machine's greatest flaw was apparently in the cutter bearings which could not take the pressure. In addition, the machine was run by steam and it is highly unlikely that steam could have been piped very far in from the portal without condensing.

A second machine tried at the west portal was introduced by Herman Haupt in 1857. It was constructed by the Novelty Iron Works in New York at a cost of $25,000 and was reportedly patterned after a machine then in use in California. The machine was designed to cut an 8-foot-diameter bore which was to be used as the heading. A report by Henry Cartwright dated September 20, 1857 describes a trial run of the machine at Hoosac Tunnel in fractured limestone near the west portal. Mr. Cartwright was pleased with the performance of the machine and expected a rate of progress of between

15 and 24 inches per hour as soon as the competent mica slate in the interior of the mountain was encountered. Haupt & Company never had the chance to try the machine under those conditions, however, because their contract was terminated. Although additional tunnel boring machines were tried at various tunneling projects following the Hoosac experiment, none could be made to operate efficiently.

At the same time that experiments were proceeding with tunnel boring machines, other attempts were being made to mechanize the tunneling process. The two most important results of those experiments were the development of a practical compressed air rock drill, and the development of blasting compounds more powerful than gunpowder.

The first mechanical percussion drill was invented by J. J. Couch of Philadelphia in 1849. It consisted of a machine that hurled a "lance" at the rock and was quickly found to be terribly inefficient. One of his assistants, however, J. W. Fowle, developed a technique for direct impact of drills held against the rock; this was to prove a key to later success. Despite his partial success, Fowle did not continue to develop a practical drill.

One of the primary responsibilities of Charles S. Storrow, on a trip to Europe under the auspices of the Commonwealth of Massachusetts, was to visit the famous Mont Cenis Tunnel between France and Italy and investigate a compressed air rock drill which had been introduced there in 1861. The Mont Cenis project was important because it demonstrated the use of a drill, the concept of a drill carriage for supporting several drills at the face, and, most important of all, it demonstrated the power of compressed air as a power source. Prior to this time, steam had been the primary source of mechanical power, but steam condensed when it was piped great distances outdoors. At Mont Cenis, it was shown that compressed air could be piped long distances without losing its "elastic force". Although Storrow was pleased to discover that the Mont Cenis drill had increased the rate of advance of the tunnel, he also discovered that the drill had not reduced the *cost* of tunneling. The cost remained high because the drill was expensive to manufacture, very heavy and cumbersome to work with in the tunnel, and subject to excessive maintenance. Storrow was confident that a more efficient drill could be developed by American machinists.

The first attempt at compressed air rock drilling at the Hoosac Tunnel was at the east end in the Summer of 1866. The drill, known as the Brooks, Gates and Burleigh Drill, had been developed under the direct supervision of State authorities at the Putnam Machine Company in Fitchburg, Massachusetts. It was used at the tunnel for six months and proved a failure. To quote Thomas Doane in his annual report for 1866, "They were beautiful machines, light in weight, compact in form, and automatic, but proved themselves in a few days to be deficient in the very necessary quality of strength."

Charles Burleigh had made extensive observations of this machine and proceeded to invent another drill, known as the Burleigh Drill, which was introduced to the tunnel on November 1, 1866. (Mr. Burleigh used the idea of J. S. Fowle mentioned earlier and had to purchase Mr. Fowle's patent later for $10,000.) The drill was an immediate success and was used at the tunnel continuously until completion. Walter Shanly purchased 60 of these drills from the Putnam Machine Company at a cost of $625 each at the beginning of this contract. The drill reportedly weighed over 500 pounds and advanced a two-inch-diameter hole at two inches per minute to depths up to 13 feet. The drill itself had a hole in its center through which water was pumped to cool the bit and clear dust from the hole. In a letter dated February 26, 1872, Walter Shanly said he estimated "the savings in time by use of these drills at fully fifty percent." The compressed air rock drill was the first important component of a more rapid tunneling technique.

Another compressed air rock drill, referred to as the Wood & Robinson Drill, was used at the tunnel during the Dull, Gowan & White contract in 1867. The fear that this drill infringed on Burleigh's patent rights caused its use to be discontinued, although it was subsequently used on other projects with great success.

The second important development toward more rapid tunneling was an invention by Ascanio Sobrero in 1847 in Italy; it was nitroglycerine. Nitroglycerine was several times more powerful than gunpowder, but highly susceptible to sudden detonation with the slightest disturbance. Careless handling of the material had resulted in many accidents and in the deaths of many innocent bystanders. Several countries had passed laws prohibiting its manufacture and shipment and the United States had severe restrictions on interstate shipment.

Alfred Nobel had begun experimenting with nitroglycerine in Europe in the early 1860's. His American representative, Colonel Tal P. Schaffner, actually conducted the first experiments with nitroglycerine at the east heading of the west shaft on the Hoosac Tunnel in 1866. In 1867, George W. Mowbray was invited to come to North Adams, Massachusetts to help with the Hoosac Tunnel project.

Professor Mowbray had become familiar with nitroglycerine by using it to enlarge oil wells near Titusville, Pennsylvania. He came to North Adams, (reportedly when his business interests in Pennsylvania had taken a turn for the worse) and constructed a plant for manufacturing nitroglycerine near the west end of the tunnel. Actual production began in January, 1868 and continued throughout construction of the tunnel during which time more than 500,000 pounds of nitroglycerine were manufactured. Some of it was shipped outside the North Adams area.

Mowbray manufactured nitroglycerine by mixing glycerine, drop by drop, with nitric and sulfuric acids while the entire solution was bathed in ice and stirred continuously by a cold stream of bubbling air. The air apparently removed from the mixture impurities which were liable to cause spontaneous decomposition and explosion. Following manufacture, the nitroglycerine was placed in stone jars, immersed in water at 60° to 70°F for several days, and skimmed of impurities which collected at the top. Then the nitro was placed in paraffin-lined metallic containers and frozen. During freezing a "reddish liquid" accumulated at the top which was "uncrystallizable" and highly explosive. The reddish liquid was also carefully removed.

It was found out quite by accident at the Hoosac that frozen nitroglycerin was more difficult to explode than the liquid form; the opposite had been believed prior to this time. William Granger was determined to bring nitroglycerine over the mountain to the east end during the winter of 1868-69 to remove anchor ice from the canal. During the trip, his sleigh was upset and the nitro cartridges spilled out onto the snow and were frozen. Despite his thinking the material now highly explosive, Mr. Granger continued to the east end and found out, to his surprise, that he could detonate the nitro only after it had been thawed. From then on, all nitroglycerine was transported in a frozen state.

Prior to blasting, the nitroglycerine was placed in metallic tubes 1-1/2 inch in diameter and 4 to 6 feet long. These were placed in the drill hole together with an exploder, wired together with all other charges, and detonated with electric blasting caps. Mowbray laid down stringent rules about handling nitro which made it reasonably safe, but any slight degree of carelessness left little margin for survival. Many miners were killed or maimed by the explosive. The biggest advantage of nitroglycerine was that it fractured harder rock and much more rock than gunpowder. It also had the beneficial side effect of not producing as much smoke and fumes as gunpowder.

A third, but somewhat auxiliary development which contributed to a more rapid tunneling rate and which was used extensively at the Hoosac Tunnel was electrical ignition or detonation. Moses Shaw had patented the idea of simultaneous *ignition* of several charges of gunpowder with electricity in 1831 and the technique was apparently used in mining operations. Electrical ignition had the beneficial effects of eliminating the smoke of common fuses, of allowing all the men to be withdrawn before firing any charges, and of much more dependable performance than the common fuse which was sometimes cut by early explosions or simply failed to ignite the gunpowder. The first use of electrical ignition at the Hoosac Tunnel was at the east end working area in the summer of 1865. By 1866, the technique was in general use.

With the advent of nitroglycerine, electricity was used together with blasting caps for *detonation* as well. At the Hoosac Tunnel, blasting caps (exploders) were made by Charles A. and Isaac S. Browne in a small factory near the west end of the tunnel. As many as 30,000 caps a month were produced at the height of construction. The cap consisted of a small wooden plug with two wires, between which was placed a small quantity of fulminate of copper. This plug was inserted into a larger outer shell containing fulminate of mercury, all of which constituted the blasting cap. Later improvements of the cap were made to eliminate the too-sensitive fulminate of copper. Charles Browne, in fact, was blinded by a premature explosion of fulminate of copper.

All of the above developments, together with drill carriages designed by

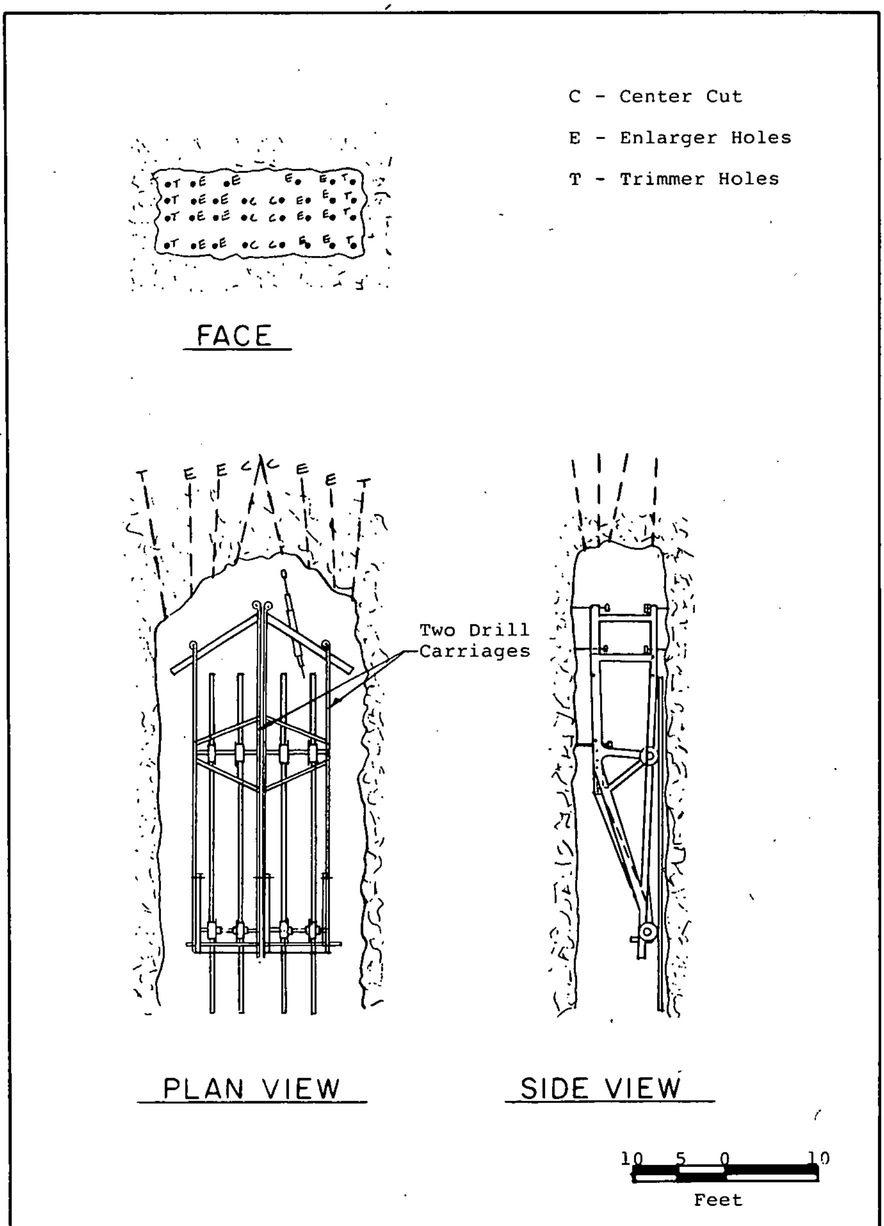


Figure 3. Center-cut system of heading advance.

Thomas Doane, were combined at the Hoosac Tunnel in the so-called "center-cut system" of heading advance, Figure 3. The V-shaped set of holes at the center was drilled first, followed by enlarger and trimmer holes. Each set of holes was loaded and shot before drilling the next set. The drilling advance was increased from the three feet possible by hand drilling to ten feet and Walter Shanly estimated that tunneling progress was increased five-fold with the center-cut system. A comparison of Shanly's and Haupt's work shows this to be the case. Significantly, Shanly's average production rate was even 50 percent greater than at the Mont Cenis Tunnel in terms of cubic yards of rock removed per month from a heading opening to a portal.

The center cut system of heading advance represents the Hoosac tunnelers' chief contribution to tunneling technology. To quote Gillette (1904), "The center-cut system of drilling was first used in the celebrated Hoosac Tunnel in Massachusetts . . . .". Even as late as 1969, Dupont's *Blaster's Handbook* said: "The V or wedge cut is one of the oldest of the angled cuts and is still commonly used." To the Hoosac tunnelers belongs the distinction of having firmly established a new method of underground excavation which, with some modifications, has been used in almost every rock tunnel constructed in the world until recently.

Another significant contribution of the Hoosac tunnelers was the demonstration of modern surveying accuracy. There is a popular misconception to the effect that Herman Haupt had made a mistake with his survey control and that he was excavating two tunnels. This is not true. Herman Haupt was actually excavating one tunnel along two headings with slightly different bearings, so that when the headings met and the alignment was found to be off by several feet (as was common) the lines could be connected by a simple curve. At the Mont Cenis Tunnel referred to earlier, closure was quoted as excellent, although the discrepancy was nearly 18 in.

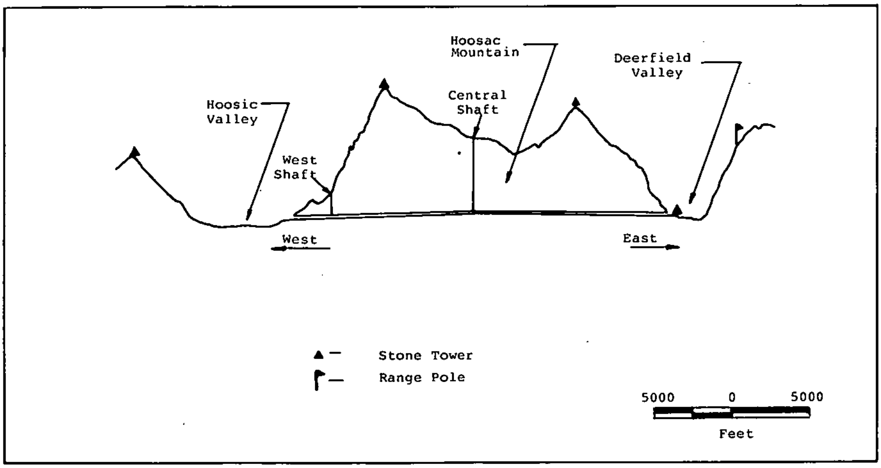


Figure 4. Profile of Hoosac Mountain showing survey control layout.

When the State took control of the Tunnel in 1862, Thomas Doane was said to have "boldly" re-established control and set the tunnel on a single tangent. This was "bold" because if the two portions of the line did not meet at the center, it would require an S-type curve to connect them. Shown in Figure 4 is the survey control established by Tom Doane. It consisted of eight signal stations: one at each portal, one at each of two shafts, one at each summit of Hoosac Mountain, and one on each mountain opposite the portals. Four of the stations were permanent 10-foot-square stone towers. The averaging of numerous observations in different weather conditions was used to obtain accuracy.

At the central shaft, the surveyors had to contend with a vertical drop of 1030 feet and a base length of only 23 feet. Air currents, water infiltration, equipment vibrations and normal pendulum action caused considerable motion of the lines at the bottom of the shaft. However, complete enclosure of the plumb lines, suspension of the plumb bobs in water, and numerous repetitions of observations resulted in a very successful survey. Closures at the Hoosac Tunnel were 5/16 inch and 9/16 inch at the two hole-throughs. These closures would be satisfactory even by today's standards and represented an order of magnitude improvement over contemporary procedures.

V. Construction Activities at the Hoosac Tunnel

Chapter V contains a discussion of specific construction activities at the Hoosac Tunnel which can be used together with information in Chapter III for an overall understanding of the Hoosac Tunnel project. Figure 5 is a cross-section of Hoosac Mountain showing the four principle working areas of the tunnel. Discussion in Chapter V is divided on the basis of these working areas beginning with the east end and proceeding westward. Each

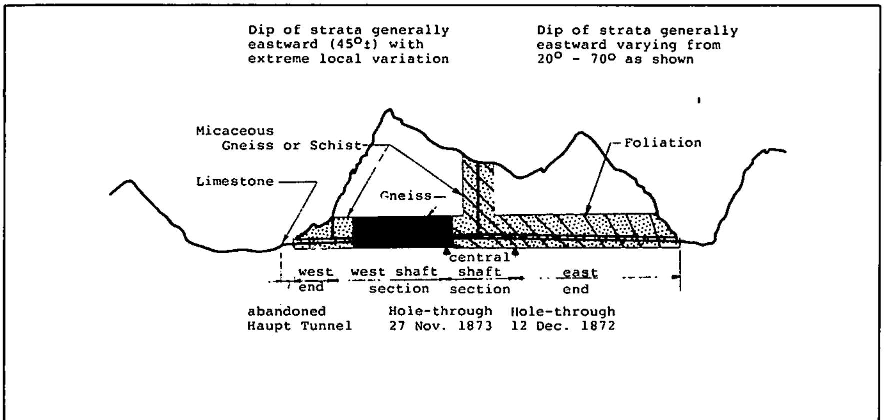


Figure 5. Construction working areas and general geologic information.

working area is described from beginning of construction to hole-through in that area to avoid extensive cross-referencing of contractors associated with the project. Reference to Table IV in Chapter III may help to clarify the chronological sequence of contractor involvement.

Also shown in Figure 5 is simplified geologic information for Hoosac Mountain. This information is based on geologic mapping of the tunnel immediately after excavation in conjunction with proposals for lining the tunnel. In general, bedrock from the east end to beyond the central shaft and near the west end was described as a micaceous gneiss or schist. Rock foliation dipped generally to the east being steepest near the east end (70°) and decreasing rather uniformly toward the center of the mountain. Dips of 20° to 30° were noted west of the central shaft. Dips along the west portion of the tunnel were noted as generally eastward (45°+), but were subject to extreme local variation.

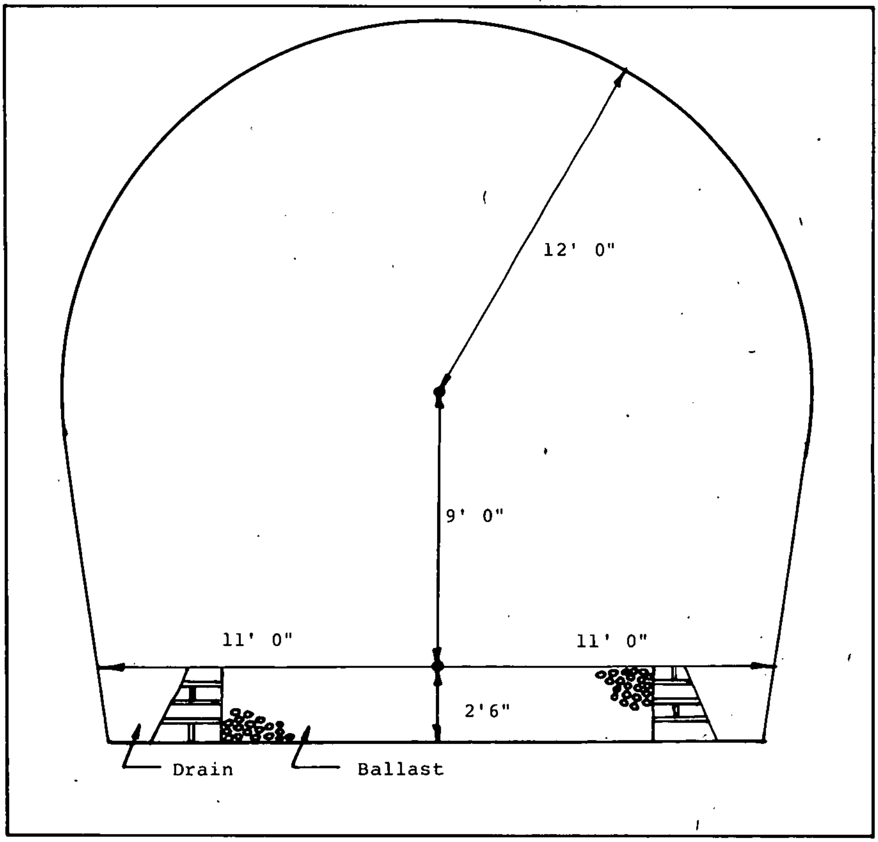


Figure 6. Tunnel cross-section recommended by State Commissioners, 1863.

The west-central portion of the mountain contained a rock described as a gneiss or granitoid gneiss. It was more coarsely textured and harder than the rock described above.

The mountain was apparently intersected throughout with hard seams of quartz varying in thickness from a few inches to several feet. The mountain also contained numerous shear zones parallel to the foliation with fractured rock and clay gouge, and seams of weathered feldspar. These weak areas generally had the greatest instability and inflow of groundwater.

Conditions at the west end were greatly complicated by a thrust fault which caused an abrupt change in rock type at the west portal from schist or gneiss to limestone. This, together with hydrothermal alteration resulted in a rock mass that was severely weathered, fractured and disintegrated. It was referred to in contemporary terminology as "demoralized" (See West End Working Area).

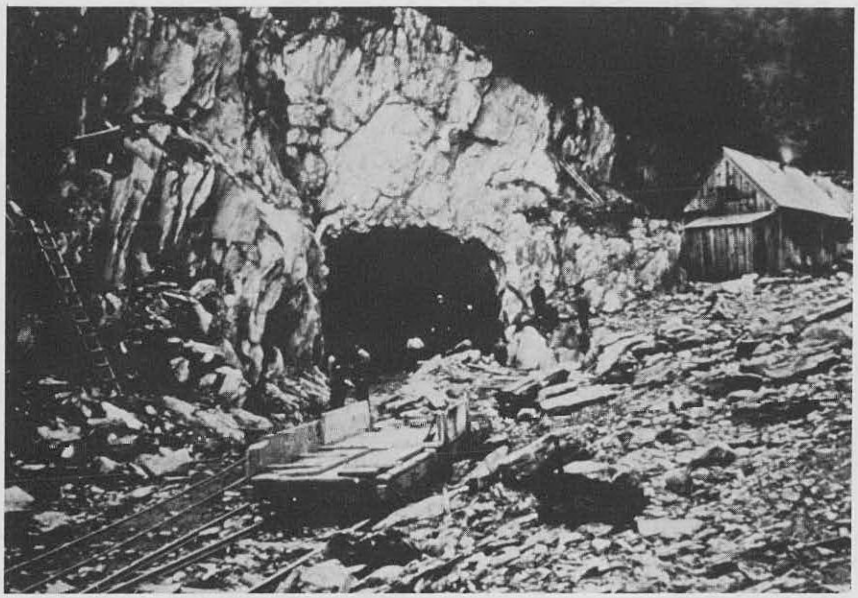
East End Working Area

The first productive work on the Hoosac Tunnel was accomplished by Herman Haupt from 1855 to July 12, 1861. At the east end, Haupt excavated 2399 ft of 14-foot by 6-foot heading; 2129 feet of which were enlarged by means of two, 6-foot high benches to full, *single-track* dimensions of 14 x 18 feet. A single-track tunnel was allowed in Haupt's contract with the Troy and Greenfield Railroad with provisions for later enlargement to double-track dimensions at the railroad's discretion. A reasonable, average advance rate for the east end heading was 50 feet per month. Haupt estimated the cost of the completed tunnel at $50 per foot or $5 per cubic yard.

When the State took over the tunnel in 1862, a three-man commission was appointed to oversee construction. One of their recommendations was to enlarge the tunnel to double-track dimensions as shown in Figure 6. Work actually began on the enlargement in 1863 and was completed in March, 1865. As the work progressed, it became obvious that a brick arch would not be used at the east end, and the tunnel was excavated to a rectangular shape; 24 feet wide and 20 feet high. Work on the enlargement was estimated to have cost $10.64 per cubic yard.

With the enlargement complete, the State began excavating a new heading near the bottom of the tunnel as shown in Figure 7. It was felt that the bottom heading would result in more efficient drainage, continuous mucking to the heading, and the possibility of enlarging the tunnel in any desired configuration. The heading was driven by three shifts of eight hours each. Each shift consisted of five holders and five strikers with one foreman, who was "in the habit of relieving one of the men for a few moments, now and then". Five 1⅜-inch-diameter holes were drilled and blasted every two hours resulting in an average daily advance rate of 2½ feet.

Extensive work was also undertaken during this period on a dam-canal-machine shop complex for use with compressed air rock drills which were then in the development stage. Although the dam at the east end was quite an accomplishment in its own right at the time, especially in a river as wild as



East end of Hoosac Tunnel during construction. Portal erected here in 1877 by B. N. Farren.

the Deerfield River, it never really fulfilled its expectations. Originally, it was planned to pipe compressed air to all the working faces from the east end, and to maintain the dam after construction of the tunnel to furnish power for a small manufacturing facility. Ice jams in the winter and low flows in the summer resulted in intermittent power, however, and all power produced by the water was needed at the east end. In fact, steam compressors had to be erected at the east end to provide supplementary power. Maintenance costs for the dam were also high because of perennial, violent floods in the Deerfield River, especially during spring ice flows.

As stated in Chapter IV, the successful Burleigh Drill was finally introduced at the east end of the tunnel in November, 1866. With this drill, heading advance at the east end was twice as much in 1867 (1187 feet) as in 1866 (570 feet). This was the case even though the heading had been progressively enlarged from 15 feet by 7 feet to 24 feet by 8 feet, so there was an even better improvement in terms of cubic yards of rock removed. The monthly working rate was still further improved during 1868 although the total advance (575 feet) was less because work was performed for only 5½ months. The primary causes for delay were lack of power from the dam and decreased activities preparatory to turning the work over to the Shanlys. By the time the State ceased work in 1868 the heading had been advanced 5282 feet from the portal, and the tunnel was complete or nearly complete for 2635 feet.

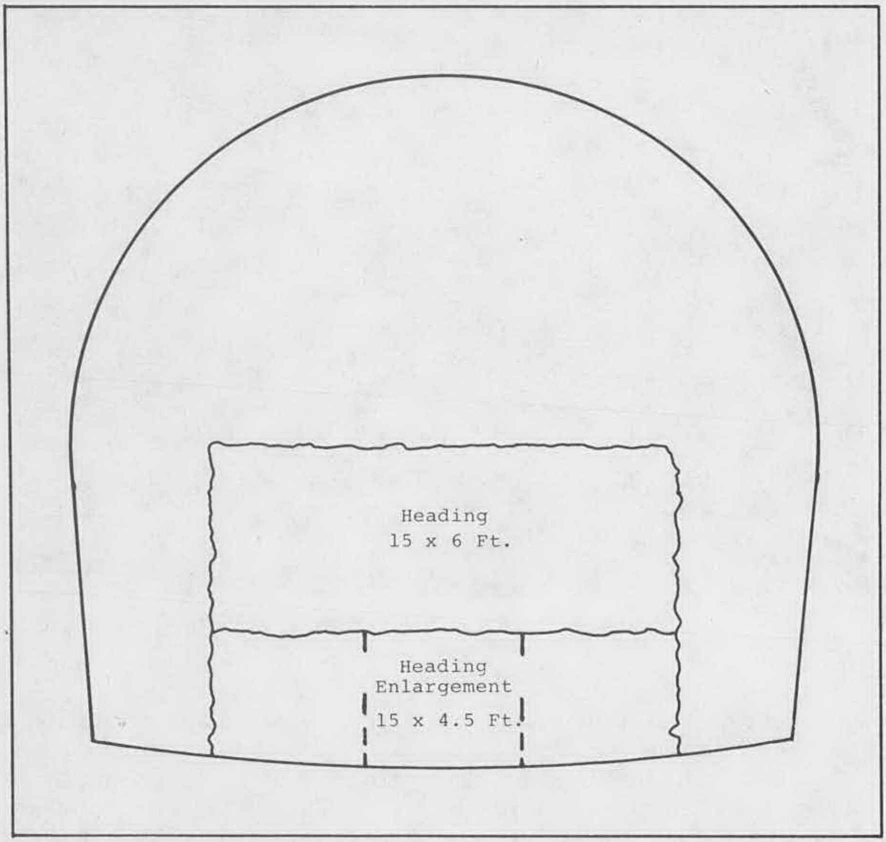
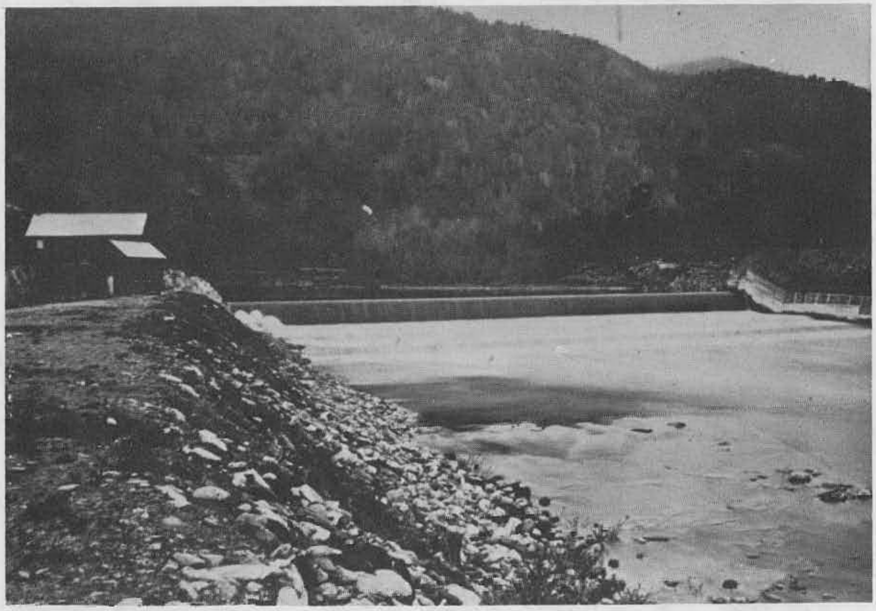


Figure 7. Heading advance at east end and first portion of eastward heading from west shaft, 1865. Note: Heading moved to crown on west side by Dull, Gowan & White in 1867.

Work began in earnest by the Shanlys in April, 1869. At the east end, the Shanlys erected new steam driven compressors to supplement water power from the Deerfield River. They also began using a small locomotive to remove muck from the enlargements. Tunnel advance was made with a 24 foot by 8 foot bottom heading and two, 6-foot overhead enlargements for a total of 20 vertical feet. Gunpowder was used in the heading as an economy measure and nitroglycerine in the overhead enlargements. Compressed air rock drills and drill carriages were used continuously at the heading; work proceeded as smoothly as could be expected. A total of three 8-hour shifts, 15 men each shift, worked at the east end heading 6 days per week. Advance rates increased to as much as 167 feet per month as the work progressed. Hole-through of the east-end heading with the heading driven eastward from the central shaft occurred on December 12, 1972, 11,274 ft from the east portal.

Machine shop near east end of tunnel. Note "muck" pile in the background.



Famous Deerfield Dam constructed under supervision of Thomas Doane, Circa 1864.

Central Shaft Section

The 15-foot by 27-foot elliptical, central shaft was started by the State in December, 1863. The reasons for the shaft were to provide for two new headings and to provide ventilation for the completed tunnel. The shaft was sunk through 25 feet of soil and 47 feet of rock by September, 1864 when worked ceased temporarily. Rock removed from the shaft was used to construct a thick masonry retaining wall in the soil portion and to extend it to 10 feet above ground surface.

By the end of 1865, the shaft reached a depth of 232 ft. An attempt was made during the spring of 1865 to introduce "Mr. Harsen's" steam-driven drilling machines but the drills became too hot to handle, filled the shaft with "hot vapor", and were removed. A "Mackenzie" blower was used for ventilating the shaft after a blast; clearing the air could reportedly be accomplished in five minutes. In October, a "naphtha" gas apparatus was installed by a firm from Meriden, Connecticut for lighting the shaft.

The shaft was worked by three shifts of eight hours each. Drill holes were made by hand to an average depth of three feet. Each gang loaded and shot its own holes at the end of the shift. All rock was removed by hand and water by bailing. It was reported that water infiltration in 1865 averaged 5 gallons per minute.

Work proceeded smoothly at the shaft throughout 1866, and the shaft reached a depth of 393 feet by the end of December. The average advance rate for nine months of active excavation was 17 feet per month. The other

Central shaft working area.

three months were consumed installing new hoisting equipment. In October, 1866, the common fuse was replaced by the Abel fuse which was fired by electricity. Reportedly, one or two holes had been lost on every shift when using the common fuse. Average water infiltration during 1866 was 11 gallons per minute. It is interesting to note that even at this low rate of infiltration two to ten tubs of water had to be removed from the shaft for every tub of rock.

Work continued quite smoothly during 1867 until the fire at the shaft on October 19, 1867. Work at that time was under the direction of Messrs. Dull, Gowan & White. The fire was caused by the accidental ignition of naphtha gas used to light the shaft. By this fire, almost every structure at the shaft was destroyed, along with thousands of board feet of lumber. More than a year was needed to reconstruct the buildings and recover the bodies of the thirteen men lost at the bottom of the shaft, then at a depth of 583 feet. The cost of excavating the shaft during the period of State control was placed at approximately $25.00 per cubic yard.

Work by the Shanlys at the central shaft began early in 1869 and was plagued by the usual problems of insufficiency or malfunction of equipment. The Shanlys spent considerable time and money upgrading these works. Hand methods were used for both drilling rock and removing water. Various attempts to introduce drilling machines into the shaft were unsuccessful. Blasting was by nitroglycerine and electrical blasting caps. The shaft was carried to its full depth of 1030 feet by August, 1870.

As the tunnel headings started away from the shaft, the Shanlys installed pumps to remove water. Apparently, pumps were placed at 270 foot vertical intervals in the shaft, each with its own tank to receive water pumped up from below. All of the water was pumped into a small adit 1009 feet from the floor which emptied into a nearby ravine. The maximum pumping rate was approximately 225 gallons per minute.

During shaft sinking, rock and water were removed in one-cubic-yard buckets. Upon completion of the shaft, the walls were trimmed and flooring strengthened to accept three-cubic-yard buckets and vertical guides. It is not known whether these buckets and guides were designed or installed by the celebrated Otis Brothers & Company or not. Otis Elevator Company, which is still in business in Yonkers, New York, has no currently available record of such an installation although the record may have been lost or destroyed. The fact that the cars were confined to their "own vertical channel by guides built into a rigid framework" would not qualify them as Otis elevators, because Otis had patented a safety mechanism which stopped cars from plummeting to the bottom in case of supporting cable failure, and three men were killed at the central shaft in October, 1870 for this very reason. A vague reference to many "inventors" having visited the site (Walker, 1957) suggests that one of the Otis brothers may have visited the Hoosac. The vertical rise at the Hoosac was impressive, however, for any type of elevator at the time. By way of comparison, Otis did not install an elevator in a building with more than 1000 feet of travel until 1929.

The final attack on the tunnel began with the advance of two headings, east and west, from the central shaft. Hand methods were used for mining until the headings were approximately 300 feet apart and room existed to introduce drilling machines. No sooner were these machines introduced, however, then the west heading began to penetrate a water-bearing zone with some seams producing as much as 50 gallons per minute. The Shanlys decided to abandon this heading, over strong objections of the State, and make a through connection to the east to allow water to drain out of the tunnel. This they did, with the east side headings meeting on December 12, 1872 at a point 1563 feet east of the central shaft. Advance rates for the heading east of the central shaft increased to as much as 148 feet per month.

With a path now complete for water to drain from the tunnel, the Shanlys attacked the west heading with vigor. Advance rates varied from 131 to 184 feet per month during 1873 until November 27, 1873 when final hole-through occurred at a point 2056 feet west of the central shaft.

West Shaft Section

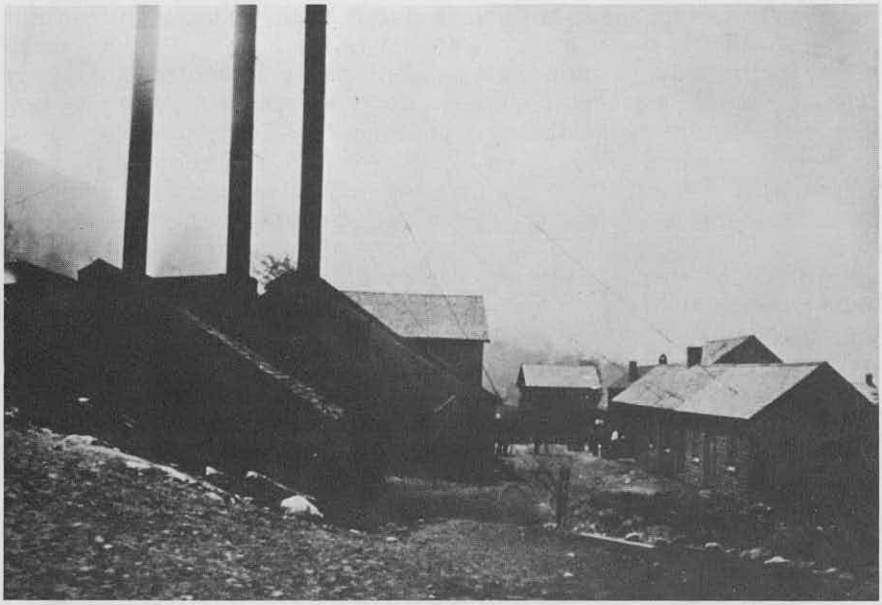
Work on the west shaft began in the late 1850's under the direction of Herman Haupt. Haupt excavated the west shaft in order to open a productive working face at the west end of the tunnel. Earlier, Haupt had discovered the loose, weathered rock and large water flows near the west portal which were to "embarrass" work in that area for years to come. When Haupt's contract was terminated on July 12, 1861, the west shaft had been sunk to grade at a depth of 320 feet, and 50 feet of tunnel had been excavated easterly from the bottom of the shaft.

Tunneling at the west shaft was performed rather haphazardly by the State during the latter part of 1863 and throughout 1864. By the end of 1864, 128 feet had been driven to the east and 155 feet to the west. Early in 1865, several buildings at the west shaft were burned by striking workmen, further delaying the work.

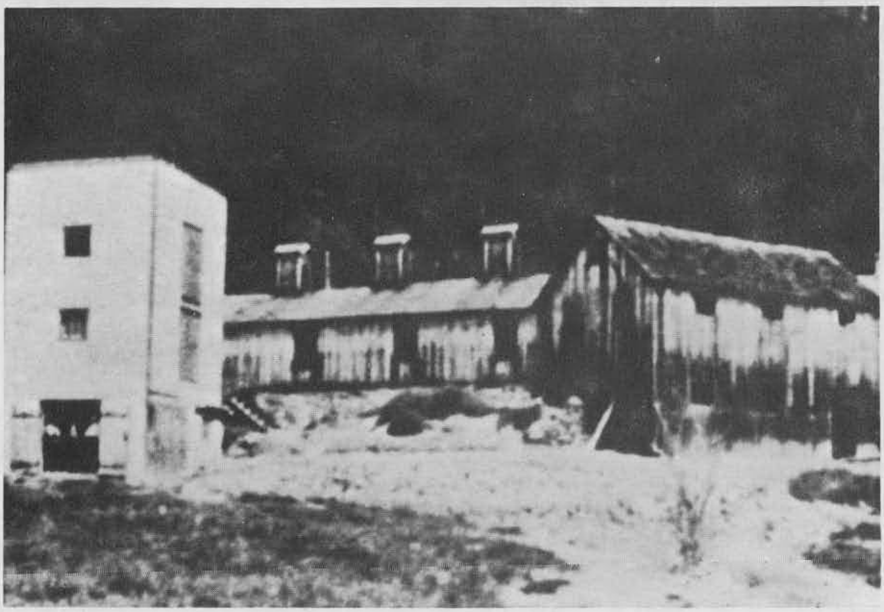
Work on the east heading was begun in earnest on June 1, 1865 at which time the bottom heading was increased in size from 11 feet by 5 feet to 15 feet by 6 feet. Progress from June 1, 1865 to the end of 1866 was approximately 870 feet. The first nitroglycerine experiments were tried at this heading by Colonel Schaffner in August and October of 1866. Early in December, 1866, all of the men were driven from the heading by a great influx of water (estimated at 250 gallons per minute) and no work was performed here again until June, 1867. Total water flow from the west shaft at this time was estimated at 1000 gallons per minute.

In 1867, some of the work at the west shaft was performed under contract by Messrs. Dull, Gowan & White. It was during this time that the eastward heading from the west shaft was raised to the crown, (See Figure 7) and increased in size again to 24 feet by 8 feet. Progress during 1867 was 290 feet.

In 1868, the State made the final introduction of "modern" tunneling appliances to the east heading of the west shaft preparatory to turning the



West shaft working area.



Professor Mowbray's nitroglycerine factory.

work over to the Shanlys. These included the introduction of drilling machines into the heading in June and the final adoption of nitroglycerine for general heading advance in August. Mowbray's nitroglycerine factory was located approximately 1000 feet south of the west shaft. A drift connection was also made with the west end allowing water to flow out of the tunnel. No longer would progress be delayed because of insufficient pumping capacity at the shaft. By the time work ceased directly for the State in 1868, the main heading had been extended 1609 feet eastward from the west shaft.

In 1869, the Shanlys spent considerable time and money upgrading and repairing the buildings and equipment at the west shaft preparatory to beginning excavation eastward and westward from the bottom of the shaft. Work on the eastward heading from the west shaft proceeded with a 24 foot by 8 foot top heading and two 6-foot-high benches. Drilling was done with Burleigh compressed air rock drills. Finally on November 27, 1873, the eastward heading from the west shaft met the westward heading from the central shaft at a point 10,188 feet from the west portal to herald the final hole-through for the tunnel.

West End Working Area

In this paper the term "west end" refers to the section from the west portal to the west shaft. The section changed its length several times during construction. When Haupt started construction at the west end in 1855, his contract did not contain a pay item for general excavation. He, therefore, wanted to make the tunnel as long as possible and his portal was 3008 feet from the west shaft. By the time his contract was terminated in 1861, he had excavated 450 feet eastward under very difficult tunneling conditions.

When State officials took over construction in 1862, they decided to move the portal 561 feet eastward and 20 feet northward of the original location to avoid some bad tunneling ground and to line up with Tom Doane's new straight-line alignment for the tunnel. As a result, all of Haupt's tunnel was abandoned although it was used for years to gain access to the new west end portal.

At the new portal, the State immediately began a deep open-cut and encountered great quantities of quicksand, water, boulders and "demoralized rock". Descriptions of the "demoralized rock" indicate that it was a classic example of saprolite, which is a rock completely weathered to soil, but which retains the structural features of the parent material such as foliation, joints, etc. Costs for various kinds of excavation were estimated as follows:

Earth, quicksand	$1.05/cu. yd.
Loose rock	$1.22/cu. yd.
Solid rock	$2.50/cu. yd.

Work at the west end was slow during 1865 because of the difficult working conditions and because the State was not anxious to complete this portion of the work. Money managers felt that considerable amounts of interest could be saved by delaying expenditure on this portion of the work until its completion was needed to finish the entire tunnel. The west heading from the west shaft was stopped on August 2, 1865 at an advance of 281 feet because it appeared that the heading was about to enter the "demoralized rock" and water flow increased from 25 to 65 gallons per minute. No chance could be taken on flooding the eastward heading which had far to go. A small drift was attempted from the west portal to the west heading but it collapsed with the great flow of water and had to be reclaimed by extending the open cutting.

Several test pits were excavated at this time to better define subsurface conditions. One of these indicated that the west heading could be extended by another 1000 ft. Prior to any heading advance, however, the existing heading was enlarged for 298 feet to 15 feet by 10.5 feet and a supplementary shaft was sunk 264 feet west of the west shaft. The supplementary shaft was used to improve alignment and as a pumping shaft. In December of 1866, work ceased at the west shaft until April, 1867 because of a great influx of water.

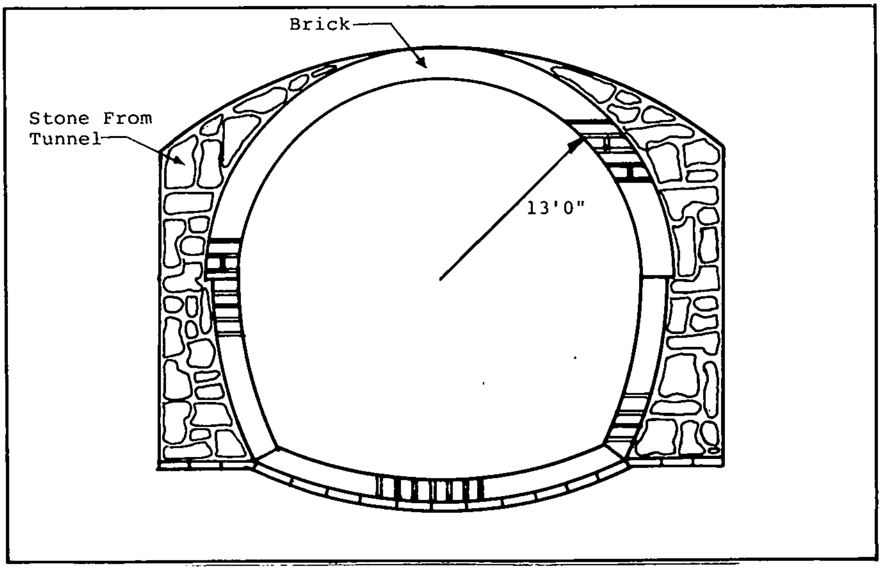


Figure 8A. Structure used by Farren in cut-and-cover area.

In the Spring of 1866, B.N. Farren amazed everyone by agreeing to excavate the west end under contract. He agreed to construct 174 feet of enclosing structure in cut-and-cover area and 200 feet of full-size tunnel lining underground within one year. Cross-sections of the linings used by Farren are shown in Figures 8A and 8B. The State agreed to provide all necessary supplies and materials at cost. Eventually, Farren had to excavate adits along and outside of the tunnel to drain the rock mass prior to excava-

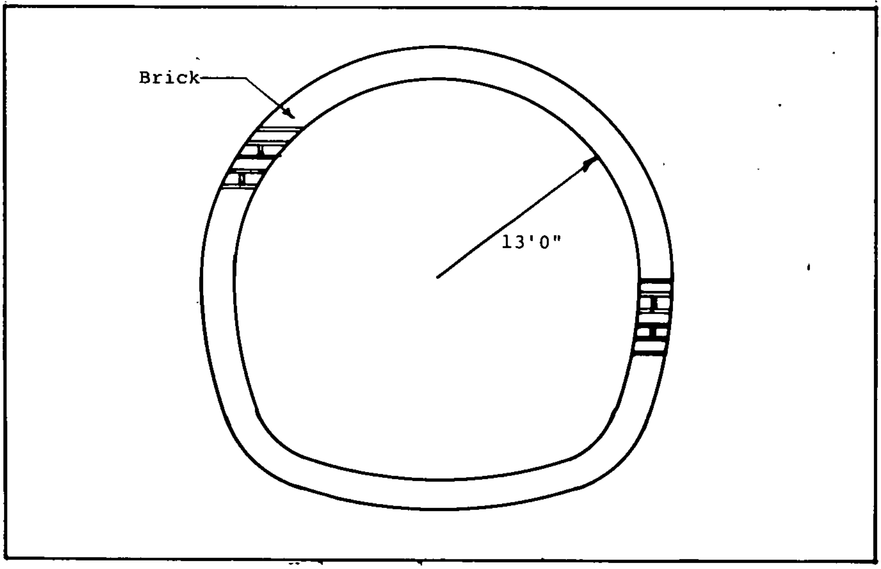


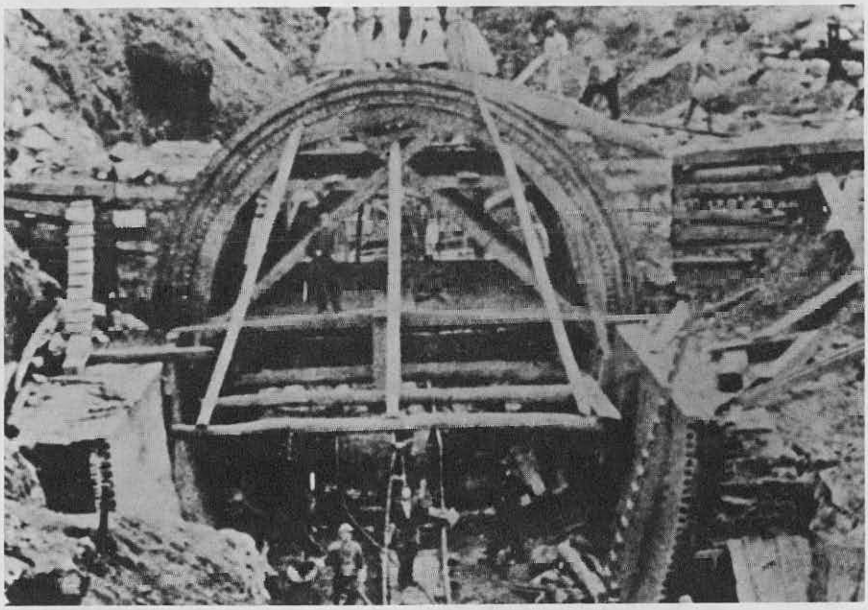
Figure 8B. Tunnel lining used by Farren underground.

tion. Upon draining, heavy timber bracing was constructed and the brick arch placed inside the timbering.

In 1867, Farren successfully completed his first contract and agreed to construct another 500 feet of full-size tunnel lining. He also agreed to construct 500 feet of adit from the west shaft heading in an attempt to provide a through-going adit along the west end. This adit was badly needed to allow water to drain freely from the tunnel workings. Water was being pumped from the west shaft at this time at an estimated rate of 700 to 1000 gallons per minute.

Delays from the water continued into 1868 necessitating completion of the adit. To assist with the work, Test Well No. 4 was enlarged and used as a shaft for adit construction. A through-going connection was finally made on October, 1868. In addition to the above, B.N. Farren continued to erect the full-size lining with vigor. He extended the portal 60 feet eastward in open cut and 500 feet westward into the mountain. At a point approximately 800 feet from the portal, he encountered rock sufficiently strong to serve as a footing for the lining and was able to dispense with the "inverted arch" at the bottom. In all, he completed 931 feet of lining by early in 1869.

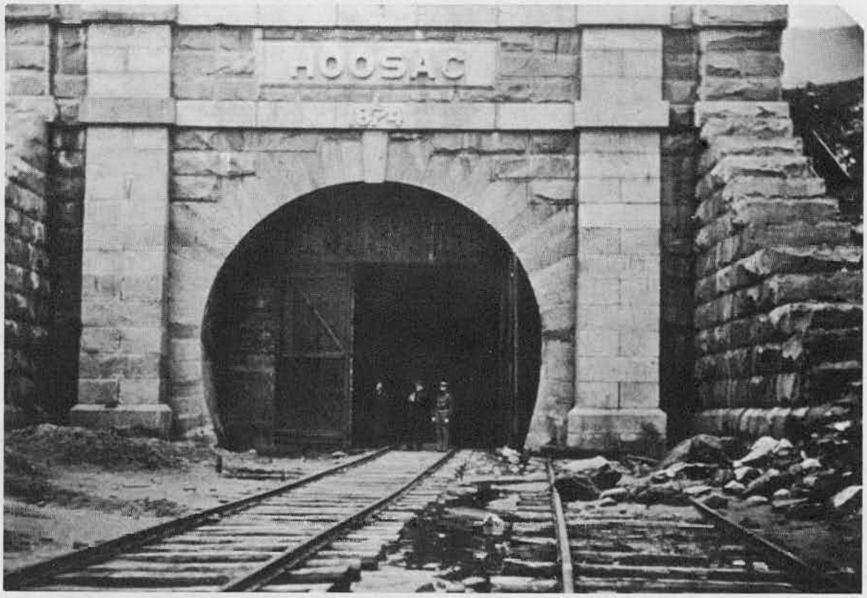
Farren had demonstrated how to conquer the west end, and work proceeded relatively smoothly under Shanly's supervision, the work having been let to Holbrook and Hawkins. In 1871, a contract was let to Messrs. McClallan, Son & Walker to excavate soil and rock along the abandoned Haupt tunnel. Eventually, the entire distance from the west portal to the west shaft (2447 feet) was lined with brick by early in 1873. The work was not without difficulties, however. On October 3 and 4, 1869, a rainstorm of "unparalleled severity" occurred in Western Massachusetts. Total rainfall was measured as 6 inches at Williams College with the most intense rain falling on the afternoon of October 4. A brook crossing the tunnel next to the west end overflowed its banks, dammed the Haupt tunnel with a great quantity of debris, and completely flooded the west end workings. It took nearly a month to clean up the mess and this severely interrupted Shanly's progress.



West end lining being constructed by B. N. Farren, Circa 1867.

In another instance, a major crown failure occurred in the tunnel on March 30, 1870 at about station 12+00. It was estimated that 1200 to 1400 cubic yards of material collapsed into the tunnel, crushing timber supports and approximately 25 feet of completed lining. Clean-up required three months. The lining was reconstructed three feet thick in this vicinity.

Following complete excavation of the tunnel, a decision had to be made as to how much brick lining would be necessary in addition to that already in place from the west portal to the west shaft. To assist with this decision, the railroad asked two geologists and three civil engineers to view the tunnel and render opinions. A fourth civil engineer, Edward S. Philbrick, was asked to analyze their reports and make a final recommendation. Mr. Philbrick recommended that 1600 feet be lined in addition to approximately 2500 feet already lined, that 3500 feet be more thoroughly examined and probably lined, and that the entire remaining 17,500 feet of tunnel be carefully stripped of all loose rock. Eventually, 7573 feet of the tunnel was lined with brick and a 50-foot masonry extension was added to the portal at the west end.



Famous West Portal of the Hoosac Tunnel constructed by Francis and Walter Shanly in 1874.

VI. Claims For Extra Compensation

There were three principal claims for extra compensation arising from the tunnel work. The first was by Herman Haupt who requested compensation for his being thrown off the job in 1861. There is no doubt that Haupt could have finished the tunnel, and that he was dealt with very harshly by the State. Haupt went on to become one of the great engineers and contractors of his time.

Haupt worked diligently on the tunnel and related railroad, but the result was not up to the standards of a finished road. Haupt insisted, with some justification, that his early work on the railroad was intended primarily to allow him to proceed with excavation of the tunnel which was the key to completion of the entire operation. The State, however, in the form of Chief Engineer Whitwell, insisted on each foot being finished prior to payment. Haupt had already invested so much of his own or borrowed money into the enterprise by this time that he was unable to make the necessary improvements and ceased work.

It was not until 1868 that Haupt received $75,814 as a final settlement. He placed his damages by that time in excess of $600,000 including actual payments made on the tunnel and interest on his money with no allowance for "pain and suffering". The fact that he was able to survive such a loss and continue to maintain the trust of individuals who knew him is a measure of his character and fortitude. His family insisted to his dying day that he was permanently scarred by his experiences in Massachusetts.

Another individual who was dealt with quite harshly by the State was Charles Burleigh. He first became involved with the tunnel while an employee and stockholder of the Putnam Machine Company, having helped one of the commissioners, J.W. Brooks, design a drill. This drill was known as the Brooks, Gates and Burleigh Drill, was introduced to the tunnel early in 1866, and proved a failure. The State had invested a good deal of money in development of this drill, however, and had obtained its use free of charge.

After investigating the causes of the failure of the first drill, Burleigh proceeded to design a new one, and it worked well. He patented the drill and allowed it to be used in the tunnel under a *verbal* agreement with Mr. Crocker that he "should receive no payment whatever at the time, but the State should have the full use of the machine, and when it could be determined of how much value the invention was to the State, he should be fairly and fully rewarded". In order to obtain clear title to the drill, he had to pay $10,000 to obtain rights to another patent. Putnam Machine Company provided sixteen drills for the State at cost. These drills were turned over to the Shanlys in 1869 along with other State equipment and the Shanlys proceeded to purchase another 60 drills at $625 apiece.

It should be borne in mind that it was not possible to sue the State for just compensation. The only recourse was to file a bill and hope that it would be passed by the Legislature and not vetoed by the Governor. People like Mr. Burleigh and Mr. Haupt were at the complete mercy of the legislative process. Although Burleigh did not name a specific figure for his claim he demonstrated that the State had saved millions of dollars by using his drill and that he would be satisfied with $100,000. He received $10,000 and a pat on the back.

A claim by the Shanlys in 1875 involved a classic example of "changed condition". Upon tunneling westward from the central shaft, the Shanlys intersected a water bearing zone which threatened to flood the shaft. They decided that it would be better to finish the eastward heading so that water could drain from the tunnel by gravity. The State insisted on pushing westward, however, under any circumstances and threatened nonpayment if it was not done. With this threat, the Shanlys invested months of time and thousands of dollars installing pumping equipment in the shaft. It was as if, as Walter Shanly said, "The engineers seemed to say, 'Never mind the *rock*, get all the *water* you can and bring *it* up.' " It was estimated that during 1872 the Shanlys lifted 13,800 tons of rock and 316,000 tons of water from the central shaft!

The Shanlys eventually received (in 1875) $147,000 in addition to $141,894.83 which was paid to them for payment items in excess of their bid price. A further claim for $129,495.62, although approved by the Legislature, was vetoed by Governor Butler in 1888.

VII. Closing and Conclusions

There is considerable disparity in the published literature about the time for completion and about the cost of the Hoosac Tunnel. There were four principal working stages of the tunnel beginning with Haupt in 1855, proceeding through the State control to the Shanlys, and ending with Farren who completed the tunnel, 1874 to 1876. Total working time during these 21 years was approximately 186 months or 15½ years. The average rate of advance for 25,081 feet of full-sized tunnel with the necessary lining was 135 feet per month.

The cost of the tunnel has been reported at anywhere from 7 to 20 million dollars, the most common figure being 14 million dollars. Analysis of the costs, however, shows Drinker (1878) to be the most accurate. He set the cost of tunnel construction at 10 million dollars, the cost of the associated railroad from Greenfield to the Vermont state border at Williamstown at 4 million dollars, and the cost of interest paid on the debt during construction at 3.3 million dollars. The railroad had cost almost $100,000 per mile and the tunnel $400 per foot of $2,000,000 per mile.

A question asked frequently is, "Was the tunnel worth it?" There is no doubt that the tunnel has paid for itself over the last 100 years and that it has generated considerable business for towns in its vicinity and for Boston, but it did not lower freight rates and it did not open the "west" as was originally intended. By the time the tunnel was finished, it had cost so much that freight rates had to remain high to pay for it, and the "west" by that time had moved from New York to California with completion of the transcontinental railroad in 1869. The tunnel is an interesting, but somewhat auxiliary episode in the history of railroad development in America.

The tunnel's chief contribution was to tunneling technology, including the firm establishment of the center-cut system of heading advance, the incorporation of simultaneous ignition or detonation electrically, the generalized use of nitroglycerine, and the use of compressed air rock drills and drill carriages. The Hoosac tunnelers' use of two tunnel boring machines and a 1000-foot elevator at the central shaft must be considered highly innovative. In addition, the Hoosac tunnelers achieved modern surveying accuracy. It might all have been done at a different time, during construction of some other tunnel, but it wasn't. It was done at the "Mighty Hoosac" when Francis and Walter Shanly put "Daylight Through the Mountain."

Epilogue

People sometimes wonder how the tunnel would be constructed today under modern requirements and with modern construction methods; how much it would cost; and how long it would take to build. Below are a few comments about what might happen if the tunnel were constructed today, although it is emphasized that there is really no way to form an accurate picture. As always, conduct of the project would depend on the *people* involved and their ability to deal with problems.

The tunnel certainly would not be built on the basis of "opinions" about the subsurface conditions. The actual site of the tunnel would be carefully surveyed and investigated, probably with aerial photographs, test borings and other methods of exploration. The fault at the west end would be discovered and no one would suppose that the tunnel "would go below where the ground water percolated". Properly describing the subsurface conditions, however, is not the same thing as correctly evaluating their potential impact on tunnel construction. It is still possible that more trouble at the west end and more water in the tunnel would be encountered than anticipated.

If constructed today, the tunnel would probably be shorter, larger in cross-section, and built without shafts. The open-cut at the west end would be more extensive with the portal moved as far eastward as possible. The tunnel cross-section would be more like 30 feet in diameter rather than 26 feet, for double track dimensions. No shafts would be necessary for a tunnel which by today's standards would be comparatively short. Ventilation during construction would be provided by pipes or conduits laid within the tunnel.

Excavation of the tunnel would be by either a tunnel boring machine or by drill and blast procedures. Large diameter machines are available today which bore their way through rock at rates which, under favorable conditions, exceed in a day what the Shanlys accomplished in months. A tunnel boring machine, however, might not be used at the Hoosac. Delivery time for a machine is long; the tunnel is relatively short; and those quartz veins in Hoosac Mountain are difficult to penetrate even with today's equipment.

If the contractor were to use drill and blast procedures, his basic approach would not be much different than that of the Shanlys although the headings would be larger and the process more highly mechanized. Compressed air rock drills today, for instance, penetrate the rock at one to two *feet* per minute rather than one to two inches.

It is estimated that the tunnel would take 3-1/2 years to construct and cost $75,000,000 for a full double-track cross-section. It is possible that a single-track cross-section could be provided at a cost of approximately $60,000,000. This cost escalation is not as great as it seems when you consider that wages for miners have increased from two dollars a day to nine dollars an hour.

Acknowledgements

The author would like to thank Haley & Aldrich, Inc. for allowing time for preparation of this paper. Mr. Thomas F. Cleary of Haley & Aldrich assisted with the literature survey. Appreciation is also expressed to several libraries in the Commonwealth of Massachusetts, especially the Massachusetts State Library and the North Adams Public Library, and to the New England Electric System for providing information about the tunnel. The thirteen volumes of documents relating to the tunnel assembled by the Massachusetts State Library were particularly helpful. The author would also like to thank Dr. Robert F. Legget and the Engineering Institute of Canada for providing the author with a copy of *Daylight Through the Mountain.*

Special thanks are due to the author's brother, Wayne Brierley, and to Mrs. Joanne Serpe for drafting the figures and typing the paper, respectively. Doctor Charles Ladd and Doctor Herbert Einstein of Massachusetts Institute of Technology provided the author with timely and pertinent comments on the first draft of this text. Their assistance is gratefully acknowledged. Mr. Robert Jenny of Jenny Engineering Corp. assisted with preparation of the Epilogue.

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THIRD INSTALLMENT

HYDRAULICS IN THE UNITED STATES 1776 - 1976

BY

HUNTER ROUSE
Carver Professor Emeritus

Institute of Hydraulic Research
The University of Iowa
Iowa City

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CHAPTER VI

THE RISE OF FLUID MECHANICS

When John R. Freeman began to promote the modeling of rivers in the laboratory at greatly reduced scale, it was still an essentially unknown procedure in the United States. In Europe, however, the first movable-bed model had been built by Fargue as early as 1875, and further tests were conducted by Reynolds, Vernon-Harcourt, and Engels well before the turn of the century. Small-scale testing as such was even older, of course, for Smeaton had experimented with model water wheels, and d'Alembert, Condorcet and Bossut (not to mention Benjamin Franklin), with model ships more than a century before; yet it was not till the time of Reech and Froude in the third quarter of the 19th century that the principle of gravitational similarity received its initial formulation. Since then Rehbock and his 20th-century contemporaries greatly improved the various experimental techniques but scarcely extended the rules of similitude. (Judging by German lectures paraphrased in the Freeman book, in fact, the hydraulician's understanding of dimensional analysis was years behind rather than ahead of Buckingham's 1915 article.) On the whole, the civil-engineering branch of hydraulics simply continued its testing program with little further innovation. Unfortunately, whereas adoption of the practice of river modeling at reduced scale represented for American engineers a great step forward, with this practice they inherited as well the tendency toward continued cut-and-try design that had beset the civil-engineering hydraulicians of Europe.

Civil engineers had long since developed an essentially empirical sort of hydraulics, as exemplified by the many tabulations of coefficients in the textbooks reviewed in Chapter IV. At the other end of the spectrum, mathematical physicists had refined a subject known as classical hydrodynamics, best exemplified by Horace Lamb's *Hydrodynamics*, first published (in Great Britain) in 1879 under the title *A Treatise on the Mathematical Theory of the Motion of Fluids* and well into its 5th edition at the time of Freeman's major influence. Neither subject, however, was of much use in the new profession of aeronautics. On the one hand, the theoretical approach had little direct contact with reality; on the other hand, pure empiricism did not lend itself to application beyond the conditions of observation. What was needed was a combination of the good points of each subject, without its weaknesses. Just such a hybrid approach was provided early in the century by Ludwig Prandtl of Gottingen, Germany, and his many followers, nearly all of whom were mechanical engineers. Proceeding from Prandtl's boundary-layer hypothesis of 1904 (that a state of flow can be approximated by a wall zone of viscous influence and an outer zone of irrotational motion), these men developed a quasi-analytical approach now known as fluid mechanics, in which the mathematics was simplified to the greatest possible extent still in accord with experimental indications. Aided by his student Heinrich Blasius, Prandtl further developed his boundary-layer theory and its application to immersed bodies. In friendly competition with his former student Theodor von Kármán and with the Cambridge meteorologist Geoffrey Taylor, and assisted by his students Johann Nikuradse and Hermann Schlichting, Prandtl greatly advanced the theory of turbulent resistance. His colleague Albert Betz specialized in the mathematical process of conformal mapping and the development of flow instrumentation. His student Adolf Busemann established in large measure the theory of compressible-fluid motion. And his contemporary Richard von Mises, also a mechanical engineer, not only formed his own school at Berlin but edited a journal on applied mechanics in which much of the new work appeared. All of those just named published papers that have become classics.

In parallel with European developments, the U. S. Congress established on 3 March 1915 the Advisory Committee for Aeronautics as a rider to a naval appropriations bill, with an allocation of $5000 annually over a five-year period. The word National was soon added to its title, and it became popularly known as the NACA. W. F. Durand, then a Stanford professor, was one of the twelve original appointees to the Committee, and in 1916 he was elected chairman; that same year Langley Field was founded north of Hampton, Virginia, as the Committee's primary research establishment. A year thereafter the NACA was ruled independent of the Navy Department. Its primary purpose was the coordination of all aeronautical research in the United States, and it gradually developed a prodigious output of excellent research reports, including translations of foreign literature of significance. Thus, NACA Report 116 of 1921 was a paper by Prandtl on "Applications of Modern Hydrodynamics to Aeronautics," and in 1929 Prandtl's original boundary-layer paper was published in English as NACA Technical Memorandum No. 452. The NACA publications were to have a salutary effect not only on aeronautics but also on such other fields as came to be related through the new science of fluid mechanics.

In keeping with the traditional independence of civil and mechanical engineers, most of the advancement in fluid mechanics on the part of the mechanical (and aeronautical) engineers took place without attracting the attention of the civils. One of the MIT Fellows, Hunter Rouse (1906-. . . .), an Ohioan who spent two years with Rehbock, does not recall having heard the name Prandtl the whole time he was in

Karlsruhe. In fact, not till just before his departure did he hear the name of the mechanical-engineering professor of hydraulic machinery on the same campus, Wilhelm Spannhake (1881-1959), who was of course thoroughly aware of the new contributions and had himself participated in them. Apparently only one of the Freeman Scholars—Victor Lyle Streeter (1909-. . . .)—spent any appreciable amount of time on the Gottingen and Aachen campuses, though at least two—Clifford Kittredge and the Canadian George Ross Lord (1906-. . . .)—studied at the hydraulic-machinery institutes of Munich and Karlsruhe, and Robert Knapp surely visited these and similar institutes during his travels. It is hence the more to Freeman's credit—civil engineer and traditional hydraulician that he was—to have seen that Prandtl, Thoma, and eventually Spannhake all lectured at MIT.

Though a civil engineer by education, Morrough O'Brien taught mechanical engineering when he went to Berkeley in 1928 and became head of that department in 1934. This possibly explains the fact that of all the early Freeman Scholars he was the one most receptive to the new concepts, as reflected in many of his technical writings. A noteworthy example was his 1933 "Review of the Theory of Turbulent Flow and its Relation to Sediment Transportation," which applied Wilhelm Schmidt's theory of the turbulent diffusion of atmospheric dust to the suspension of sediment by flowing water. Hunter Rouse, also educated as a civil engineer, spent much of his time with Rehbock trying to understand the hydromechanics of the free overfall, and he continued experiments on flow over sharp-crested weirs of various relative heights after his return to MIT in 1931. During the next two years, on the other hand, he served as unofficial assistant to Spannhake, who was then visiting professor in mechanical engineering. Rouse attended Spannhake's lectures the first year and transcribed those on hydrodynamics for student use the second. During the summer between, after taking the doctoral examination at Karlsruhe, he had the opportunity of visiting both Prandtl and von Mises, with whose work he had become acquainted through Spannhake's lectures. In addition to lecturing on hydrodynamics in general and conformal mapping in particular (especially with respect to hydraulic machinery), Spannhake himself spent much of his time at MIT in the design and operation of a cavitation stand, in which the basic nature of cavitation damage at a simple Venturi throat was studied. The work was supported by at least one hydroelectric company, and considerable interest was aroused in the search for materials with high resistance to pitting.

Quite independently of Freeman's influence, at least one other European had come to the United States well before Spannhake, and his effect upon American hydraulics was to be still greater—in large part because he became a permanent resident of the country. This was Boris

Alexandrovitch Bakhmeteff (1880-1951), a native of Tiflis, Georgia, who had studied at the St. Petersburg Polytechnic Institute and then taught civil engineering there and developed a private consulting practice. In 1912 he published a dissertation on open-channel hydraulics which first made use of the energy and momentum diagrams and refined the French methods of handling the backwater equation. This book continued to be reprinted by the Soviets for a number of decades, and their revised introduction lauded Bakhmeteff's stature as a hydraulician but made no mention of what had become of him. As a matter of fact, he had come to the United States as ambassador under the Kerensky regime, remained in America after the Revolution, and acquired wealth and prestige as one of a group of White Russians manufacturing paper book matches.

In 1932 an enlarged version of Bakhmeteff's Russian dissertation was published in English as an Engineering Societies Monograph under the title *Hydraulics of Open Channels,* and about the same time he became a part-time professor at Columbia University. There he began the construction of a modest facility for studying the hydraulic jump, similar to one that he had built at St. Petersburg, and developed successive sets of lecture notes for use by his undergraduate students. Reproduced by offset from typewritten copy in 1932 and 1933, his two-part *Mechanics of Fluids Compendium* thus became the first in a growing stream of such writings to leave the American press. Published by the ASCE in 1934 with the coauthorship of Arthur Edward Matzke (1908-1962), a Columbia graduate who had made the painstaking measurements, his paper on the hydraulic jump stressed the geometric characteristics of the profile in a nondimensional manner, and it might fruitfully be compared with the previous papers of Karl Kennison and Sherman Woodward. Woodward, in fact, submitted a brief discussion that disparaged Bakhmeteff's attempt at generalization. It is a mark of the latter's diplomatic charm that, when the two first met some time thereafter, it was not long before their arms were around each other's shoulders!

Another immigrant to whom the profession owes very much was Theodor von Kármán (1881-1963), a mechanical-engineering graduate of the Royal Polytechnic Institute of Budapest before becoming one of Prandtl's early doctoral students. In 1912 he was appointed professor and director of the newly established aeronautical laboratory at the Polytechnic Institute of Aachen. Following the advent of the Nazi movement, a similar post was created for him at the California Institute of Technology in 1930. His interests, like those of Prandtl, extended into practically every field of mechanics. So far as the present treatment is concerned, special mention should be made of his work on the pendulating wakes of immersed bodies, surface resistance to turbulent flow, and the analogy between sound and gravity waves.

With the appearance in Europe of books on the new approach to the study of fluid motion, it would have been surprising if no translations had been released in the English language. The first of these consisted of Prandtl's lectures which had been transcribed and published in German by his student Oskar Tietjens, the translations of which appeared in the United States in 1934 as *Fundamentals of Hydro- and Aeromechanics* and *Applied Hydro- and Aeromechanics* in the Engineering Societies Monograph Series. Hunter Rouse, then building a small laboratory under Bakhmeteff at Columbia, published in the ASCE *Proceedings* of January 1936 a review of the Prandtl-Kármán-Nikuradse contributions to pipe-resistance analysis under the title "Modern Conceptions of the Mechnics of Fluid Turbulence," which was to receive the Society's Norman Medal. Bakhmeteff's lectures at Princeton on the same subject were reproduced in book form as *The Mechanics of Turbulent Flow* later in the year. The first full-fledged undergraduate textbooks on the subject to appear in the States were by Dodge and Thompson and by O'Brien and Hickox. Though the titles were somewhat similar—*Fluid Mechanics* and *Applied Fluid Mechanics,* respectively—the publisher was the same and the preface dates (April 1937) were identical. Russell Alger Dodge (1893-1972) and Milton John Thompson (1904-. . . .) were Michiganders by birth and education. Dodge, however, was a civil engineer teaching engineering mechanics at the university, whereas Thompson was an aeronautical engineer who had recently spent a year as Guggenheim Fellow studying aerodynamics at the Warsaw Polytechnic Institute in Poland. Their book was obviously a combination of traditional hydraulics and modern fluid mechanics without full correlation between the two. Nevertheless, it followed Bakhmeteff's lead in introducing into the undergraduate curriculum concepts of flow analysis that had not been there before. Morrough O'Brien has already been mentioned as the Freeman Scholar first interested in the broad approach, and George Hickox as the first director of the TVA laboratory. Theirs was a slightly smaller volume than Dodge and Thompson's, dedicated to Freeman and placing more emphasis on the liquid aspect in accord with the prefatory remark, "These notes are a gradual development from what was originally a course in hydraulics."

Though a mechanical engineer from start to finish, Robert Knapp at first showed a passive rather than an active interest in fluid mechanics at Caltech, but he did place a very high value on von Kármán's presence there and sought his advice in all his undertakings. His first graduate student was Richard Gilman Folsom (1907-. . . .), an assistant who taught Knapp's classes while the latter was in Germany (1929-30); his doctoral dissertation on ultra-rough surfaces was reviewed by Knapp and von Kármán together in 1932, and the following year Folsom moved to Berkeley under O'Brien. A researcher rather than a teacher, Knapp had a keen sense of what problems were important and how they might be solved. At times, however, his primary abilities seemed to be those of research initiation and gadgetry. So highly mechanized were his investigations that members of the staff amusedly coined the slogan "It's automatic, but it won't work!" And so able did he rapidly become in attracting financial support that his steadily growing staff had difficulty in carrying out all his contract projects. These began in 1932 with a model study of a cooling-water intake for the local power company, of which the principal investigator was Vito August Vanoni (1904-. . . .), a Californian of Italian background who had just completed his second Caltech degree. Vanoni was thus the first of a series of young men from all parts of the country who were supported at Caltech by Knapp's activities and thereby exposed to the stimulus of proximity to von Kármán.

In 1933 Knapp contracted with the Metropolitan Water District of Los Angeles to conduct a fundamental study of pumps for the Colorado Aqueduct, Robert Daugherty joining von Kármán as consultant. As described in the ASME *Transactions* for 1936, the resulting laboratory seemed like a gadgeteer's dream, remote control permitting discharge, head, speed, and power to be measured with a reproducibility—if not absolute accuracy—of 99.9%. Not only were performance tests run on manufacturer's models, but considerable research was done on transient flows; of particular interest was a 1934 study of pump characteristics in all four quadrants, prompted by Freeman Scholar Clifford Kittredge's dissertation in Thoma's Munich laboratory. Most of this—well ahead of its time—has since become standard practice. Five successive doctoral students were in turn active in this laboratory: Frank Leslie Wattendorf (1906-. . . .), a Bostonian who had studied previously at Harvard, MIT, and Gottingen and was to have a varied career in aeronautics, the field in which he took his degree; Ralph Mayhew Watson (1905-. . . .) of Pasadena, who was to go with the Worthington Pump and Machinery Corporation before completing the doctorate; George Friederich Wislicenus (1903-. . . .), who had come from Germany to take his three degrees at Caltech, whereafter he also went to Worthington; Raymond Charles Binder (1907-. . . .) of Chicago, who had previously studied at MIT and was later to join the staff at Purdue; and James Wallace Daily (1913-. . . .), a Missourian and Stanford graduate who remained with Knapp through the War. Freeman Scholar Donald Barnes, who had studied civil rather than mechanical engineering there, was later to be in residence at Pasadena as representative of the Bureau of Reclamation during pump tests.

Arthur Thomas Ippen (1907-1974), born in London of German parents and educated at Aachen, had come to Iowa City in 1932 to study with Floyd Nagler. Left high and dry on Nagler's death in 1933, Ippen then joined Knapp's staff at Pasadena. Knapp had recently become acquainted with Walter Clay Lowdermilk (1888-. . . .) during the latter's move from the U. S. Forest Service, through the Soil Erosion Service of the Interior Department, to become director of research of Agriculture's new Soil Conservation Service, and between them a sediment laboratory was planned for Caltech. It was to have a veritable mushroom growth. Vito Vanoni was project supervisor, and two early members of his staff were Nephi Albert Christensen (1903-. . . .) of Utah and Merit Penniman White (1908-. . . .) of Massachusetts, both doctoral candidates at the Institute. Ippen was an intended member of the SCS staff, and at von Kármán's suggestion he undertook the solution of O'Brien's sediment-suspension equation through use of Krey's logarithmic velocity-distribution formula for open channels. However, when it was found that he could not be employed by the SCS because of his foreign citizenship, Ippen was shifted to a project which Knapp had just arranged with the Los Angeles County Flood Control District, to investigate the superelevation of the water surface at bends in high-velocity flood-relief channels. A tilting flume of rectangular cross section with several bends of different radii was built, numerous tests were run, and a first report was under way when von Kármán drew Knapp and Ippen's attention to the analogy between gravity waves and sound waves in supercritical flow, the latter already being subject to analysis; Ippen's dissertation in 1936, as well as subsequent papers, made much of the analogy in solving the superelevation problem. He continued to study the phenomenon in trapezoidal channels until his departure for a teaching position at Lehigh University in 1938.

At the beginning of 1936 Hunter Rouse joined the SCS staff at Caltech, at the invitation of Knapp, whom he had known in Germany, but attracted in no small measure by the presence there of von Kármán, whom he had met as Bakhmeteff's guest at Columbia. At Pasadena Rouse first devised a series of "turbulence-jar" experiments to verify the hypothesized interrelationship of turbulence, fall velocity, and distribution of sediment concentration predicted by O'Brien from Schmidt's theory of atmospheric mixing. Then, without knowledge of Ippen's previous work, Rouse independently performed a similar combination of the sediment-suspension and the velocity-distribution equations, using von Kármán's form for the latter instead of Krey's; the results were published in the 1937 closure to the discussion of his ASCE turbulence paper. In the evenings of his second year at Caltech, Rouse completed the manuscript of *Fluid Mechanics for Hydraulic Engineers,* a book begun at Columbia and intended to correlate the analytical and experimental aspects of the subject in a manner that would be significant to the practicing hydraulician. Reflecting the teachings of Rehbock (flow patterns), Spannhake (conformal processes), Bakhmeteff (viscosity and drag), and von Kármán (turbulence and wave motion), the book was published as an Engineering Societies Monograph in 1938.

While engaged in his sediment studies, Rouse chanced upon a 1936 Berlin dissertation by one A. Shields in which a relationship was shown to exist between roughness effects on the laminar sublayer and the beginning of sediment movement. Because of its obvious excellence, Rouse not only made available an English translation of the dissertation but publicized it in his own writings. Not till after the Fifth International Congress for Applied Mechanics in 1938 at MIT, which each attended without knowledge of the other, did Rouse learn that—far from being German—Albert Frank Shields (1908-1974) was also a native Ohioan, who had graduated from Stevens Institute of Technology, gone to Berlin in 1933 on an exchange scholarship, and conducted an original bed-load study at the Prussian Experiment Station for Hydraulic and Marine Engineering as a temporary employee. From subsequent correspondence Rouse learned that Shields had never received the printed copies of his dissertation, which apparently became lost in the mails, nor had his early hope to find employment in the fluids field at either Vicksburg or Caltech been successful. He hence returned to the paper-manufacturing business, where he had previously done design work and in which he eventually obtained some 200 patents. What a loss to the fluids profession!

The 1938 Congress at MIT also saw the arrival in the States of Paul Felix Neményi (1895-1952), a Hungarian migrant who had published *Wasserbauliche Stromungslehre* while Privatdozent at Berlin. Except for a 1914 text by Richard von Mises (1883-1953), this book was probably the one most slanted toward the new approach of all those on hydraulics that had appeared in the German press. Unfortunately, neither it nor the von Mises volume was translated into English, but the establishment of residence in America on the part of both (von Mises later came to Harvard from Berlin via Istanbul) had a somewhat comparable effect. Before crossing the ocean, Neményi had spent time at Copenhagen and London, and following the Congress he devoted several years to fishway investigations at Iowa. His knowledge of the fluids literature was encyclopedic, and he gradually veered in the direction of mathematical hydrodynamics.

Not all sediment studies were conducted on the west coast by any means, but before other parts of the country are considered, four additional projects warrant mention. One was a 1934 paper by O'Brien and his student B. D. Rindlaub on bed-load transportation, still susceptible only to the empirical approach. Another was a 1937 booklet published by O'Brien and Folsom, "The Transportation of Sand in Pipe

Lines''; this contained a good review of the theory of both turbulent flow in pipes and sediment movement in flowing water, and an analysis of extensive experiments with a wide range of grain sizes in a special pumping rig, including the effect of the sediment load on pump performance. (Though obviously not involving sediment, the 1939 O'Brien-Folsom paper on the design of pumps and fans must be mentioned in passing.) Still another sediment investigation was a series of tests on localized scour by Rouse (1939), which indicated that the excavation of uniform material tended to progress as an inverse logarithmic function of time and hence to be without apparent limit. The fourth was a continuing study by Vanoni on the transportation of uniform material in suspension; his 1941 AGU paper, ''Some Experiments on the Transportation of Suspended Load,'' contained measurements in good accord with the analyses by Ippen and by Rouse.

On the east coast, the third of the MIT Fellows, Cedric Hugh MacDougall (1901-. . . .) of Canada took over a graduate student's inconclusive bed-load study, converted it into a significant piece of work (albeit purely empirical), and presented it at the same meeting of the AGU at which O'Brien gave Schmidt's theory of suspension. (After his release from MIT because of the Depression, MacDougall took a post at a preparatory school—much as Blasius had done a decade before—and never returned to hydraulics.) At Iowa, in the years following his return from Europe, Theodore Mavis directed the thesis endeavors of a series of Chinese graduate students in the investigation of bed-load transportation. Emory Lane, who had consulted on the improvement of the Grand Canal and neighboring Chinese rivers, also wrote extensively on the subject of sediment movement, his approach remaining wholly empirical till the beginning of his collaboration in 1936 with Anton Adam Kalinske (1911-. . . .). The latter, born and educated in Wisconsin and one of those brought to Iowa by Dean Dawson, at first assisted Dawson in studies (such as the prevention of back-siphonage) for the National Association of Master Plumbers. However, Kalinske was a voracious reader of the technical literature—particularly in the field of turbulence, though from the Taylor point of view rather than that of Prandtl; he not only supplied the theoretical understanding to balance Lane's practical approach, but supervised graduate students in turbulence and sediment projects and published extensively in his own right and with various graduate students. One of these students was Edward Reginald Van Driest (1913-. . . .) of Cleveland and Case Institute, who—after completing doctoral requirements at both Caltech and Zurich—was to specialize in the thermal phases of fluid mechanics. Two other men who had been on the Iowa staff almost as long as Mavis will be mentioned repeatedly in later pages: Joseph Warner Howe (1902-. . . .), an Iowan by birth and education, who was beginning to specialize in hydrology; and Chesley Johnston Posey (1906-. . . .), a Minnesotan with a Kansas education, who was beginning to develop his Rocky Mountain Hydraulic Laboratory at Allenspark, Colorado, for summer use.

Though even less in the direction of fluid mechanics than some of the other sediment projects, note must surely be taken at this point of Lane's organization in 1939 of an Interdepartmental Sedimentation Committee, which under various names continued its activity for several decades and did much practical good. The agencies involved were the Geological Survey, the Indian Service, and the Bureau of Reclamation of the U. S. Department of the Interior; the Flood Control Coordinating Committee of the Department of Agriculture; the U. S. Engineers of the War Department; and the Tennessee Valley Authority. Representatives of these organizations were stationed at the Iowa Institute of Hydraulic Research, where, under Lane's direction, they prepared a series of reports on various aspects of the sediment problem: primarily means of measuring the suspended load and bed load in natural streams and of interpreting the results; several widely used instruments for both sampling and size-frequency determination were devised. Eight reports on the initial findings were published in 1940 by the U. S. Engineer Suboffice at Iowa City under the general title *A Study of Methods Used in Measurement and Analysis of Sediment Loads in Streams*. The Committee shifted its headquarters to the St. Anthony Falls Laboratory at Minneapolis in 1948, with personnel from both the Corps and the USGS. Subsequent decades saw the participation of six additional agencies and the publication of five more numbered reports, plus a long series of lettered ones including a summary of the work up to 1963.

Most decidedly in the direction of fluid mechanics was the research done in the Thirties at the National Hydraulic Laboratory by two or three members of the staff, though it is ironic that practically none of this research required the enormous establishment in which they were housed. Garbis Keulegan was the guiding force; a mathematical physicist by background, it is only logical that the major part of his work should have been analytical by nature. He thought very highly of Boussinesq, moreover, and much of his writing stemmed from what he knew by heart to exist in the tome *Essai sur la théorie des eaux courantes*. The first of his investigations, albeit an experimental one, was done in collaboration with Hilding Beij on the resistance to laminar flow in curved pipes. Next he discussed at length the free-surface counterpart of the Prandtl-Kármán pipe-resistance analyses in the paper "Laws of Turbulent Flow in Open Channels." At much the same time he undertook some simple but original tests on the stability of the interface between fresh- and salt-water layers, introducing what he called the "densimetric" (i.e. gravimetric) Froude number ($v/\sqrt{d\Delta\gamma/\rho}$) as similarity parameter, not to mention the misnomer "density current" for what is actually a gravitational phenomenon; both terms are firmly embedded in the literature. Finally, on becoming interested in open-channel wave motion, he set out on a series of noteworthy analyses, some of which were in collaboration with other members of the staff but most were his alone. Essentially all were published in the Bureau's *Journal of Research,* although—despite his retiring nature—he was eventually persuaded to take actual part in national congresses.

At several points in this chapter mention has been made of the Fifth International Congress for Applied Mechanics. The first one of the series to be held in the United States, it was to have a considerable effect upon American fluid mechanics. The series had grown out of a meeting called in Innsbruck, Austria, by Theodor von Kármán to bring together once again specialists from many countries who had become separated by World War I. The first formal congress had been convened in Delft, Holland, in 1924; this was followed by those in Zurich in 1926; Stockholm in 1930; and Cambridge (England) in 1934. Many of the more recent accomplishments in fluid (as well as solid) mechanics were described in the proceedings of these meetings, particularly in the field of turbulence. The 1938 congress was held in Cambridge, Massachusetts, with Harvard and MIT as the official hosts. As Karl Taylor Compton, President of both MIT and the Fifth Congress, said in his opening address,

> To this Congress have come over three hundred delegates from more than a dozen countries. While not large in membership, compared with some scientific bodies, this Congress is distinctive in that it deals with the most difficult problems in the most fundamental of all branches of applied science, and in that its members are scientists and engineers of the highest degree of distinction in this difficult field.

Among the more than 400 who actually attended the sessions were at least 20 American hydraulicians, many of whom have already been mentioned in the foregoing pages, and seven of whom presented papers (Bakhmeteff and Feodoroff, Kalinske and Van Driest, Knapp and Ippen, and Rouse). As in previous congresses, the fluids half of the program stressed the turbulence phenomenon, and American hydraulicians were among the contributors. Interestingly enough, the hydraulics problem of pipe resistance again was the subject of papers by aerodynamicists from various countries, in one of which von Kármán's Caltech colleague, Clark Blanchard Millikan (1903-1966), theoretically derived the logarithmic form of the velocity-distribution function. Another of the papers on turbulence was presented by the MIT mathematician Norbert

Wiener (1894-1964), with emphasis on his theory of chaos; von Kármán, who chaired that session, thanked Wiener and (himself no mean mathematician) said he was only sorry that he could not understand the mathematics involved. Before the end of the Congress it was decided that the next one would be held at Paris in 1942. By then, of course, the world was engaged in its second great war, and 1938 represented for many of the participants their last international professional gathering.

Although the Hydraulic Division of the ASME had sponsored sessions in the annual meetings of the organization since its establishment in 1926, the ASCE depended upon the Irrigation and Waterways Divisions for the sponsorship of hydraulics papers. Then in 1938 the ASCE Board of Direction, at the instigation of Fred Scobey, Boris Bakhmeteff, and others—authorized the formation of a Hydraulics Division, with Scobey as its first chairman. Probably the most active of its original committees was that on Hydraulic Research, under the chairmanship of John Cyprian Stevens (1876-1970), a consulting hydraulic engineer and instrument manufacturer of Oregon. The AGU Hydrology Section, of course, had existed since 1931, and many papers by Freeman Scholars appeared in its *Transactions*. The first national conference purely for hydraulicians was that organized by Theodore Mavis at the State University of Iowa in June of 1939, the year that he left for Pennsylvania State College and was replaced by Hunter Rouse. Some two hundred hydraulicians—including representatives of the Corps of Engineers, the Geological Survey, the Bureau of Reclamation, and the Department of Agriculture—from all parts of the country attended the four-day June meetings. One of the eight half-day sessions was devoted to an open house at the Institute of Hydraulic Research, and the remaining seven involved the presentation of 20 invited papers. As was to be expected, these ran the gamut between the old and the new, the trite and the imaginative. With reference to the foregoing pages, mention should be made of papers on the mechanics of bed movement by Straub, similarity and scour by Rouse, and suspended-load control by Lane; liquid turbulence, by Kalinske; and—of particular note—the propagation of flood waves, by Harold Allen Thomas (1885-1973), a native of Michigan and professor at the Carnegie Institute of Technology; his paper combined a mathematical analysis of the roll-wave phenomenon with experiments in which the roll waves were brought to rest on a moving belt. So well-received was this gathering that it became the forerunner of six additional Iowa conferences, an indefinite series of annual conferences later sponsored by the new Hydraulics Division of the ASCE, and many other meetings under the auspices of various organizations dealing with the mechanics of fluids.

The accomplishments of this period were perceptively reviewed by

Arthur Ippen in his address during the 1965 dedication of the Straub Memorial Library at Minnesota:

> Thus, a unique and most fertile new age dawned in the American hydraulic world, leading to the present eminent position of American hydraulic research . . . . This position has been achieved as the result not only of the earlier injection of massive doses of hydrodynamic theory and of largely empirical model and experimental techniques into United States hydraulics over a generation ago, but by the gradual pragmatic blending of the entire spectrum of hydraulic knowledge into a sound system of purposeful action. This philosophy of simultaneous promotion of knowledge through theory, experiment, and field observation has come to form the basis of our profession . . .

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CHAPTER VII

THE WAR YEARS AND THEIR AFTERMATH

War invariably produces a change in nearly every phase of civilized life, and World War II had as much effect on hydraulics as on most other professions. The change in the Forties, however, displayed several unexpected aspects. To be sure, some hydraulicians enlisted in the Armed Forces, and some were drafted; in view of the decreasing university enrollments, some teachers decided that they could be more effective in industry than in education; some researchers even closed their laboratories; but a few became so deeply involved in experimental studies for the war effort that their professional lives were never the same again. Because of America's initial isolationism, the effect of World War II became apparent only slowly. The Depression was still strong in people's memories, and had it not been for the resumption of industrial output as the result of Lend-Lease demands, the lean years would probably have continued much longer. At the same time, however, the Draft began its inroads on university activities, and a gradual variation in pedagogical emphasis took place.

At Iowa, for example, Lane at first continued his endeavors in the field of sediment, as did Kalinske in that of turbulence. Rouse, newly arrived, joined the two in the hydraulics laboratory. Mavis's position as head of Mechanics and Hydraulics was taken over by Joseph Howe, who thereafter played father-confessor to the 400 or more graduate students who were to study hydraulics at Iowa prior to his retirement. Chesley Posey had chosen to be an understudy of Sherman Woodward well before the latter's departure for the TVA; not only did he then continue Woodward's deliberate style of teaching potential-flow theory, but he combined the latter's lectures based on his Miami Conservancy findings with his own work on backwater analysis in the form of a book that was published jointly in 1941 under the title *Hydraulics of Steady Flow in Open Channels*. During the summer of 1940 Rouse taught a graduate class in fluid mechanics at Colorado State at the invitation of Dean Nephi Christensen; unsponsored, this was to be followed by many sponsored summer classes in future years. In the course of his second year at Iowa he prepared notes for an undergraduate text on the mechanics of fluids, and Howe and Kalinske taught the course with him. Then in 1941 Kalinske obtained summer employment in a new laboratory of the Navy at Washington DC, and a relationship that was to prove of lasting value to the Iowa Institute was established.

During the century or more that has elapsed since William Froude built his first towing tank at Torquay, Devonshire, essentially every country engaged in shipping has followed suit. The U. S. Navy's Experimental Model Basin at Washington was established in 1899 after designs by Rear Admiral David Watson Taylor (1864-1940), who directed its operations for the next fifteen years. The need for expansion became apparent in the late Twenties, but limitations on space at the Navy Yard made it desirable to seek a suitable location outside the city. In 1936 Congress authorized a new establishment at Carderock, Maryland, some 10 miles northwest of Washington, and the following year it was named the David W. Taylor Model Basin. Most of the design had proceeded under Commander Harold Eugene Saunders (1890-1961), who had been assigned to the Experimental Model Basin in 1929 as senior assistant to the officer in charge; he eventually became director of the EMB and then of the new TMB as he was promoted to the captaincy. In addition to the very extensive model shops, the principal features of the establishment were its three towing tanks: a shallow one, 303x51x10 feet in size; a deep one, 963x51x22 feet; and one for high speed, 1168x21x10 feet; the second and third were so long that their tracks were not linear but curved with the earth's surface. In 1940 the 12-inch and the 27-inch water tunnels for propeller testing, built at the EMB in 1930 and 1937, respectively, were moved to the new establishment. Next plans were begun for a huge recirculating channel that would permit models to be held stationary in flowing water, and Kalinske brought several problems connected with its use back to Iowa City for investigation under contract.

Primary among these problems was the effect of free-surface slope on the measurement of model drag and possible means of minimizing this error. Both the 10-foot and the 16-foot river channels of the Iowa laboratory were adapted in 1942 to simulate the proposed facility. The gravitational component was shown to be a very real factor in the case of a sloping or undulating surface, but it was also found that proper manipulation of discharge, depth, and bed slope could produce a level surface in the vicinity of the model. The effect of turbulence on the drag was also investigated. Many of the tests were conducted by Wallis Sylvester Hamilton (1911-. . . .), a graduate staff member from New Jersey who had studied at Carnegie and there assisted Professor Harold Thomas. Hamilton's doctoral project involved the measurement of the detailed velocity distribution around a model hull in flowing water and the calculation therefrom of the surface drag for comparison with the measured total drag. The prototype channel which was put into operation at Carderock in 1944 had a test section that was 60 feet long, 22 feet wide, and 9 feet deep, with a maximum water velocity of 17 feet per second. It was initially under the supervision of Lieutenant Clyde Warren Hubbard (1903-1971), one of "Prof" Allen's former students at Worcester; he was assisted by Charles Allen Lee (1915-. . . .), a

Montanan who had been Arthur Ippen's first graduate student at Lehigh and was later to serve in uniform with the Navy's Construction Battalion before returning to the Model Basin. Probably as a result of this contact, one of Kalinske's doctoral students, James Mueller Robertson (1916-. . . .) of Illinois, was to join the TMB staff on completion of his dissertation on air entrainment in pipes.

In the course of a 1941 trip by car to a conference at the Waterways Experiment Station, Dawson, Lane, Robertson, and Rouse had decided that a Second Hydraulics Conference should be held at Iowa City in 1942 to maintain the momentum acquired in 1939. Howe, Kalinske, and Rouse arranged a program to emphasize the "astonishing similarity of principles utilized by the wide variety of professions dealing with fluid motion." Twenty-four speakers (including Bakhmeteff and von Kármán) were invited from such varied fields as aeronautical, chemical, civil, marine, and mechanical engineering, and geology, meteorology, and oceanography—with particular heed to those who could call attention to knowledge of fluid behavior which might benefit the war effort. The Conference was attended by 150 engineers and scientists from thirty different States; though because of wartime conflicts the attendance was smaller than before, the subsequent volume of *Proceedings* was completely sold out.

Not long after the Conference, Lane decided that he could do more for the country with the Tennessee Valley Authority, and he was granted a two-year leave of absence by the University. Rouse and Kalinske were appointed associate directors in his stead, the former being placed in responsible charge. On returning from one of his visits to the Taylor Model Basin, Kalinske presented a seminar talk comparing the characteristics of water tunnels and air tunnels, in many respects to the advantage of the former. Funds were then sought from the University for the construction of a small water tunnel for contract research. John Stephenson McNown (1916-. . . .), a Kansan who had obtained higher degrees from Iowa and Minnesota, was brought back to Iowa City from the Navy's Radio and Sound Laboratory near San Diego to design the new facility. With a water velocity of 35 feet per second at a test section 1 square foot in cross-sectional area, surplus pump, and a gasoline-engine drive, the tunnel was used for the next five years (whereafter it was sold to the Waterways Experiment Station) to study the pressure distribution around torpedo heads of various forms at different stages of cavitation, under a contract administered by the Model Basin. The measurements and supplementary analyses were the work of McNown and En-Yun Hsu (1915-. . . .), a Chinese doctoral student who later went to Stanford by way of Caltech, various naval laboratories, and Lockheed.

At about the same time that the water tunnel was being constructed, a contract was signed by Rouse with the National Defense Research Committee, for the construction of a low-velocity air tunnel to study atmospheric-diffusion problems for the Chemical Warfare Service. The tunnel had a 4x6-foot cross section with an air speed of only 25 feet per second, and was under the direct supervision of Maurice Lee Albertson (1918-. . . .), a Kansan with degrees from Iowa State and Iowa who had been brought back from the TVA to serve as a wartime staff member. Before this project was well under way, however, a higher-priority study of heat requirements for fog dispersal over airport runways was undertaken in the air tunnel for the Navy's Bureau of Aeronautics; the diffusion of heat downwind from a line of gas burners was shown to be a gravitational phenomenon depending upon Garbis Keulegan's modified Froude number as similitude parameter. After this interlude, Albertson and several colleagues conducted experiments on the diffusion of smoke and gas over urban regions, as well as on the generation of large-scale turbulence over mountainous terrain. Kalinske was able to correlate analytically the diffusion expected from point bursts and observed from continuous point sources. A training film prepared in the air tunnel for CWS personnel proved to be the forerunner of a series of subsequent educational films on the mechanics of fluids. In fact, the air tunnel itself was proclaimed by Rouse to be as valuable a tool for hydraulic research as any in the laboratory. In 1940 Alexander Kolin (1910-. . . .), a Russian immigrant, moved to Iowa from Columbia University, where he had developed under Bakhmeteff what he called an electromagnetic velometer for measuring the velocity of flowing liquids. Because tenure at Iowa could not be guaranteed, Kolin soon left for Chicago, and his place was taken by Philip Gamaliel Hubbard (1921-. . . .), a Missourian educated at Iowa, under whom electronic instrumentation flourished—particularly the constant-temperature hot-wire anemometer.

The Third Hydraulics Conference of the Iowa Institute had to be postponed from 1945 to 1946 because of wartime exigencies, but then it purposefully emphasized the peacetime utilization of war experience. Some 325 people attended the sessions, and 18 invited papers were presented. The theses of this and the preceding conference were aptly summarized by Rouse in his discussion of still another paper on research by Commander E. A. Wright, then deputy technical director of the TMB, from which the following excerpt is taken:

> So forceful and inclusive a case for research has been presented by the author of this paper that the writer can do little more than attest to a wholehearted agreement with each and every point. Such agreement is particularly significant due to the fact that the author and the writer differ considerably in professional background and immediate endeavors, however close their indirect interests may be. The author is by training a naval architect, the

writer a civil engineer; the author, as an officer of the Navy, is directly engaged in the strengthening of American protective power, whereas the writer, as a university professor, is concerned primarily with the discovery and propagation of scientific information. Professions with even closer mutual interests than these have long made their independent ways with little mutual assistance. However, as indicated by the author's entire paper, one of the few great blessings of the recent war has been the lesson which it has taught of the value of close collaboration among all professional groups having the slightest common ground of endeavor.

Two of the several research needs stressed by Commander Wright are identical with certain aims of any large technical school: the training of men to do creative work in research laboratories, and the gathering of fundamental knowledge in science and engineering. It goes without saying that the interest of men so trained will vary directly with the eventual demand for their services, and that the amount of fundamental knowledge so acquired will depend to a great extent upon the availability of research funds. If all Federal agencies followed the pattern thus set by the Navy for sponsoring university training and research, the ultimate benefit to the technical strength of the country could not be overestimated.

Of particular importance to the writer, who is engaged in research in general fluid mechanics, is that portion of Commander Wright's paper which deals with fluid motion. Quite apparent from the illustrative matter accompanying his arguments is the fact that ship resistance is by no means the only phenomenon involved in the research program which he has envisaged, nor is ocean water the only fluid with which he is concerned. The writer, in turn, must emphasize the fact that problems of naval architecture are by no means the only ones with which he would wish to deal, nor is he particularly interested in seeking principles which are restricted to a narrow field of application. Fortunately for both the success of the author's program and the satisfaction of the writer in assisting with a small phase of it, technological development has at last reached a stage at which no single branch of science is sufficient for its further progress, while science itself has so broadened in scope that its same basic principles are applicable to a thousand and one different fields of practice. The author, for example, cites the use by naval architects of boundary-layer theories of aerodynamics, sound-wave theories of ballistics, and open-channel theories of hydraulics; and the writer, at the moment, is occupied with studies (sponsored by the author's organization) which are applicable at one and the same time to meteorology, river control, and sanitary engineering, as well as naval architecture. Indeed, all branches of technology are fast becoming so closely interlaced that progress in any one branch in some manner or other invariably advances the rest.

While the wartime research of the Iowa Institute was probably the most varied among American hydraulics laboratories, and hence the best illustration of this point of view, it was by no means on the grandest scale. Instead, the program masterminded by Knapp at Caltech was surely the most extensive and elaborate investigation of a particular subject—the interaction between projectiles and the air or water through which they travel. To quote his final report to the NDRC:

> During the four-year period from the fall of 1941 to the fall of 1945, the Hydrodynamics Laboratory of the California Institute of Technology devoted its entire resources to the prosecution of a war research program for the Office of Scientific Research and Development under the direction of Division 6 of the National Defense Research Committee. The general assignment was to observe and analyze the hydrodynamic forces acting on bodies moving through fluid media, and to develop shapes for these bodies that would result in the specific performance characteristics desired. With very few exceptions, the bodies studied were projectiles. The larger part of the time and energy available was used in studying the behavior of projectiles whose trajectories were either partly or wholly under water. However, a very significant part of the laboratory activities was given over to work on airflight projectiles operating at velocities enough lower than the velocity of sound so that the air could be considered incompressible. Much consideration was also given to the water entry problems associated with air-launched underwater projectiles such as aircraft torpedoes and antisubmarine rockets.

In the late summer of 1941, work was begun by Knapp and his assistants on what was to become the primary piece of equipment of the new facility: a high-velocity water tunnel having a test section 14 inches in diameter and 6 feet long, with pressure controls and water speeds as high as 75 feet per second. Much of the equipment in the hydraulic-machinery laboratory was incorporated into the system, but additional instrumentation—particularly a recording three-component dynamometer—had to be designed, an operation in which Knapp was in his element. The personnel was rapidly augmented, three members of the prewar staffs forming the nucleus: Vito Vanoni, again general manager and buffer between Knapp and those under him; James Daily, primarily responsible for operation of the tunnel; and Hugh Stevens Bell

(1899-. . . .), a natural-science teacher from Ohio who had come to the SCS by way of a career as free-lance writer and photographer in the American Southwest; at his hands, unsurpassed photographic studies of the cavitation process were to be produced. Mention should also be made of the Palestine-born Joseph Levy (1906-1972), a Caltech graduate who was to contribute to various phases of the laboratory program. Above all, however, note must be taken of the superb group of machinists assembled by Knapp for fabricating the projectile models, none of which was greater than 2 inches in diameter and some highly detailed in form.

Within barely a year after the water tunnel had begun operation, space in the former hydraulic-machinery laboratory became inadequate for future needs, and in 1944 a new building was completed next to the old (which in turn, had formed an integral part of von Kármán's Guggenheim Aeronautical Laboratory). In addition to offices and shops (and the water tunnel, which was eventually moved), this was to house two new units. One was a controlled-atmosphere launching tank, 13 feet in diameter and 29 feet long, with a centrifugal mechanism for projecting torpedo models through air of controlled density into carefully filtered water, and windows to permit photographing their complete trajectories. The other unit was a free-surface water tunnel, having a test section to accommodate a stream 20 inches square over a length of 8 feet, and windows permitting observation both above and below the free surface; in addition to studying free-surface phenomena, the necessary deaeration system beyond the test section also made possible the use of models discharging air for propulsion purposes. These units were not ready for operation till after the end of hostilities.

Fully as important as the three major pieces of equipment were supplementary items of instrumentation which could be used on each one. Principal among these was the lighting system to permit high-intensity short-duration (5-microsecond) flashes for still photography of cavitation. As the launching tank came into use toward the close of the war, observation by high-speed motion pictures became necessary, which required not only as many as 3000 flashes per second with synchronized batteries of lights, but also cameras with continuously moving loops of film. (Fully 20,000 frames per second were ultimately realized in the old water tunnel.) Since cavitation noise was an essential element of study, means of focusing microphones on definite underwater points of observation had to be devised. Finally, analysis of countless successive movie frames to determine projectile trajectories and their kinematic characteristics required a whole new system of instruments and techniques.

While the launching facility was not activated in time to be of any use in World War II, tests of projectile trajectories were conducted well into the Korean War to provide general information to the Navy. The free-surface water tunnel continued in operation for another quarter of a century, and by no means exclusively for military purposes (for instance, studies of fish propulsion). The original high-speed water tunnel, on the other hand, was completely rebuilt by 1947 in order to accommodate a novel 4-pass resorber system; this extended 85 feet below the test section and thus insured that all gases released by pressure reduction at the test section would be redissolved. The revised unit became the primary piece of research equipment for the study of cavitation. High-speed motion pictures, also utilized for launching studies, were specially adapted for these investigations, the film again moving continuously and the flashing lights determining the position of the image on the film. The result, of course, could not be projected in the usual manner, because the images were not properly spaced. In the mistaken belief that Knapp would not approve such an expenditure of effort, Bell spent many an hour of his own time clandestinely rephotographing the individual frames to provide a film that could be shown with a standard projector to reveal in slow motion the details of cavitation-bubble formation and collapse—and subsequent rebound. A letter from Vanoni to the author sheds further light on the accomplishment:

> I have talked to Hugh Bell about his work on the development of high-speed motion pictures of cavitation. This work started with the use of an Edgerton camera which takes standard 35-mm frames at 2000 per second. It soon became clear that this was not fast enough, so the frame was cut in half and the pictures taken at twice the speed or 4000 per second. Now the problem was to make a projectable motion picture out of this. This was done, first by making enlargements of each frame and copying them, but later by actually photographing each picture on the negative itself, using a milling-machine bed to advance and register the film. These pictures would be taken by registering each picture according to some fixed point on the tunnel, in which case the cavitation bubbles moved, or by focusing on a bubble and watching its development as it stood still in the picture.
>
> Higher-speed pictures were taken by further reduction of the size of the picture taken. These pictures were always of standard width but reduced in height to as little as one millimeter. To take these higher-speed pictures, the flash lamps were driven independently of the camera with an electronic circuit. With this scheme, pictures were taken at the rate of as high as 30,000 per second. These motion pictures were taken on 100-foot strips of 35-mm film. Total exposure time was 1/10th of a second, which exposed only part of the 100-foot strip. The heat generated by the

lamps was extremely intense and would have melted the lamps if the exposure time had exceeded this short duration. Hugh admits that all of this activity kept him up nights.

Shortly before the onset of war, Hans ("My friends call me 'Albert' ") Einstein had moved from the Greenville office of the SCS to Caltech, where the staff gradually shifted their activities from sediment to problems more closely associated with military endeavors. Einstein engaged in a number of such projects, principally the operation of a ripple tank to simulate supercritical flow of either a gas or a liquid with a free surface—the Kármán-Knapp-Ippen wave analogy in reverse, so to speak. Sediment was still Einstein's primary love, however, and over the years he had developed an empirical means of bed-load evaluation, which he published in the ASCE *Transactions* of 1942. This departed from customary procedures in ignoring the concept of initial movement and introducing a statistical notion of successive particle steps of constant average magnitude, the rate of transport varying with the frequency of the steps. In 1947 Einstein left the SCS for an associate professorship at Berkeley, there joining Joe Johnson, who had already made the change in 1942 and was by then a specialist in coastal problems (the O'Brien-Folsom influence was reflected in the fact that both were placed in mechanical rather than civil engineering). At California Einstein was able—at least to his own satisfaction—to convert his empirical transport formula into an analytical one, which he published in 1950. In later years, moreover, he sought to combine his analysis of bed load movement with those of Ippen and Rouse for the distribution of suspended load, by using the former to define a particular value of the latter, but this was not too successful. At best a very complex function, the Einstein bed-load formula was probably fully understood only by its creator, although he trained a number of graduate students who regarded his work highly and published jointly with him. Prominent among these were Robert Blackburn Banks (1922-. . . .), of Kansas and Northwestern, and Ning Chien, a Chinese graduate student from Iowa who later returned to the People's Republic. While a consultant in the Corps of Engineers, he collaborated with Nicholas Leonard Barbarossa (1915-. . . .) of the Missouri River Division. Einstein probably suffered as much as he profited from his family name; in any event, he seldom mentioned his father to friends or acquaintances. As a consultant his advice was practical, sound, and widely sought. But his intuitive grasp of a sediment problem was not easy to inculcate in others.

During the decade between the founding of the Waterways Experiment Station and the onset of World War II, considerable headway had been made in the development of a steadily growing experimental program. Joseph Tiffany, who had been responsible for establishing much of the test and report procedure (and had himself conducted an extensive investigation of bed-load transport), became the first Chief of the Hydraulics Division in 1938, Technical Director in 1940, and Acting Director during two of the war years. Eugene Fortson succeeded Tiffany as Chief of the Hydraulics Division, though while he was on active duty his place was taken by Bradford Fenwick. The latter had already laid the foundation of his expertise on river hydraulics, as had Robert Hudson his on waves and breakwaters. Three staff members of note were added during the decade: Frank Bixby Campbell, who came to the Corps in 1938 by way of the USGS, the USBR, and the SCS; Freeman Scholar Haywood Dewey, who reached the Experiment Station in 1942 after six years with the Bureau of Reclamation; and Henry Brown Simmons (1915-. . . .) of Mississippi, who began as an engineering aid in 1940 and was eventually (in 1971) to succeed Fortson as Chief of the Hydraulics Division. The War diverted much of the WES attention to such defense matters as model studies for dry-dock improvements, the design of pontoons and pneumatic floats, breakwaters at naval air stations, and the development of harbors used in transoceanic shipping. At the end of hostilities, work was resumed on the accumulated backlog of model tests for the thirty-odd District Offices of the Corps. Civil works projects of this nature ran the gamut of tests on spillways, sluices, fuse-plug levees, penstocks, diversion works, stilling basins, prevention of shoaling, salt-water intrusion, dredges, cavitation-free baffle piers, and floodway structures.

In 1946 a group of consultants were appointed to advise the WES staff on its various projects on an intermittent (usually annual) basis. The original group consisted of Boris Bakhmeteff, Arthur Ippen, Robert Knapp, Morrough O'Brien, Hunter Rouse, and Lorenz Straub. Among the repeated items of advice given by the group over its quarter century of existence were the upgrading of the staff by continuing education both internal and external, and the upgrading of its product by the conduct of research as well as development. Two years later the Corps established its Committee on Tidal Hydraulics, whose task was to advise on research related to estuarial analysis; this body—the first report of which was issued in 1950—consisted of a dozen or more of the Corps' own civilian personnel, plus half a dozen external consultants. Though most of the members have already been mentioned, note should be taken of Jacob Henrick Douma (1912-. . . .) of California, a long-time member of the Chief's Office; since practically all hydraulic designs were eventually to pass through his hands, Douma was involved as well in most of the planning for the Corps, model tests included, not to mention considerable private consulting.

Freeman Scholar Martin Mason transferred in 1940 from the Bureau of Standards laboratory to the Beach Erosion Board. The following year the Board began the publication of a series of technical reports. Number 1, by Mason, was "A Study of Progressive Oscillatory Waves in Water," and this was followed the same year by "A Summary of the Theory of Oscillatory Waves" by Morrough O'Brien and Mason together. As the War progressed, the Board undertook an intensive study of potential landing operations on the African and European coasts. Garbis Keulegan, already a specialist in wave studies, was borrowed from the Bureau of Standards, and William Christian Krumbein (1902-. . . .) moved to Washington from the University of Chicago for the same purpose; a geologist with interest in water-borne sediment, Krumbein had just completed a Guggenheim year at Iowa and California. Though the entire wartime staff of the BEB never exceeded 35, they produced more than 50 highly valuable reports on beach intelligence.

At the end of the War, in 1945, the 79th Congress formally established research and development as legal activities of the BEB. The latter's shore-protection counterpart was then abolished and its functions absorbed by the BEB, and the following year Congress authorized federal participation in the cost of protecting publicly owned shores. The first research contracts with non-federal organizations were written in 1948: with the Scripps Institution of Oceanography, the University of California (under O'Brien and Joe Johnson), and New York University (under Thorndike Saville). In 1943 Joseph Caldwell, who had been with the Waterways Experiment Station for ten years, transferred to the Board and was thereafter the designer of the new 635x15x20-foot wave tank that was installed in 1949-50; because of the Korean War, the tank was not activated till 1955. Another unit constructed during this period was the 300x150x3-foot Shore Processes Test Basin, with 10 movable wave generators. 1949 also saw the addition to the staff of Thorndike Saville Jr, Maryland-born and educated at Harvard and California, who ably carried on the professional interests of his father. When Mason left the Board in 1951 to become dean at George Washington University, he was succeeded as chief engineer by Caldwell. During Boris Bakhmeteff's membership on the board of the Engineering Foundation in 1950, a Council on Wave Research was formed, with O'Brien as chairman and Johnson as secretary. That year an Institute of Coastal Engineering was held at Long Beach, California, followed in later years by many more in various cities of the world. The year 1954 saw the appearance of the BEB's Technical Report No. 4, the 390-page volume *Shore Protection Planning and Design,* in its first of several editions.

The widely varied program of research begun at Iowa even before the War did not end, of course, when the War did—or even many years thereafter. For example, the low-velocity air tunnel was used by Maurice Albertson for his doctoral investigation of the relationship between boundary layers and evaporation layers, and he promoted similar studies in air at Colorado State College after moving there in 1947. The necessary generation of turbulence in the diffusion studies culminated in a paper on the velocity and scale of eddies downwind from coarse grids. The work on submerged jets involved in the fog-dispersal project appeared as several graduate theses and a paper on the diffusion of jets from slots and orifices. Not too remote from the submerged-jet study was a project on the improvement of fire monitors and nozzles for the Coast Guard, reminiscent of the earlier tests by John R. Freeman for his fire-insurance companies; but whereas Freeman made no mention of turbulence in his prize-winning papers, the Iowa studies sought to produce a design that would yield minimum initial turbulence—and hence maximum throw—of the free jet (a criterion which continues to be ignored by the fire-fighting world). Similarly, when it was proposed by the Navy to reduce propeller noise and cavitation by locating the propeller in an enlarged duct within the ship and using a high-velocity jet at the stern for propulsion, it was pointed out by Rouse that noise might still result from the cavitation of eddies generated by the diffusing jet. Navy-sponsored tests were then begun at Iowa on the mechanism of submerged-jet cavitation, to which John Peter Whitehouse, a master's-degree student from England, and David Woodhull Appel (1924-. . . .) and Sung-Ching Ling (1925-. . . .), doctoral students from Washington DC and China, respectively, strongly contributed. Individually, the latter two also produced independently a number of instruments for the measurement of sediment and others for that of turbulence—in particular Ling's hot-film anemometer—under the guidance of Philip Hubbard.

Two other series of investigations at Iowa were also the outgrowth of the wartime research. One had to do with the diffusion of heat from point and line sources. Measurement of the temperature distribution over a point source, its analytical evaluation for laminar conditions, and the empirical establishment of the critical Reynolds number (using a cigarette as the heat source) comprised the doctoral project of Chia-Shun Yih (1918-. . . .), a Chinese graduate assistant who then continued to distinguish himself at Colorado State, Iowa, and Michigan. The temperature distribution over single and parallel line sources was the work of Harold Wesley Humphreys (1921-. . . .) of North Carolina. William Douglas Baines (1926-. . . .) of Canada assisted in the completion of measurements for the resulting papers of 1952 and 1953. The other series of studies was concerned with surface resistance. At the Second Hydraulics Conference, in 1942, Rouse had presented a resistance diagram incorporating the British Colebrook-White smooth-to-rough transition function. The parameters $1/\sqrt{f}$ and $\mathbf{R}\sqrt{f}$ were used instead of the customary f and $\mathbf{R}$, because of the generality that this would yield; *f* and **R** were available, however, on supplementary scales. After the Conference, Lewis Moody of Princeton suggested using the latter variables as primary rather than supplementary, as in the past, but Rouse resisted the temptation because he felt that to do so would be a step backward. So Moody himself published such a plot, and it is known around the world as the Moody diagram! Baines' doctoral dissertation involved measurements of the velocity distribution in the boundary layer along a smooth plate, and he later (1951) prepared an Institute report on all that was then known about boundary layers. Subsequently, studies were conducted on the effects of sand, screen, and bar roughness in channels and boundary layers by Baines, Walter Rand (1914-. . . .) of Estonia, and Walter Leon Moore (1916-. . . .), a doctoral student from California, respectively. The results were analyzed in a 1954 paper by Francis Ryosuke Hama (1917-. . . .) of Japan, like Rand a post-doctoral research associate of the Iowa Institute for several years.

In the late summer of 1946 Rouse went to Europe under TMB sponsorship with a triple purpose: to assess the postwar laboratory situation in the various countries; to inspect water tunnels in preparation for a new one to be built at Iowa; and to present a paper on Iowa's wartime fog-dispersal studies at the Sixth International Congress for Applied Mechanics held at Paris after a four-year postponement. The German hydraulics laboratories were at a standstill, some having been partially destroyed. Prandtl was visited at Gottingen (the city was intact) and Spannhake at Karlsruhe (the city was in ruins), and the latter was then invited to Washington for work with the TMB. Three laboratories in other countries (those at Zurich, Grenoble, and London) impressed Rouse with their activity, however, and he recommended them through a letter in *Civil Engineering* to prospective Freeman Scholars. At least at Grenoble, where Martin Mason had been attracted by Pierre Danel before the War, the recommendation had a long-time effect. As recounted by Rouse in a subsequent memoir honoring Danel:

> The second Freeman Scholar, George S. Dixon, Jr., of the Corps of Engineers, actually arrived in Grenoble that fall and had received the engineering doctorate by 1949. My enthusiasm next led my colleague, John S. McNown, to spend his year as Fulbright Research Scholar with Danel in 1950-51; there he wrote a comprehensive paper on fall velocity, did research on seiche, and passed the examination for a doctorate in sciences. During McNown's absence from the Iowa Institute of Hydraulic Research, his chair was filled for a year by Antoine Craya of Grenoble, who later returned to the States to teach at Columbia after the death of Boris A. Bakhmeteff. McNown was followed immediately at Grenoble by Charles W. Thomas, of the Bureau of

Reclamation, also a Fulbrighter, as was I in 1952-53. At Grenoble I met Enzo O. Macagno, of Argentina, who was studying there for the doctorate, and in 1956 he moved from La Plata to Iowa City as a member of the Institute staff. My Fulbright successor at Grenoble was Maurice L. Albertson, of Colorado State College, who was the fourth to receive the local doctorate. Ira A. Hunt, of the Corps of Engineers, was the third Freeman Scholar, in 1953-54, and the fifth doctor. [A. R. Chamberlain, Albertson's first doctoral student at Fort Collins, was a Fulbright Scholar at Grenoble in 1955-56.] The fourth Freeman Scholar, in 1961-62, was Jacques W. Delleur, of Purdue University (and previously one of Craya's students at Columbia). Several other Americans were there a month or more, and literally hundreds must have visited Neyrpic, and more recently SOGREAH, at one time or another.

In view of the attention that has been given to the subject of pipe resistance, a pertinent story might well be told at this point. Benjamin Miller (1904-. . . .), a New York consulting engineer to the oil and gas industries, while checking some of Nikuradse's experimental results shortly after the War, discovered that the published raw and computed velocity-distribution data differed by a constant additive factor. During an ASME meeting Miller happened to tell Rouse about the discrepancy, and the latter, recently returned from his visit to Gottingen, offered to transmit a letter of inquiry from Miller to Prandtl; this was soon done. Nikuradse was then back in Gottingen from Breslau, but Prandtl, who was no longer on speaking terms with him, asked his associate Reichardt to question him instead. The eventual response was that Nikuradse had added the constant factor (which had an appreciable effect on the semi-logarithmic expression only in the wall vicinity) because his measured values would otherwise not be compatible with the laminar-film theory; Prandtl added his own opinion that the correction was hence justifiable, whereas the author's failure to mention it in the text was not. Though Miller interpreted the subterfuge as evidence against the existence of the laminar film, subsequent measurements by the Hungarian-born aerodynamicist John Laufer (1921-. . . .), of Caltech and the Bureau of Standards, verified Nikuradse's assumed function. [It has recently been pointed out by Landweber at Iowa that the discrepancy in measurement resulted from Nikuradse's having placed his stagnation tube in the free-shear zone somewhat beyond the end of the pipe rather than within the pipe itself.]

Little mention was made of the St. Anthony Falls Hydraulic Laboratory in the foregoing chapter on fluid mechanics, because the limited amount of work that was done before the War was confined to Lorenz Straub's studies of sediment and river control involved in his growing consulting practice. As soon as the War was under way, moreover, Straub was among those who decided that they should contribute more to the defense effort than was possible at home, and he spent the years 1942-45 with the National Defense Research Committee in its Divisions of Rocket Ordnance and Subsurface Warfare at New York; for essentially half a year (while the bombs were falling) he was in London on a related mission. During Straub's absence from his laboratory, the work of the cooperating federal agencies was continued with their own reduced staffs. Practically the only laboratory projects that remained active were on the aeration of high-velocity flow on steep slopes, which was studied as a doctoral project by Warren William DeLapp (1912-. . . .), an instructor from Colorado by way of Iowa, who was to return to Colorado in 1947; and on soil conservation structures by Fred William Blaisdell (1911-. . . .) of New Hampshire and MIT, who had been with the SCS since 1936, first at the Bureau of Standards and then at Minnesota. At the close of the War Straub surrounded himself with Minnesotans who had been active in the country's defense: Edward Silberman (1914-. . . .), who had served 5 years with the Army, was to take a strong part in teaching and research in the mechanics of fluids; Alvin Anderson, already mentioned in connection with the SCS, had been several years with the NDRC at New York, and thereafter continued his studies of sediment transport at Minneapolis; John Frederick Ripken (1914-. . . .), who had participated in the design of the Minnesota laboratory before the War, spent four years in naval research at Columbia University and one with the Taylor Model Basin before returning to pursue his special interests in instrumentation and cavitation. In the postwar period the St. Anthony Falls Laboratory not only initiated an active program of model investigations, but through their wartime naval connections the staff also developed strong research programs on cavitation, wave motion, underwater acoustics, hydrofoils, and polymer additives.

Two other hydraulicians who did wartime work at the Model Basin before returning to nonmilitary research have already been mentioned—James Robertson and Charles Lee. As a matter of fact, during the War the TMB played much the same catalytic role as Caltech had done a few years earlier. Charles Edward Bowers (1919-. . . .) of Wyoming was there from 1942 to 1945, and upon Lee's return from the South Pacific, he worked under the latter's direction on experimental studies for a sea-level canal in Panama; their joint paper on the investigation received the ASCE Collingwood Prize; thereafter, Lee went into research with the paper industry, and Bowers—after graduate study at Minnesota—spent two years with the Bureau of Reclamation and then joined Straub's staff. Freeman Scholar Victor Streeter, who had been a hydraulic engineer with the Bureau of Reclamation and the International Boundary Commission before going to the Illinois Institute of Technology, spent the summer of 1942 at the Basin reducing Lamb's *Hydrodynamics*, as the saying went, "from words of five syllables to words of four"; the eventual outcome was a series of advanced and elementary textbooks on fluid mechanics which went into many editions; Streeter was to remain with the Armour Research Foundation—originally a part of IIT—till his return to Michigan in 1954. Phillip Eisenberg (1919-. . . .) of Michigan did graduate work at Iowa and Caltech before joining the TMB staff in 1942, remaining there in cavitation analysis till going to the Mechanics Branch of the Office of Naval Research in 1953 for contract administration. A latecomer to the TMB because of his youth, Marshall Peter Tulin (1926-. . . .) of Connecticut, after study at MIT and Brown and service with the National Advisory Committee for Aeronautics, went to the TMB in 1950 and then followed Eisenberg to the ONR in 1953. Eisenberg and Tulin together were to found the private research firm Hydronautics in 1959, where they were joined the following year by Virgil Evans Johnson (1927-. . . .) of Florida, Georgia Tech, and MIT, whose experience had included (instead of the TMB) the WES, the MIT Hydrodynamics Laboratory, and the NACA.

Boris Bakhmeteff succeeded Fred Scobey as chairman of the ASCE Hydraulics Division in 1943. Among his early innovations was the appointment of Committees on Hydraulic Data and Facts and on the State of Art and Science of Hydraulics. The latter was short-lived, giving way in 1946 to a Committee on Fluid Mechanics, with Hunter Rouse as its first chairman (the ASME Hydraulic Division soon following suit in both respects). One of the initial committee activities was the listing of available motion pictures on fluid-flow phenomena. Another was the sponsorship of a symposium on high-velocity flow in open channels. Four papers on the subject were written (basic principles, by Ippen; flow in bends, by Knapp; flow at contractions, by Ippen and Dawson; and flow at expansions, by Rouse, Bhoota, and Hsu), and these were presented at an annual meeting of the Society. The symposium was published in the 1951 *Transactions*, and Ippen received the Hilgard Prize for his initial paper. By the end of the four-year terms of Scobey and Bakhmeteff, the Division had gathered considerable momentum, and one-year chairmanships were instituted. Most of the people named in these pages served on its Executive Committee at one time or another, and the Division has remained one of the most active in the ASCE.

While completing at Lehigh a noteworthy study of the influence of viscosity on the performance of centrifugal pumps, Arthur Ippen was invited by MIT in 1945 to replace KC Reynolds, who had left for Cooper Union the year before. The hydraulics faculty then consisted of George Russell, already mentioned in Chapter IV, and Allan Thurston

Gifford (1906-. . . .), an MIT graduate who had had several years of hydrologic experience with the TVA. Donald Robert Fergusson Harleman (1922-. . . .) of Pennsylvania, who by chance had arrived in Cambridge the very same day as Ippen, became Ippen's first graduate assistant, and attention was given to reestablishing Reynolds' original laboratory, which had lain idle during the War. The same period saw the initial post-war influx of officers from the Corps of Engineers as graduate students, and this continued at a rather high level (about 15) for the next five years. When Russell retired in 1946, his place was taken by Ippen's close friend at Caltech, James Daily, and that year the second graduate assistant was employed: Henry Martyn Paynter (1923-. . . .) of Illinois, who had received his undergraduate degree two years earlier. With the support of the US Air Force, Harleman completed his doctoral research in 1950 on the validity of the hydraulic analogy to supersonic flow; Paynter at the same time worked on the application of analog and digital computers to surge-tank transients, receiving his degree in 1951. The hydraulics faculty then consisted of Ippen, Daily, Gifford, Harleman, and Paynter, and the number of research assistants had grown to 13.

The War years also saw the beginning of the tremendous upsurge that was to follow in the publication of textbooks on fluid mechanics. The first of these was written by John King Vennard (1909-1969) of New Hampshire, who had assisted Spannhake at MIT before joining the teaching staff at New York University and then at Stanford; published in 1940, his *Elementary Fluid Mechanics* was to go through many editions prior to his untimely death. The second was published by Raymond Binder in 1943, a few years after he went to Purdue from Caltech; somewhat simpler and slanted toward the mechanical engineer's interest, his *Fluid Mechanics* also came out in many successive editions. The notes prepared by Rouse finally appeared as *Elementary Mechanics of Fluids* in 1946; though limited to a single edition, it was translated into several languages, including mainland Chinese! In 1947 a noteworthy volume, *Fluid Mechanics of Turbomachinery,* was published by George Wislicenus; begun while he was at Caltech and written during his ten years with Worthington, it reflected the new approach to a considerable degree. While on the subject of publications, it should be remarked that the *Proceedings* of the Fourth Hydraulics Conference, held at Iowa City in 1949, took the form of a 1000-page reference book, *Engineering Hydraulics.* All thirteen invited chapters were preprinted for discussion at the Conference, and the fluid-mechanics viewpoint was strongly evidenced in each one: fundamental principles, by Rouse, the editor; hydraulic similitude, by J. E. Warnock of the Bureau of Reclamation; flow measurement, by J. W. Howe; hydrology, by G. R. Williams of Knappen Tippetts Abbett

Engineering Company; ground water, by C. E. Jacob of the University of Utah; steady flow in conduits, by V. L. Streeter; water hammer, by J. S. McNown; channel transitions, by A. T. Ippen; gradually varied flow, by C. J. Posey; flood routing, by B. R. Gilcrest of the Corps of Engineers; wave motion, by G. H. Keulegan; sediment transportation, by C. B. Brown of the SCS; and hydraulic machinery, by J. W. Daily. Some 425 attended the Conference, and the group photograph appears as the frontispiece of this book. The volume itself, which appeared in 1950, was dedicated to Boris Bakhmeteff, who had originally advised against the venture because of its difficulty of accomplishment! The following year the Engineering Societies Monograph *Hydraulic Transients* was published by George Rollo Rich (1896-. . . .) of Massachusetts and Worcester, a consulting engineer with various private firms, the TVA, and the Corps of Engineers, and guest lecturer and adviser to several universities.

Emphasis has already been laid upon the accelerative effect of war requirements on certain types of research, and upon the catalytic action of the Office of Scientific Research and Development in this regard. Much of its success, it should be noted, had stemmed from its authority to select individuals and teams for particular projects without requiring competitive bidding. At the close of hostilities, the OSRD properly terminated its activities. But one of the few salutary results of the war had been its demonstration of the importance of federal sponsorship of research on a broad basis. To provide continuity, Congress authorized in 1946 the establishment of the Office of Naval Research, the scope of which ranged surprisingly far beyond purely military interests. Competitive bidding on announced programs was still not required, competition taking the far more effective form of excellence of staff and proposals. The ONR's effectiveness was vouched for by no less an authority than Vannevar Bush, who had led the OSRD throughout the war:

> The Navy . . . has done a magnificent piece of work in this regard (sponsored research). It understands scientific and university-service relationships . . . .

Thanks to the efforts of Bush and his colleagues, in 1950 Congress finally authorized formation of the National Science Foundation, to take over the non-military activities of the ONR, including the support of education as well as research in science and engineering. In the words of the first NSF director, Alan Waterman,

> During the five years after the war, a considerable evolution took place. Academic institutions learned that Federal aid to research was possible without Federal control. Agencies with practical

missions found that even basic research done by academic professors could prove useful to them.

In the years to follow, both ONR and NSF support was to be of primary importance in hydraulic research.

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PROCEEDINGS

BOSTON SOCIETY OF CIVIL ENGINEERS SECTION

AMERICAN SOCIETY OF CIVIL ENGINEERS

Meetings Held — Technical Groups

Computer Group

October 20, 1976. Evening meeting at Parsons Laboratory, MIT, Chairman Lewis H. Holzman presiding. Speaker, Roy N. Freed, Partner, Powers and Hall, Boston. Subject "Legal Questions Related to The Acquisition and Use of Computer Technology." Attendance, 18.

Construction Group

September 22, 1976. Luncheon meeting at Red Coach Grill. Chairman Rieksts opened the meeting. An election of officers was held for the 1976-1977 season, with results as follows: Chairman, Norman W. Bennett; Vice Chairman, John P. Sullivan; Clerk, Stephen G. Walker; Members Executive Committee, Laimonis Rieksts, Samuel E. Rice, Joseph B. Kerrissey, Jr.

New Chairman Bennett introduced the speaker, Dov Kaminetsky of the firm of Feld, Kaminetsky & Cohen, who spoke on his 25 years of experience in the analysis and prevention of structural failures. Attendance, 40.

Hydraulics Group

October 6, 1976. Dinner meeting at Mystic River Flood Pumping Station, Chairman Edward P. Dunn presiding. Speakers, Mr. William Brutsch, Senior Mechanical Engineer, MDC, and Edward P. Dunn, Assistant Vice President, CE Maguire, Inc. The speakers conducted a tour of the flood pumping facility and described its features. Attendance, 35. This was also an official meeting of the main Section (BSCES).

Structural Group

October 13, 1976. Evening meeting at the MIT Center for Advanced Engineering Studies, Chairman Kentaro Tsutsumi presiding. This was the 1976 T.R. Higgins Lecture of AISC, and the meeting was co-sponsored by AISC Structural Steel Fabricators of New England. Speaker, Dr. Robert H. Scanlon, Professor of Civil Engineering, Princeton University and Recipient of the 1976 T. R. Higgins Lectureship Award. Subject, "Modern Approaches to Solution of the Wind Problems of Long Span Bridges." Attendance, 45.

Transportation Group

September 16, 1976. Luncheon meeting at Dukes in the Park Restaurant, Boston, Vice Chairman McDonagh presiding. Speaker, Representative Louis R. Nickinello, Co-Chairman of the Joint Committee on Transportation, Commonwealth of Massachusetts, whose subject was "Transportation Futures." Attendance, 40.

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(Required by 39 U.S.C. 3685)

1. TITLE OF PUBLICATION: Boston Society of Civil Engineers Section American Society of Civil Engineers

2. DATE OF FILING: October 1, 1976

3. FREQUENCY OF ISSUE: Quarterly

A. NO. OF ISSUES PUBLISHED ANNUALLY: @2402

B. ANNUAL SUBSCRIPTION PRICE: $10.00

4. LOCATION OF KNOWN OFFICE OF PUBLICATION *(Street, City, County, State and ZIP Code) (Not printers)*: 230 Boylston Street, Boston, Ma 02116

5. LOCATION OF THE HEADQUARTERS OR GENERAL BUSINESS OFFICES OF THE PUBLISHERS *(Not printers)*: 230 BoylstonStreet, Boston, Ma 02116

6. NAMES AND COMPLETE ADDRESSES OF PUBLISHER, EDITOR, AND MANAGING EDITOR

PUBLISHER *(Name and Address)*: Boston Society of Civil Engineers Section American Society of Civil Engineers

EDITOR *(Name and Address)*: Edward C. Keane, 230 Boylston Street, Boston, Ma 02116

MANAGING EDITOR *(Name and Address)*:

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