The Role & Contributions of Hydraulic Testing Labs: Part I, Industrial Revolution to World War I

Hydraulic testing laboratories have played key roles in advancing the science, practice and teaching of fluid mechanics. One on-going laboratory has made far-reaching contributions in the field.

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Prior to the 19th century, water power in the United States was furnished mainly by undershot, overshot, breast and paddle wheels (see Figure 1). In the early 1800s, experimentation with different types of hydraulic wheels, still mostly constructed of wood, began. Flutter wheels, Barker's mills and tub mills were utilized in the various industries of the times. In the 1820s and 1830s, Claude Burdin and Benoit Fourneyron experimented with iron turbines, which culminated in a patent issued to Fourneyron for an outward-flow wheel (see Figure 2). Samuel Howd of Geneva, New York, patented an inward-flow wheel in 1838 and an outward-flow wheel in 1842. At the Lowell, Massachusetts, mills in the mid- to late 1840s, James Bicheno Francis and Uriah Boyden experimented with turbines and diffusers, initially using Howd and Boyden patents. Asa Swain, in 1857, and John McCormick, in 1870, improved the blades of the turbines that to this day bear the name of Francis (see Figure 2).

The Industrial Revolution in New England

Huge textile mills were being built in Lowell (in 1822) and Lawrence, Massachusetts (in 1845), Slatersville, Rhode Island, and Manchester, New Hampshire. A large complex of paper manufacturing companies was erected along the Connecticut River in Holyoke, Massachusetts, in the mid-1850s. These mills were greatly responsible for fostering the development of hydraulic engineering in the United States. Various types of wooden water wheels, up to 30 feet in diameter with 12-foot buckets, were

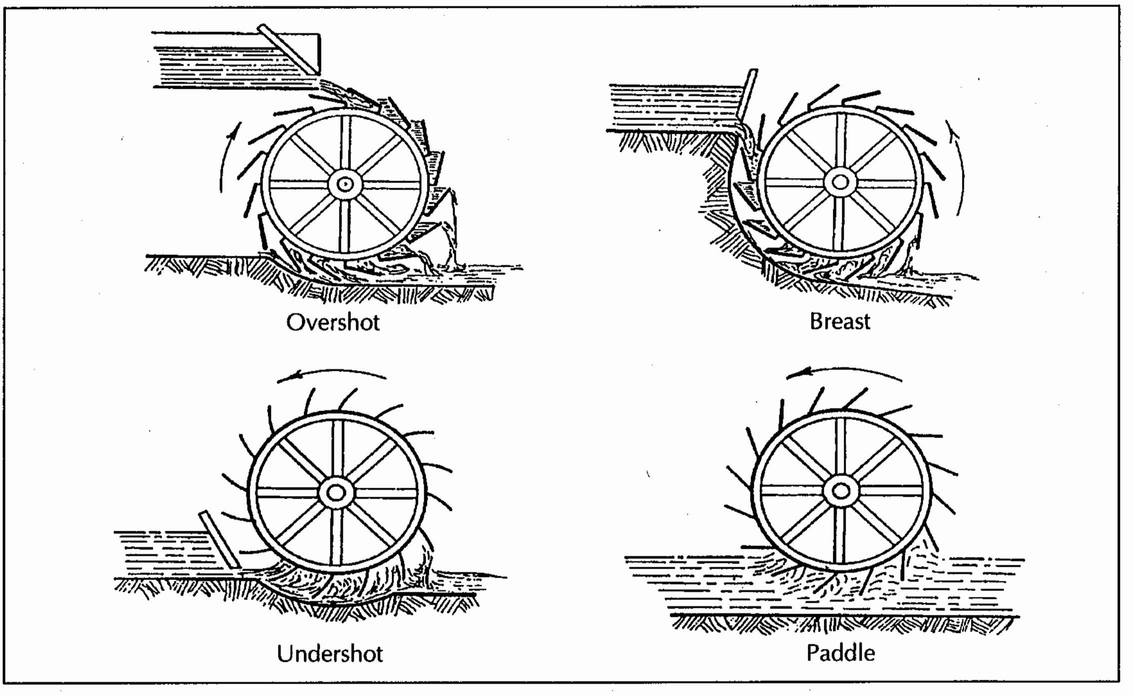

FIGURE 1. Early types of water wheels.

being used at this time). In 1828, the growth of Worcester, Massachusetts, was helped when the Blackstone Canal linking the city with Providence, Rhode Island, began operating.

Worcester was developing into an industrial city of mechanics. Immigrants were arriving in large numbers to work in developing wire/cable and the machine tool industries. In the 1830s, an expert mechanic, Icabod Washburn, was producing quality wire in Worcester and locomotives were being manufactured in Lowell. Also in Worcester, the nation's leading builder of stage coaches turned to railroad cars in 1837, quickly becoming again the nation's leader in that field. "High-speed" weaving machines and looms were being designed and manufactured in the city. From about the 1840s, many companies were supplying looms for fancy woolens to the mills in Lowell.

By the 1840s, the Industrial Revolution had truly arrived in Worcester. The city's population increased from 2,962 in 1820 to 7,497 in 1840, and 25,000 in 1860. By 1885, Worcester was a thriving industrial city of 63,000, with

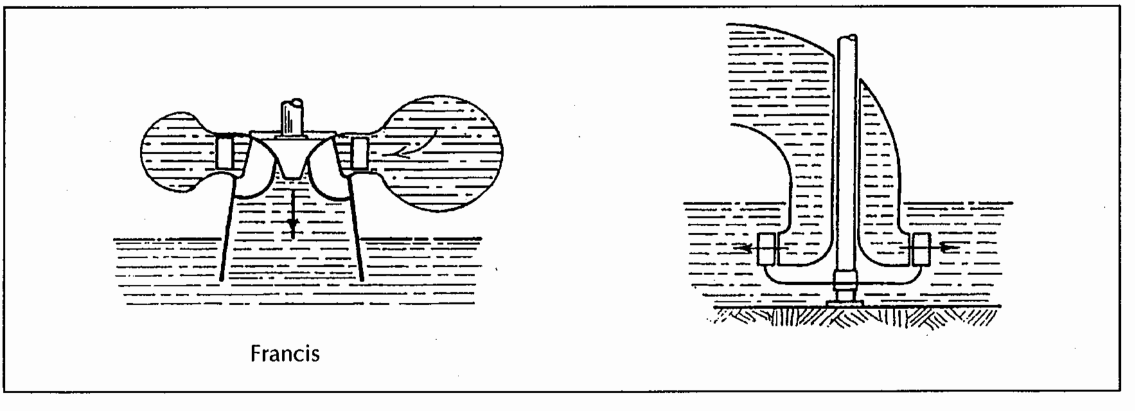

FIGURE 2. Early turbines.

722 industrial firms that supplied machinery and wire to industry. This population would increase 80 percent by 1898 to 103,000, when Worcester would be the third largest city in New England. However, economic growth slowed in 1893 when a financial "panic" occurred with a stock market crash; in the following year more than 400 banks in the United States failed.

Development of Hydraulic Engineering in New England

The growing industries in Worcester, Lowell, Lawrence and Holyoke needed a way to make more efficient use of their cheapest source of energy — water. Waterpower purveyors and users sought out the best engineering minds available to help them do so.

One pioneering hydraulic engineering writer and investigator in New England was Charles Storer Storrow (1809–1904). Born in Montréal, educated at Harvard, and trained in France, Storrow wrote the first American book on hydraulics.[1] He was retained by the Proprietors of the Locks and Canals (the Proprietors) on the Merrimack River at Lowell in 1835 to measure the quantity of water used by the mills. He later repeated the Lowell mill concept at the new mill city of Lawrence (downstream on the Merrimack) as Chief Engineer of the Essex Company.

In 1837, James Francis (1815–1892) was hired by the Proprietors at Lowell.[2] Francis worked on canals in England before coming to the United States in 1833 as assistant to George Washington Whistler (1800–1849), father of the artist, on the New York to Boston railroad. Whistler then took him to Lowell, where he later succeeded Whistler as canal superintendent and in 1845 became the Proprietors' principal engineer, remaining in that post for nearly 40 years. Among his major responsibilities at Lowell were measuring the flow to each mill so that costs could be properly and fairly assessed, and to determine the efficiency of the machinery that converted the flow to power.[2,3]

Francis' early, large-scale detailed experiments on improved turbines, weirs, stream gaging and related topics pioneered hydraulic engineering in the United States. They are described in his 1855 book, *The Lowell Hydraulic Experiments*.[3]

The development of textile mills in New England would also have a dramatic effect on another engineer starting his long career at about this time. Charles T. Main graduated from the Massachusetts Institute of Technology (MIT) in 1876 with a degree in Mechanical Engineering. After working as an assistant in MIT's Department of Mechanical Engineering for three years, Main became a construction engineer for the mills in Manchester, New Hampshire. By 1891, he was Superintendent of the Lower Pacific Mills. Over the years, Main engineered numerous hydroelectric projects, including the major developments on the St. Lawrence River at Massena and on the Niagara River at Niagara Falls.

By 1879 much was known about the measurement of water through hydraulic turbines. However, Clemens Herschel (see Figure 3) found that the Holyoke mills (which were mostly paper mills) used large amounts of water that remained unmeasured, thereby losing considerable income for his employer. Using Venturi's principle, he designed and tested a 12-inch and a 48-inch diameter meter. This type of meter that measured water flow more accurately was called a Venturi meter.

Engineering Education & Training

When the mills began to operate in America, people also saw the need for technical education. In 1861, MIT was founded by William Barton Rogers, a geologist. Its completion was delayed by the Civil War, and classes were first held on February 20, 1865.[4] Also in 1865, John Boynton, a tinware peddler, supplied the funding for a technical school in central Massachusetts. The school, initially known as the Worcester County Free Institute of Industrial Science, was built in Worcester and enrolled the first class in its three-year program in 1868. The institute was later renamed Worcester Polytechnic Institute (WPI) in 1887. Its initial teaching staff of five included George I. Alden (see Figure 4), instructor in theoretical and practical mechanics. Alden received his basic education at the newly created Lawrence Scientific School of Harvard, and was influenced by the early hydraulic work in Lowell and Lawrence.[2]

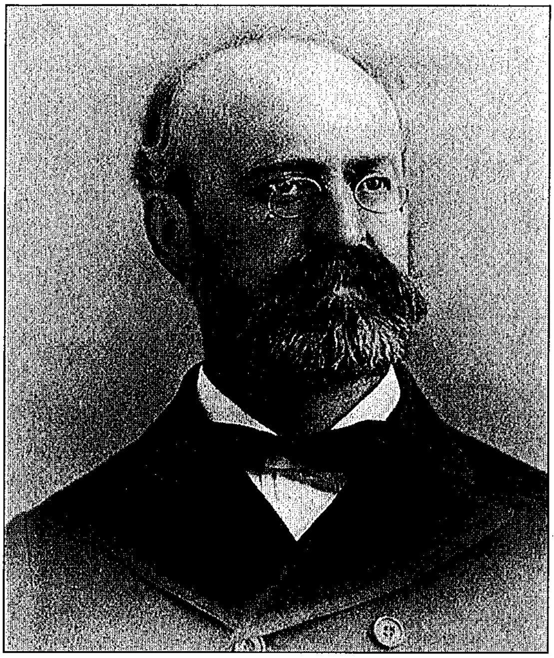

FIGURE 3. Clemens Herschel.

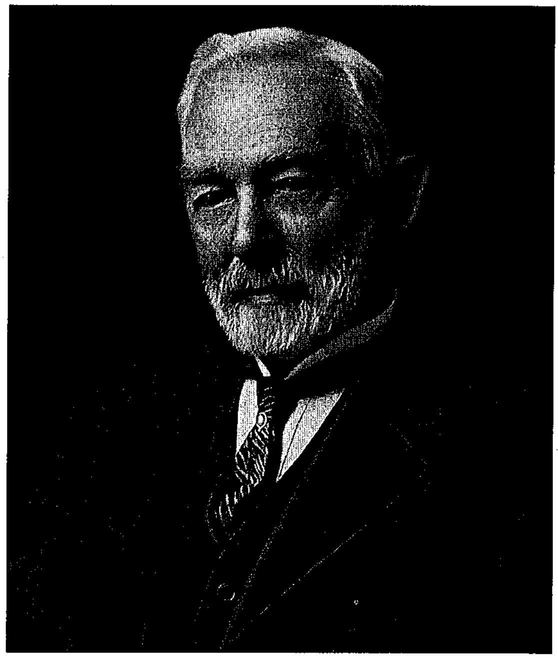

FIGURE 4. George I. Alden

Birth of a Hydraulic Testing Laboratory

Alden was an astute engineer and apparently well read on the new technologies of his time. During his first two decades at WPI, he became aware of the hydraulic developments of Francis in Lowell and those of two of Francis' former colleagues who had taken positions around 1879 at the Holyoke Water Power Company. One of these engineers, Clemens Herschel, invented the Venturi meter; while the other, James Emerson, was responsible for building a turbine test facility of 200-cubic-feet-per-second capacity under an 18-foot head. This early hydraulic facility (known as the Holyoke Testing Flume) was utilized for obtaining the efficiency of 139 water wheels located in nearby factories, most of which were in the paper industry. When its reputation spread, the testing flume was utilized by many turbine manufacturers and users of the day. As turbines became larger and the value of water and head was fully appreciated, the efficiency of the "wheels" became a major selling point. At this time, the different aspects of efficiency were just starting to be appreciated and defined.

During the period from about 1870 to 1890, great strides were made to improve the efficiency of water-powered machinery due to the increase in manufactured goods utilizing limited water supplies. Also, the invention of electricity by Thomas Edison and the ability to produce this electricity by waterpower further inspired Alden to formulate plans for facilities at WPI that would be at the cutting edge of technology. The institute's interest in waterpower in the late 1880s was probably stimulated by the appearance of electric utilities in the eastern United States during that time. These companies required engineers knowledgeable in hydraulics.

Alden proposed that WPI should build engineering facilities, a turbine that could also be used for testing and instruction, and a hydraulic laboratory. With these facilities, Alden envisioned testing relatively large equipment, something not normally associated with technical school laboratories. Alden was invited on June 8, 1893, to the home of U.S. Senator George F. Hoar, a WPI trustee, to present his ideas before a trustee committee meeting. The committee ended up recommending that the institute build the facilities and asked the school to acquire the use or ownership of some neighboring waterpower sites for making tests of hydraulic machinery.

Later that year at an alumni dinner, Alden presented the proposed facilities for WPI. Alden indicated that a water-mill power site existed in Chaffinville, a village of Holden, a town just to the north of Worcester. Stephen Salisbury III, a prominent local industrialist as well as a WPI trustee and benefactor, was in attendance and questioned Alden as to the exact location of this site. Salisbury then indicated that he was the owner and would be glad to give the school the property for a test facility. The Holden site obtained water from a 200-acre pond, and two smaller 2-acre and 4-acre ponds were on the site, which was located five miles from the school.

The hydraulic laboratory at WPI, established in 1894, was the third hydraulic laboratory established at an American school and the second at an American engineering school. Prior to 1883, the University of California, under Frederick Hesse, established the first hydraulic teaching laboratory. In 1887, Mansfield Merriam built a similar laboratory at Lehigh University. Merriam was famous for his textbook *Treatise on Hydraulics*, which was first published in 1889 and had subsequently gone into ten editions.[5] Cornell University followed WPI with a laboratory in 1899. As the importance of hydraulics grew, many of the U.S. engineering schools added laboratories in the early 1900s to supplement classroom instruction. Another notable laboratory founded about this time was at the State University of Iowa.

Site History

WPI's Hydraulic Laboratory was located on a stream whose flowage rights were acquired by John Bigelow in 1726. At that time, this section of Massachusetts was called Worcester North Half or North Worcester, and it was highly forested. Since the area had been recently opened for development, Bigelow erected a water-powered sawmill to produce lumber for the new inhabitants' houses and other necessary buildings.

Besides running the sawmill, Bigelow was active in local politics. In 1740, armed with a petition signed by 25 people, he approached the Massachusetts Legislature to have this section of Worcester incorporated as a separate town. On May 4, 1741, after two petitions, Governor Belcher signed the act creating a new town called Holden.

There is little record of Bigelow's activities, but in 1753 his property was acquired by Benjamin Flagg who built a sawmill of his own. The present dams located on Lincoln and Shrewsbury Streets were erected by Bigelow and Flagg to impound the water necessary to power their mills. Unfortunately, the impoundments flooded valuable hay meadows in an area where cultivable land was scarce. This situation led to a compromise with local farmers whereby the ponds were drained in the spring and re-flooded in the late fall. As more land was cleared, the farmers relaxed their rights to the meadow hay, and in the 1770s the ponds were allowed to remain full all year. Following the War for Independence, a grist mill (see Figure 5) was built and operated in conjunction with the sawmills. The owner was Samuel Chickering, a blacksmith who ran his shop on the site and leased the mills.

All this development in Holden was taking place when England was experiencing the Industrial Revolution and unrest was brewing in the Colonies. Isaiah Tomas, a Boston printer, began publishing his rebel newspaper, *The Massachusett's Spy*, from Worcester in 1775. John Kay's flying shuttle (1733), James Watt's steam engine (1769), Richard Arkwright's spinning frame (1769), James Hargroaves's spinning jenny (1770), Samuel Crompton's mule (1779) and Edmund Cartwright's power loom (1783) were the main factors in promoting increased production in the textile industries. These inventions were indirectly responsible for the creation of the laboratory and its early involvement in testing turbines used to power textile machinery.

The Embargo Act of 1807 caused great hardships in the new American states, and caused Americans to look into increased production of goods such as textiles, paper and metal. Water was a readily available source of power and all water sites became important, even those in Holden. At this time, Holden, as most of New England, was a self-sufficient, agricultural-based community that benefitted by close

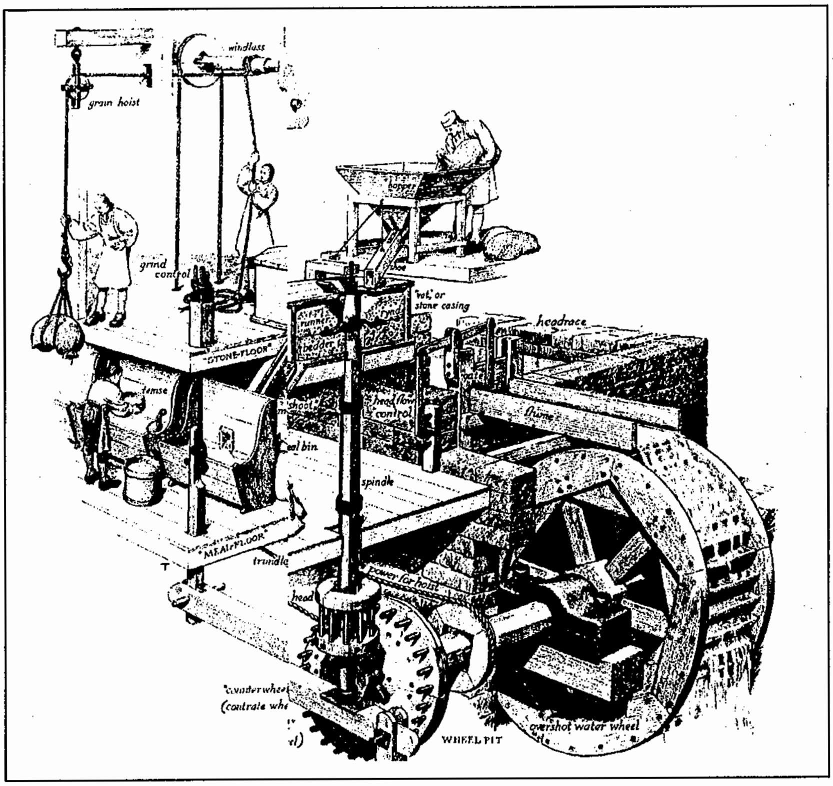

FIGURE 5. A typical grist mill.

highly flammable cotton, wool and flour dust. Alfred Chaffin had built a grist mill in 1870 only to see it demolished by fire. It was rebuilt, only to burn again in 1890. Subsequently, the site changed hands several times. The names of Daniel Hesselton, Lewis Rivers and John Shewbrook appear on deeds of various parts of the property. Shewbrook had converted the grist mill to a shoddy mill used to process woolen cloth into wool yarn. Later in the 1890s this mill, too, suffered a disastrous fire.

The deeds of the Holden site in the late 1800s record Stephen Salisbury III as the mortgage holder for all the proprietors of this site. The Salisbury family was a prominent Worcester industrial family in the 1800s, and the three Stephen Salisbury's had been long associated with WPI. The oldest known photograph, circa 1894, of the site is shown in Figure 7. It was taken standing on the south side of Shrewsbury Street, looking approximately east toward the "red barn" in the background. (This barn still exists on the site.) The new pipe being installed under Shrewsbury Street runs to the original laboratory.

proximity to a growing city — in this case, Worcester.

In 1817, Royal H. Chaffin acquired the Holden site of the future laboratory (see Figure 6), with sawmill, lumberyard and gristmill. Chaffin added wool dyeing and yarn coloring operations. In 1819, John Parks acquired the sawmill and lumberyard along with a water privilege reading "for said sawmill when there shall be more than is needed at the grist mill." Chaffin, located downstream and perhaps uncomfortable with this situation, eventually reacquired complete control of the site. His son Alfred occupied part of it, manufacturing woolen goods used in prison uniforms, and later became sole owner of the entire site and its water rights. The neighborhood of the site, including the mill ponds, was referred to as Chaffinville and is shown as such on maps from the 1870s.

During this pre-electric period, mills like those at Chaffinville frequently experienced destructive fires due to the combination of hazardous lighting and heating systems and

Initial Layout

The first laboratory structure, built on the site of Chaffin's old woolen mill, was a wood frame building, 90 feet by 40 feet, erected in the summer and fall of 1894 (see Figure 8). This site had enough water at a head of 30 feet to produce 75 horsepower. A horizontal control gate was built at the exit of Pond No. 2 (see Figure 6), and a 40-inch riveted steel pipe approximately 400 feet long was installed from

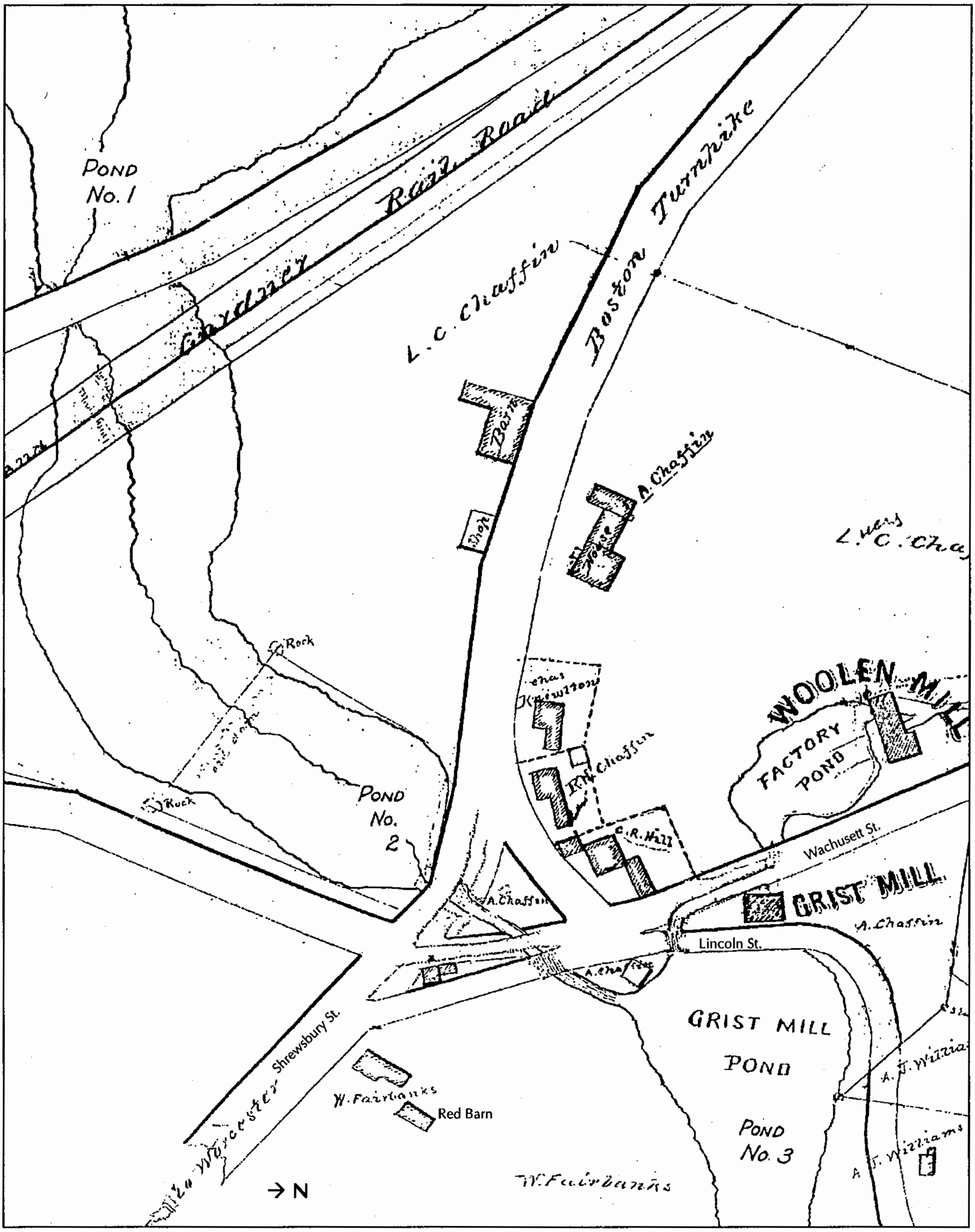

FIGURE 6. Chaffin's map, 1873.

the gate to the building to supply water for testing. A 30-foot-high tower was erected onto the building to provide access to glass tubing from piezometers located in the steel pipe and the flow measuring device (a Venturi meter). This building, enlarged and modified several times, is still used for flow meter calibration and other types of testing.

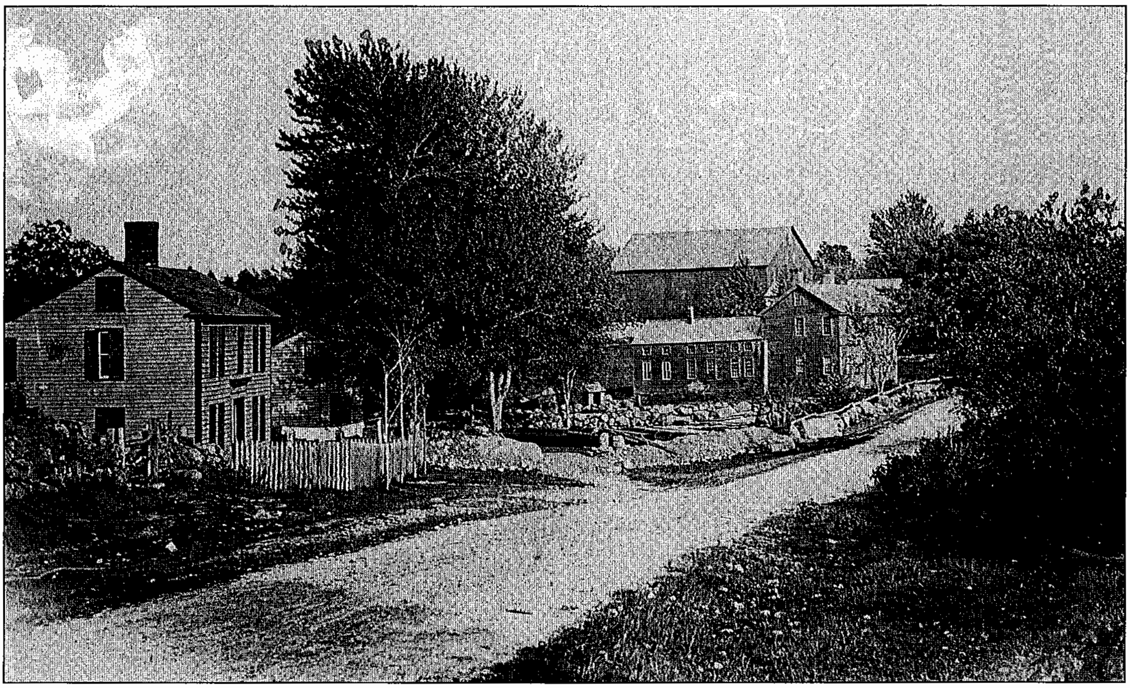

FIGURE 7. Hydraulic Laboratory site, circa 1890.

Testing Equipment

Clemens Herschel's Venturi Meter. The first piece of equipment for the new hydraulic laboratory was a 36-inch by 16-inch Venturi meter designed by Clemens Herschel for the 1893 Columbian Exposition in Chicago and the largest in the world at that time. A pamphlet published for the exposition indicated that the meter was the first commercial Venturi meter ever built. After the exposition, the meter and its automatic recorder were purchased by Stephen Salisbury III at a cost of $500 and donated to WPI. This Venturi meter is shown in its original laboratory location in Figure 9. Taps for velocity traversing and the U-tube connected to a probe should be noted. In the background is an early recorder or controller.

An interesting story exists concerning the performance of the meter at the Columbian Exposition. The meter had been installed in series with a piston pump to measure the total water supply to the exposition. It was common in those days to measure large water flows using piston pumps. Knowing the piston displacement and the rotational velocity of the pump, it was possible to obtain the flow rate, assuming the leakage was insignificant. This technique was well accepted as being a very accurate method to measure relatively large flows. Therefore, at the end of the exposition, the records of both the Venturi meter and the piston pump were compared. A discrepancy of approximately 20 percent was found. After much thought and deliberation, the discrepancy was attributed to the fact that the Venturi meter was relatively new, its theory having been presented by Herschel in a 1887 paper, and that there was the possibility that there was a flaw in the theory. Herschel could not believe that the testing he had performed at the Holyoke Water Power Company and later at the East Jersey Water Company could have produced data whose results, when applied to the exposition meter, would result in a 20 percent error. After all, the test meters and the exposition meter were of approximately the same size. Herschel, therefore, sent one of his engineers to Chicago to investigate the inconsistency between the two devices. Among the investigations the engineer pursued was a walking inspection of the site. One of the things he discovered was a manhole cover located between the piston pump and the Venturi meter. Upon removing

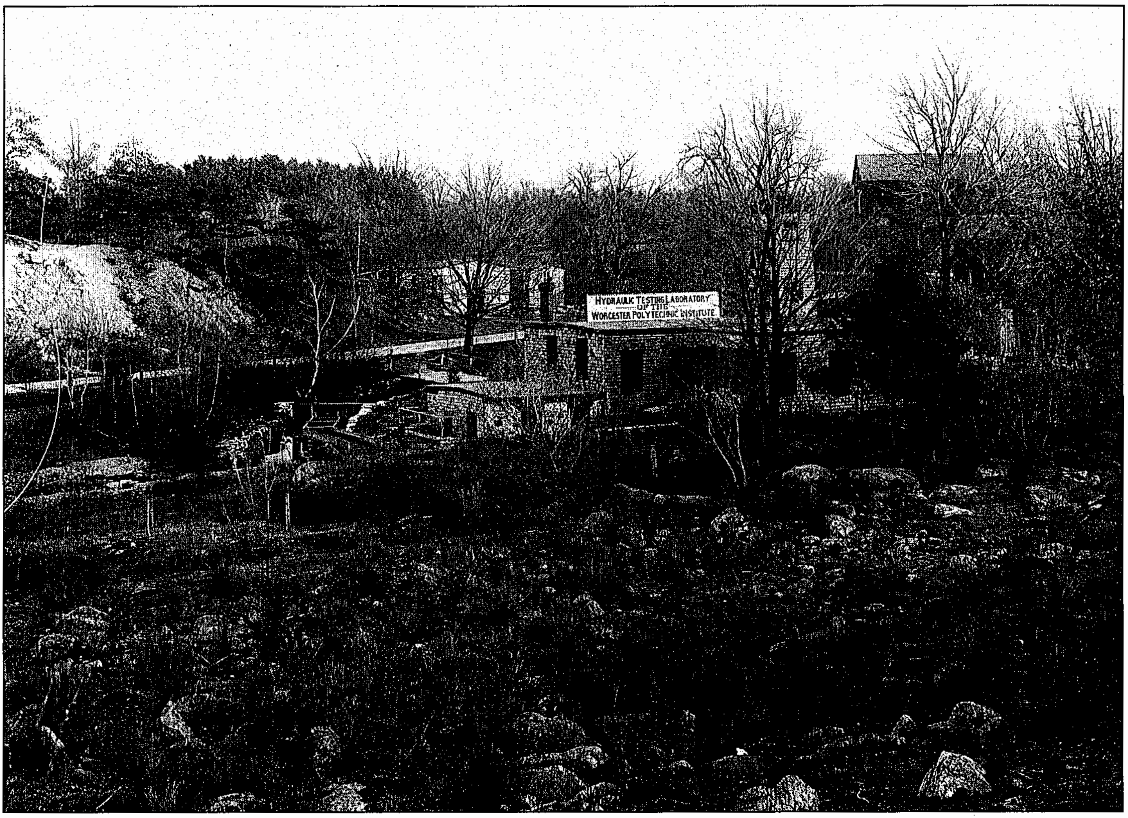

FIGURE 8. Original buildings and water supply channels in 1907.

the cover, he noticed that a 12-inch line containing a valve had been installed onto the side of the main pipe. Climbing down the manhole, he discovered the valve to be wide open. Further research traced the 12-inch line to a slaughter house. As the result of the investigation, the operators of the exposition decided to obtain the difference between the flow indicated by the piston pump and the Venturi meter and to charge the slaughter house for the use of this amount of water.

Absorption Dynamometer. Another piece of apparatus for the laboratory was an absorption dynamometer invented, designed and commercially sold by Alden, and described in the *ASME Transactions of 1890*.[6] Dynamometers that were used to measure torque had attracted the attention of inventors in the mid-1800s, who saw a need to measure power output and obtain the efficiency of various types of mechanical machinery used in the expanding mills of the United States. Alden experimented for some time with dynamometers before coming up with a design (see Figure 10) that for many years was utilized in testing automotive and train engines, hydraulic turbines and other numerous rotating mechanical equipment.[6]

The WPI student newspaper, in its January 15, 1892 issue, described the dynamometer as follows:

> "The apparatus is designed for three purposes: to maintain an uniform load upon an engine under experimentation or test, to accurately measure the useful power developed by the engine, and to automatically regulate the rate at which energy is absorbed.
>
> "This dynamometer is essentially a friction brake with comparatively large rubbing surfaces, thus giving a low intensity of pressure at any one point. Pressure is produced by water from a main, and enough water is allowed to pass to absorb the heat due to the absorbed energy. The rubbing surfaces are finished smooth and run in a bath of oil.

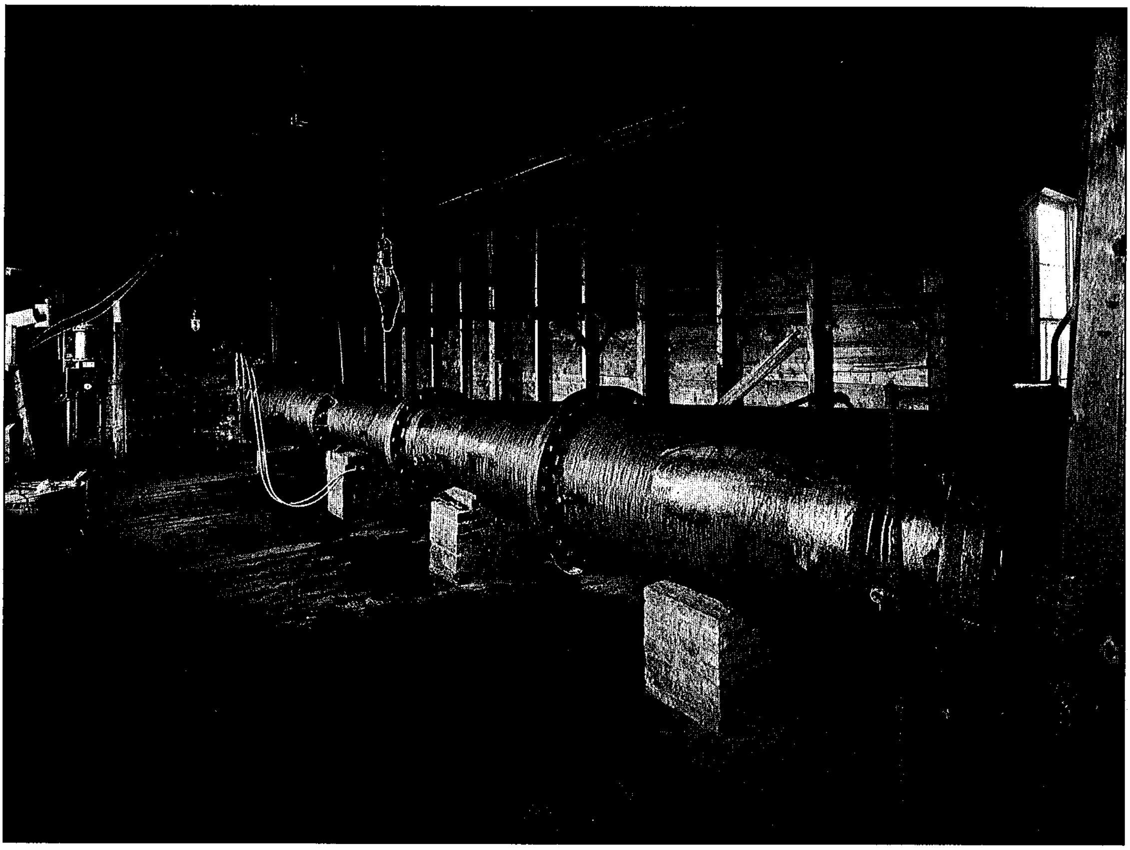

FIGURE 9. Herschel's Venturi meter installed in the laboratory with velocity traversing probe.

Automatic regulation is secured by a slight angular motion of the brake which operates the valve controlling the water supply, and hence the pressure.

"The brake consists of a disc keyed to the crank-shaft of the engine. The disc is finished smooth except for one or more radial grooves in each face. The disc is surrounded by a cast iron shell consisting of two pieces bolted to a ring of the thickness of the disc. Two copper plates, concave toward the shell, bear against the disc and form with the shell two water-tight compartment, the copper being "spun" out into a cavity in the iron and held in place by driven rings. One chamber communicates both with the main and the other chamber. A chamber filled with oil lubricates the disc by means of the radial grooves. The shaft revolves in bearings in the shell which carries an arm carrying weights. Angular motion of the arm is limited by stops.

"The automatic valve consists of two brass tubes, one fitted inside the other, but free to revolve therein. Each tube has slots nearly parallel to its axis, one is connected with the supply, the other rigidly with the brake. A flexible tube encloses the whole. The valve is so adjusted that a small angular motion of the brake varies the water passage through the slots and the apertures into the chamber being constant, the pressure is thus regulated.

"The operation of the brake is this: The oil chamber is filled and sufficient weight to give the required load is hung on the arm. The engine is then started and speeded up. Water is then admitted to the automatic valve in any suitable manner, and thence to the chambers. The pressure of the water forces the copper plates against the disc, thus causing sufficient friction to lift the weight arm. This motion operates the automatic valve, checking the flow of water to the brake, and regulating the moment of friction on the disc to the moment of the weights on the arm."

Other Laboratory Equipment. Erected inside the laboratory was an 18-inch horizontal Hercules turbine built by the Holyoke Machine Company of Worcester (see Figure 11). The wheel was mounted 18 feet below the level of Pond No. 2 and had a draft tube 12 feet long. It was located immediately downstream of the Venturi meter, which was used to measure the flow through the turbine. The water discharged from the turbine was then directed over two 10-foot weirs located in the tail race. These weirs served to measure the flow a second time and, thus, check the Venturi measurement. Figure 12 shows an early weir, circa 1907, used to measure flow from Pond No. 3 in the background. Note that the side edges were beveled and a flow distributor was used.

The test laboratory also included a 12-inch water meter, valued at $1,250, which was a gift from the mayor of Worcester, Phinehas Ball.

A copper-lined wooden weighing tank built on a 50,000-pound Fairbanks scale was also installed in the laboratory (see Figure 13). The scale had been acquired by WPI shortly after the Centennial Exposition held in Philadelphia in 1876. It had served on a strength-testing machine in another WPI laboratory and had seen other duties before coming to Holden. The scale was reputed to be so sensitive that it could detect a silver fifty-cent piece placed on its platform. The tank and scale were almost immediately incorporated into use for student experiments and to determine flow for efficiency tests. Thus, very early on, flow measurement was a major focus of the laboratory since weight and time could be easily and accurately measured.

The last piece of equipment for the new laboratory was a large hydraulic ram (see Figure 14) that was used to supply water to an air pressure tank that furnished pressure to the meter that was used to operate the friction dynamometer.

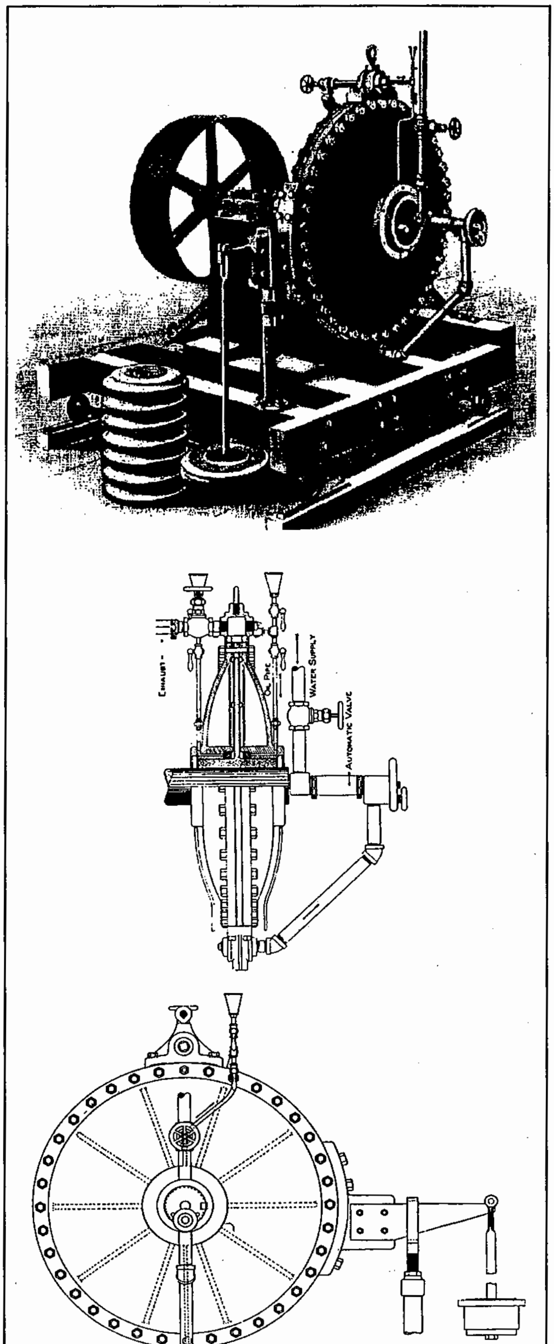

FIGURE 10. The Alden dynamometer.

Early Use of the Lab

The control gate from Pond No. 2 was opened for the first time in December 1894 and allowed water to enter the test facility. On May 8, 1895, Professor William W. Bird took two divisions of senior WPI students to the Hydraulic Laboratory to perform the first student experiment at the facility. The May 18, 1895, issue of the student newspaper detailed the testing:

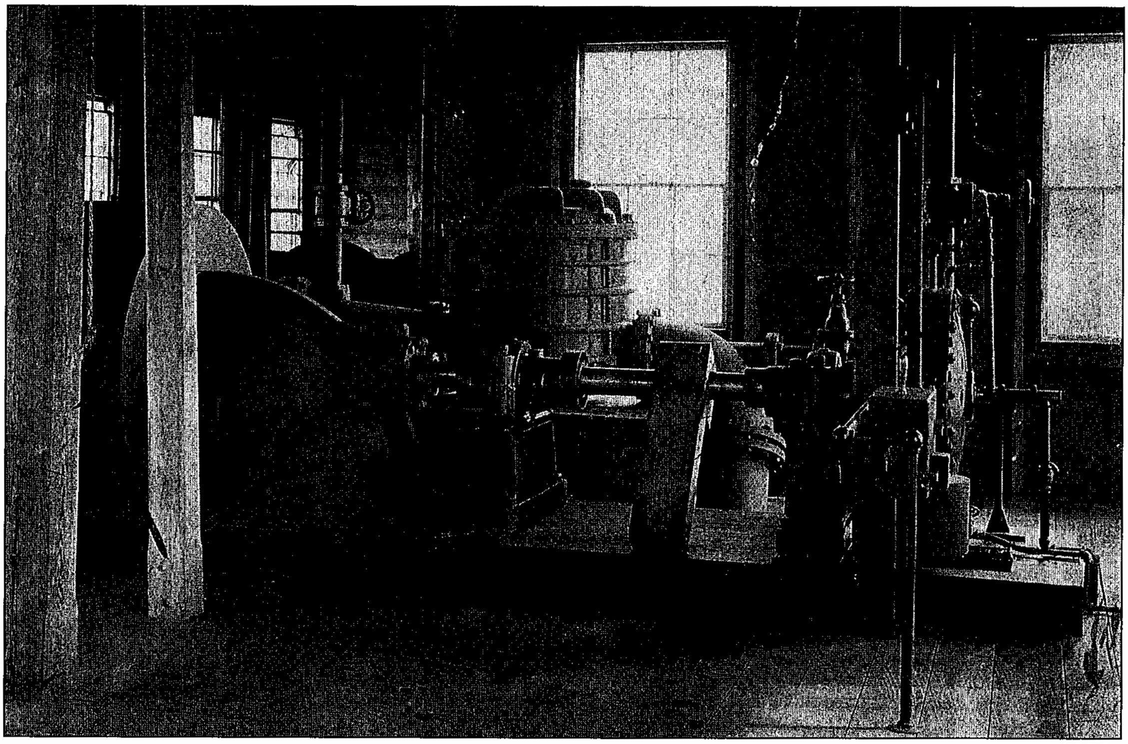

FIGURE 11. The Hercules turbine with the Alden dynamometer.

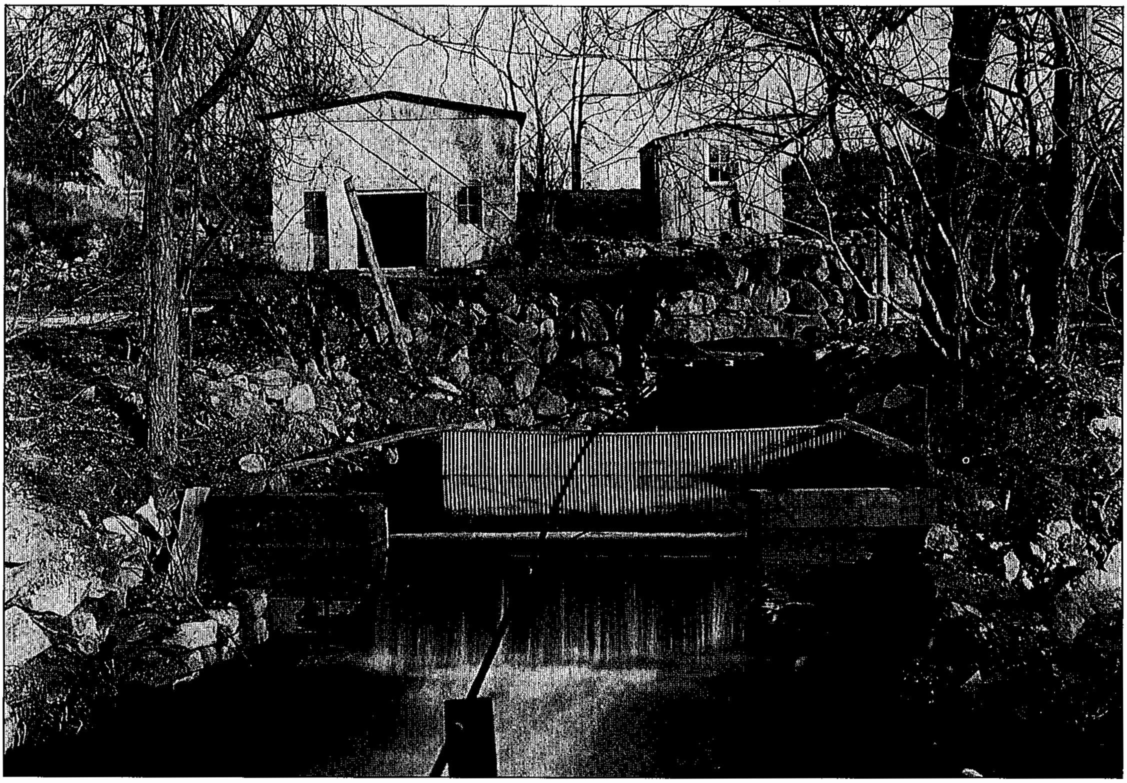

FIGURE 12. An early sharp-edged weir with an approach flow distributor (1907).

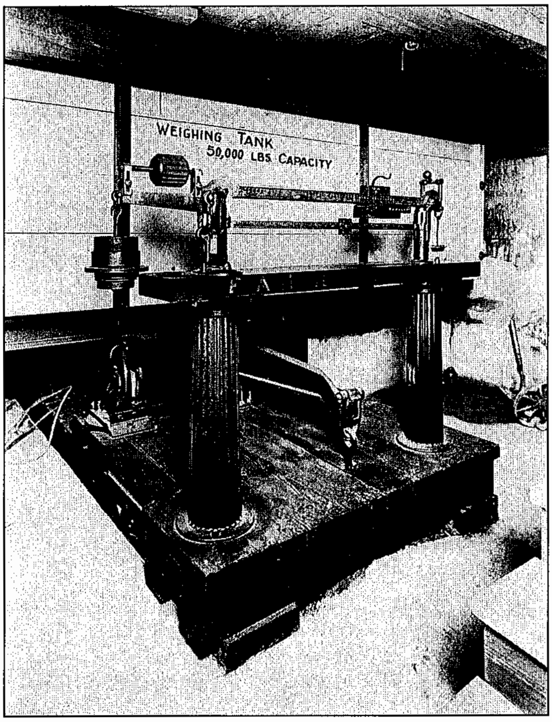

FIGURE 13. The Fairbanks scale.

"The work consisted in determining the efficiency of the 18-inch Hercules Wheel at different speeds, with different gate openings, and finding what speed gives the best efficiency. Each division makes eight tests, two on each gate, the gate openings ranging from 0.3 to full gate, and the horsepower developed from 15 to 75. In making these tests each student has the care of some special piece of apparatus, or the reading of one of the gauges, and in the subsequent test has a different assignment, so that in the several tests, he becomes familiar with all parts of the plant.

"The quantity of water used is measured before entering the wheel by the Venturi meter, and again measured, after passing through the wheel, on a ten foot weir, two hook gauges being used, one on either side. The head on the wheel is measured in columns in the tower, while the power developed is shown by the weight on the brake and the number of revolutions. The tests made were not as exact as could be desired, but as the students become more familiar, better results may be expected."

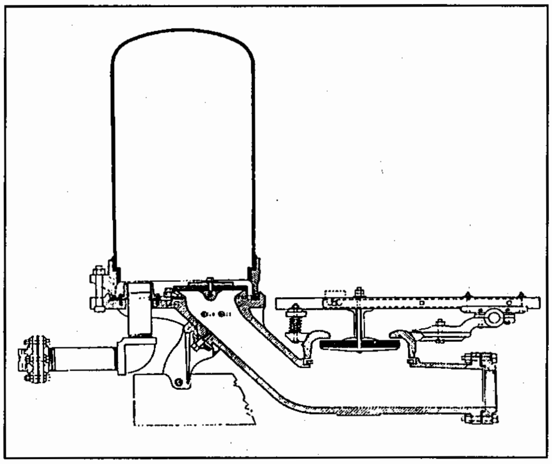

FIGURE 14. A hydraulic ram.

WPI took great pride in being able to advertise that their students were being trained on a full-sized turbine, using state-of-the-art instrumentation. It is hard to believe that this hydraulic facility, including equipment and instruments, was estimated to have cost $12,000.

The early accumulation of equipment and instrumentation set the pattern for the future. The laboratory staff became adept at acquiring, fixing, enhancing or building their own equipment and test facilities. This "can-do" attitude extended to relatively large tasks and test facilities. Also, being directly associated with industry led the laboratory early on to applied fluids engineering — *i.e.*, hydraulics. The early interest in efficiency and hydropower led to a continuous relationship with the U.S. power industry, particularly hydropower.

Hydraulic Instruction

A driving force behind the success of the Hydraulic Laboratory was Charles M. Allen (see Figure 15). As a senior at WPI in 1894, he chose as his thesis to test a 3-foot, 6-inch diameter overshot waterwheel he designed and constructed on his parent's property in Walpole, Massachusetts. The wheel produced about 0.5 horsepower and was used to pump water, saw wood and turn the crank of an ice cream maker. (As it turns out, this thesis was a prelude to Allen's lifetime work.) The test apparatus consisted of an Alden absorption

FIGURE 15. Charles M. Allen

dynamometer to measure the power output, a 2-foot sharp-edged weir to measure the flow and a hook gauge to measure the head.

In June 1894 after his graduation, Allen was hired as an assistant in the Department of Mechanical Engineering at WPI "at a salary of $100 for the year; it being understood that he is to give half of each day to the service of the Institute while he occupies the other half in study and investigations." It appears from the records that although Allen received promotions and salary increases during his stay at WPI, his half-time teaching schedule persisted throughout his 55-year career. In 1895, Allen's annual salary was increased to $700, and in 1896 to $900.

From 1895 to 1900 the Hydraulic Laboratory was utilized for student instruction and for tests performed by a variety of the teaching staff in both the Mechanical and Civil Engineering Departments. Transportation to the laboratory was by steam railroad, horse-drawn buggies or barges, bicycles or shanks mare (walking) up the track from Worcester's Greendale section. By 1903, an electric car line was built to Holden and was used by students along with the automobile, which had started to appear at about the same time.

The WPI catalog outlining course work in 1895 indicated that students were required to:

- Obtain the efficiency of the Hercules turbine;
- Measure flows with rectangular weirs, Venturi meters and water meters;
- Test a hydraulic ram; and,
- Measure the head loss in the approach piping to the turbine.

An apparataus for student testing is shown in Figure 16.

Early senior theses at the laboratory during its first five years covered a variety of tests involving the hydraulic ram and the determination of discharge coefficients for different weir types. Some of the early investigations involved turbine draft tubes. Although records of these tests have not been found, an article in the school newspaper indicated that:

> "On Friday, November 8th, Col. James Francis, Chief Engineer of Locks and Canals on the Merrimack River at Lowell, with his chief engineer, Mr. Safford, inspected the hydraulic plant at Chaffin. Prof. Alden, assisted by C. M. Allen, '94, explained the machinery, some of which was run for a short time. They were particularly interested in the dynamometer and methods used in experimenting with draught tubes."

This visit was quite an honor for the laboratory, considering Francis' many contributions in the field of hydraulics and hydraulic turbines. At Lowell, both Francis and Uriah Boyden had done considerable work in maximizing water turbine power output by use of draft tubes that conveyed the water from the turbine exit to the tailrace.

At this time and for some years to come, Allen would be primarily concerned with classroom instruction and turbine testing. Surveying instruction also was conducted on the laboratory grounds.

In 1895 WPI decided to establish a Chair of Hydraulic and Steam Engineering. To fill that position, WPI hired Sidney A. Reeve, an edito-

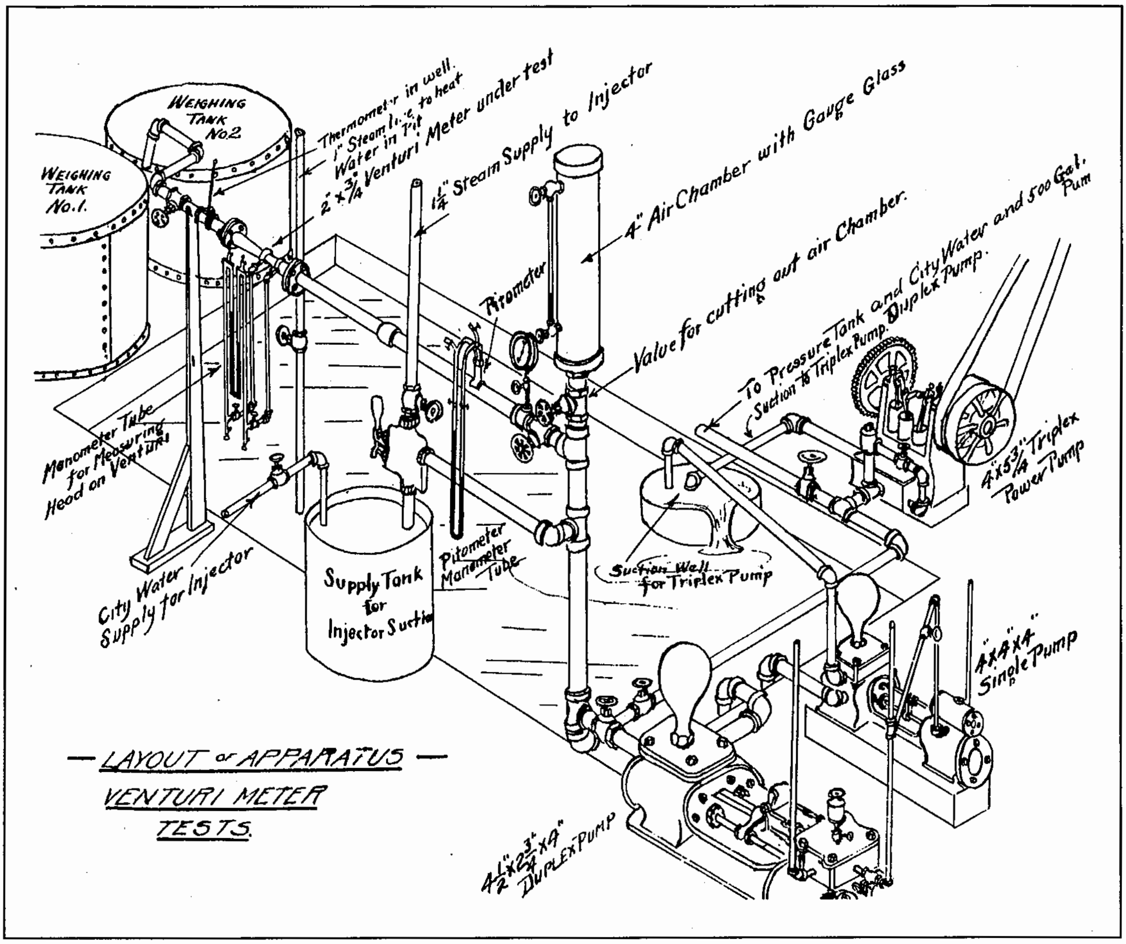

FIGURE 16. Student testing apparatus.

rial writer on *The Progressive Age*, a publication devoted to the gas industry. Reeve was a recognized authority on gas engines.

In the spring of 1896, Alden, disillusioned with proposed philosophical changes in engineering education at WPI, announced his resignation from the school effective July 1, 1896. Although Alden, who had twice served as chief officer of the school between presidential terms, left WPI, his interest in the Hydraulic Laboratory, which he had founded and headed, continued with frequent financial and technical support throughout his lifetime.

In 1898, Reeve was promoted to full professor and was named to head the newly created Department of Hydraulic and Steam Engineering, which included the Hydraulic Laboratory. He remained in that capacity until his resignation in 1906. At that time, Allen was named Professor of Experimental Engineering and officially became the Head of the Hydraulic Laboratory, a position he had held unofficially during Reeve's tenure. During his stay at WPI, Reeve showed very little interest in the field of hydraulics and the operation of the laboratory. In fact, it was mentioned in one of the student publications that due to his lack of interest, Reeve relinquished his teaching duties in the hydraulic course to Allen in the middle of a term.

During the initial five-year period of the hydraulic laboratory's existence, Allen worked toward his master's degree and did testing in the area of gears, pulleys, belting, pumps and draft tubes. The master's examination given by Alden to Allen in shown in Table 1. These areas of research showed Allen's multi-faceted interests, curiosity and creativity. Further proof of Allen's versatility was an article in the 1897 *WPI Journal* written by himself and Reeve on "The Crushing Strength of Concrete."[7]

In 1899 Allen obtained his master's degree. His master's thesis, "The Design and Construction of an Oarsman's Indicator," was inspired by his brother, who was captain of the Yale rowing team. (It is interesting to note that many years later one of Allen's research activities at the Hydraulic Laboratory involved the testing of a rowing tank that would be used to train Yale University crews.) As a fallout from his thesis, Allen designed an adjustable foot-stretcher rig for shell boats.

Dynamometer Testing

Most of the early research and testing at the laboratory involved the use of the Alden absorption dynamometer in determining the efficiency of different devices such as pumps, gears, pulleys belting, motors, etc.

The 1890s were the beginning of the American automotive industry. Pioneers Charles and Frank Duryea, Elwood Haynes, Henry Ford, Ransom Olds and Alexander Winton started an industry that became one of the largest in the United States. Allen, always being at the forefront of new technology, envisioned the use of the dynamometer in measuring and improving the efficiency of automobile engines, and wrote to various motor companies soliciting sales of the Alden dynamometer.

The Alden dynamometer was also popular in the early 1900s with many technical schools throughout the country. MIT, Georgia Institute of Technology, Iowa State, Kansas, Tufts, Colorado, Leland Stanford, Maine and other schools either bought dynamometers or plans for dynamometers. The University of Illinois bought one of the largest dynamometers built in its day for use in a large locomotive engine testing facility.

Besides teaching at WPI and conducting research at the hydraulic laboratory, Allen was involved in numerous field tests of water turbines in the early 1900s. The rental of the test apparatus in those days was $250 per test. Allen's charges were $25 per day plus expenses. Transportation in those days was not always as convenient as today. As an example, Allen was given these instructions to inspect a potential test site in Maine:

"Go to Portland, Maine, in the evening. Stay overnight and take the train on the Maine Central Railroad to White Rock. At White Rock take the stage to North Gorham and from there to the powerhouse if you request it. It will be a long cold ride and you should be well prepared."

TABLE 1.
Hydraulics Master's Examination Questions Given by Alden to Allen (June 1894)

1. What is the theoretical velocity of a liquid flowing into a vacuum under a head of 144 feet?
2. How many cubic feet would theoretically flow in one minute through an area one-twelfth of a square foot?
3. What causes would in practice modify this theoretical flow? About how much would it be reduced?
4. Find the theoretical flow through a rectangular notch depth, *h*, and breadth, *b*, upper edge of notch at surface of liquid.
5. If 200 cubic feet of water flow per minute through a vessel where its sectional area is one-seventy-second of a square foot, and the hydrostatic head is 12 feet, what is the kinetic and what is the potential energy of a quantity of the water whose weight is *w* as it passes this section?
6. What is the construction and action of a Venturi meter?
7. Deduce the formula for the quantity of water that will flow through a given meter.
8. Explain the formula:
$$\frac{\theta}{g} u(v-u) / (1-\beta) = p_x$$
9. What two values of *u* make the second member equal to 0? Why should this be so?
10. Substitute in the last formula the values of *u* and of β which make the result a maximum and explain the resulting formula.

Note: The equation is reconstructed from an unclear original.

This trip today, in the comfort of a modern automobile, would take no more than four hours.

David Gallup & Propeller Testing

In 1902, David Gallup, a 1901 WPI graduate, was appointed as an instructor in the Mechanical Engineering Department. Although there is no record that Gallup had any interest in hydraulics, he worked with Allen, as attested by his signature that appeared on many curve sheets found in the Allen reports of the early 1900s. Gallup was fascinated and interested in automobiles and, especially, automobile engines. During his stay at WPI, he gained national recognition for his work, and his engine testing plant in the Mechanical Engineering Department was visited and used by many automotive engineers of the growing automobile industry.

Gallup had read about the December 17, 1903, flights of Orville and Wilbur Wright in a heavier-than-air machine conducted in Kitty Hawk, North Carolina. Due to his interest and his realization that aviation was in its infancy and provided new challenges to engineering, Gallup proposed testing nine hand-carved wooden propellers on a rotating platform. As he wrote in a July 1911 *Aeronautics* article:[8]

> "The purpose of the investigation is to determine if possible the proper design of a propeller to give the most efficient results, taking into consideration the varying factors, such as speed, pitch, and diameter. . . It must not be understood that the stationary type of test is considered of much value, for it is very evident that the conditions existing, such as circulation over and over a given quantity of atmosphere, are very different from those met with by a propeller on an aeroplane which is going through the air."

Rotating booms, earlier called "whirling arms," had been around since 1740 when Benjamin Robbins in England built one to study the air resistance of projectile forms. In the early 1750s, another Englishman, John Smeaton, used one for windmill tests. Jean Charles Borda of France tested various shapes in water using a whirling arm in the 1760s.

Such a rotating test platform, secretly funded by Alden, had been built at the Hydraulic Laboratory in 1908 in Pond No. 2 that fed the main laboratory. The facility was called the Circular Current-Meter Rating Station and is shown in Figure 17. Allen, with two of his students, had designed a 42-foot wooden testing arm balanced by a 21-foot arm loaded with counterweights (stones). The bottom of the shaft was supported by a hole drilled in a submerged rock located 45 feet from shore and the top supports were guy wires attached to deadmen anchored on the shoreline. The rotating boom was powered by a 24-inch Hercules water wheel located under Shrewsbury Street. The power was transmitted to the boom by a series of pulleys and a rope drive. The maximum speed (at the boom end) was 10 feet per second.

The original purpose of the rotating boom was to test hydraulic equipment, especially current meters. Testing of such meters in those days was usually performed in towing tanks. The circular test facility was chosen over a towing tank because the former was much less expensive to construct, allowed longer test runs and enabled larger objects to be tested without experiencing boundary effects from channel sides. It is interesting to note that testing large objects was a continuation of the original testing concepts of the laboratory.

In 1911, the wooden boom was replaced by an 84-foot diameter steel boom (see Figure 18). The same shaft configuration, rope and pulley drive (see Figure 19), and waterwheel power were used on the refurbished boom. The steel was erected in the dead of winter so that the ice could be used as an erection platform. Ice also made it easy to slide the heavy steel members to the boom. This thinking was all in keeping with Allen's philosophy of doing things as easily as possible and with the least expenditure of money and energy. With the reconstructed boom in place, Gallup installed a 75-horsepower electric motor at the center of the boom and transmitted its power through a long shaft and angle drive to propellers mounted at the end of the boom. The thrust of the propeller caused the boom assembly to rotate while a

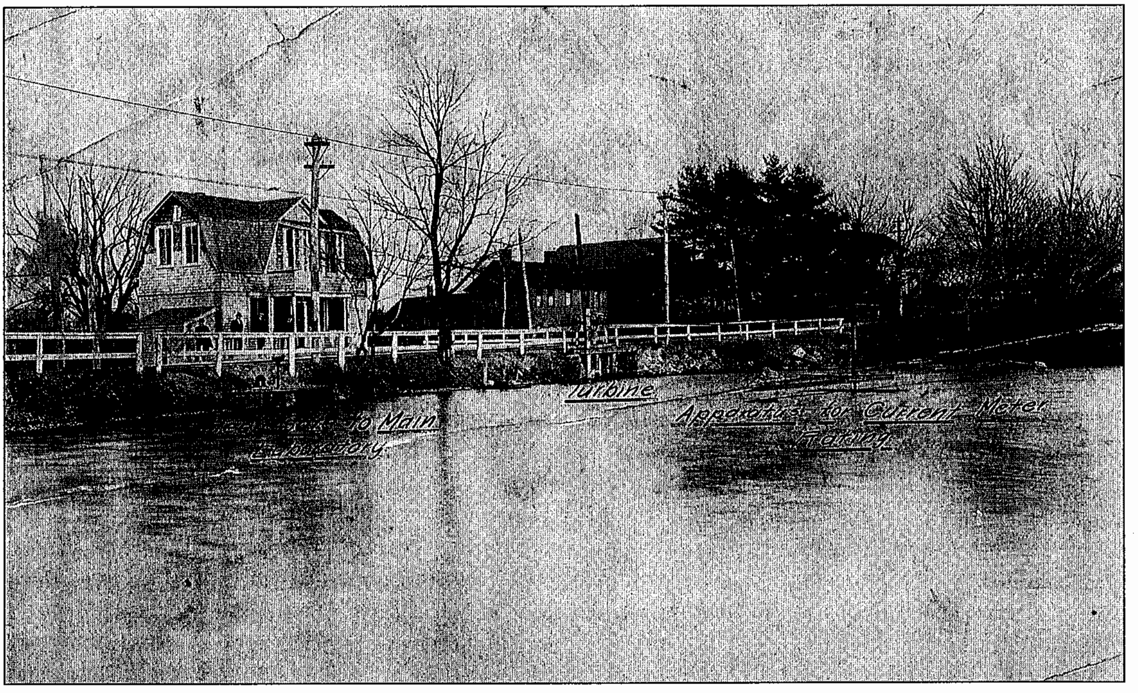

FIGURE 17. The Circular Current-Meter Rating Station (wooden boom).

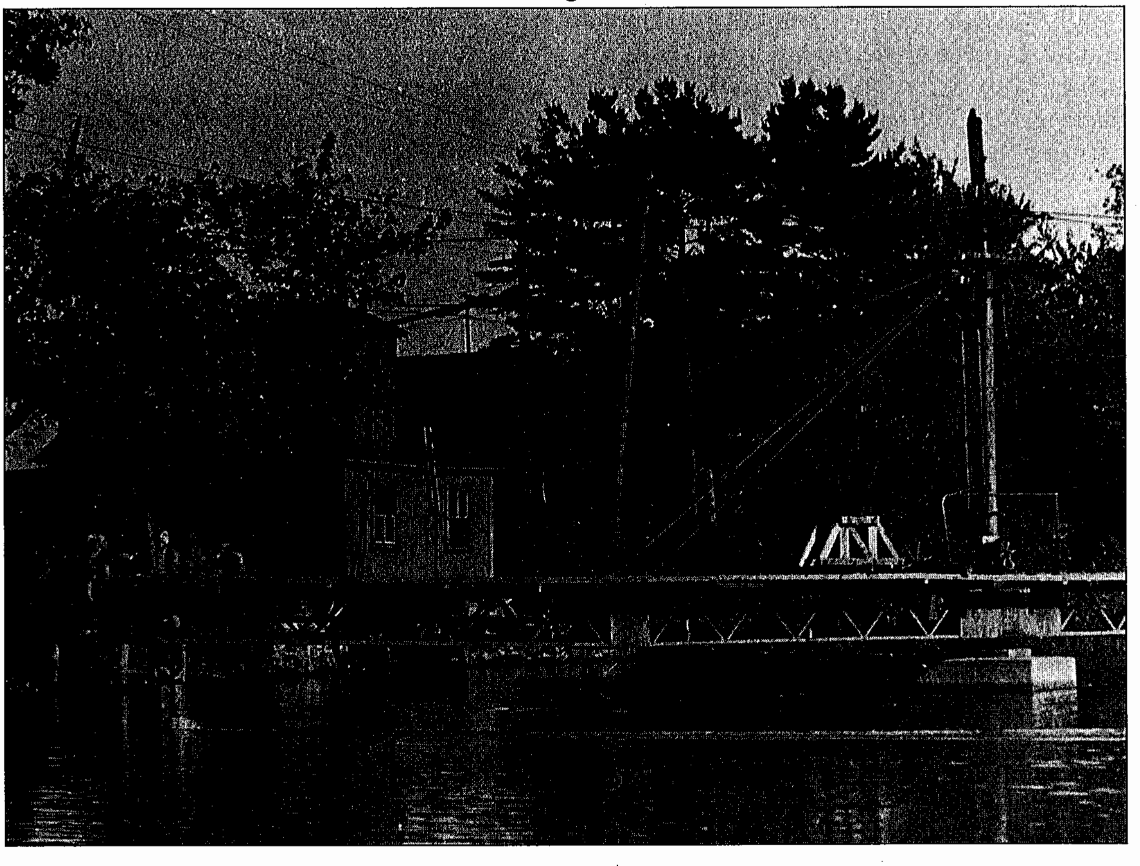

FIGURE 18. Rotating steel boom (circa 1920).

drag device in the water was used to calculate the power dissipated. Tests on nine different propellers, ranging from 6 to 7 feet in diameter, were conducted by Gallup and his students. Thrust ranged from 5 to 47 horsepower, and propeller speeds ranged from 550 to 1,300 rpm.

Testing on the same propellers had also been performed on a stationary platform erected in the Worcester Armory. In spite of the relatively similar results of both types of tests, controversy existed as to the reliability of the tests on the rotating boom. Some claimed that propellers tested on rotating booms were unreliable because the propeller encountered turbulence from its own wake after the first revolution of the boom, and, therefore, it did not see air identical to that encountered by heavier-than-air machines. To resolve this conflict, Gallup and some of his senior thesis students organized tests using a gasoline engine, mounted on an ice boat in the winter (see Figure 20) and on a pontoon boat in the summer, to turn various test propellers. The straight-line tests were conducted on Worcester's Lake Quinsigamond and gave results similar to those achieved on the rotating boom. (It was said that some of the students encountered numerous thrills during testing at the lake, especially in the summer when the boat had a tendency to "nose over" at higher speeds.)

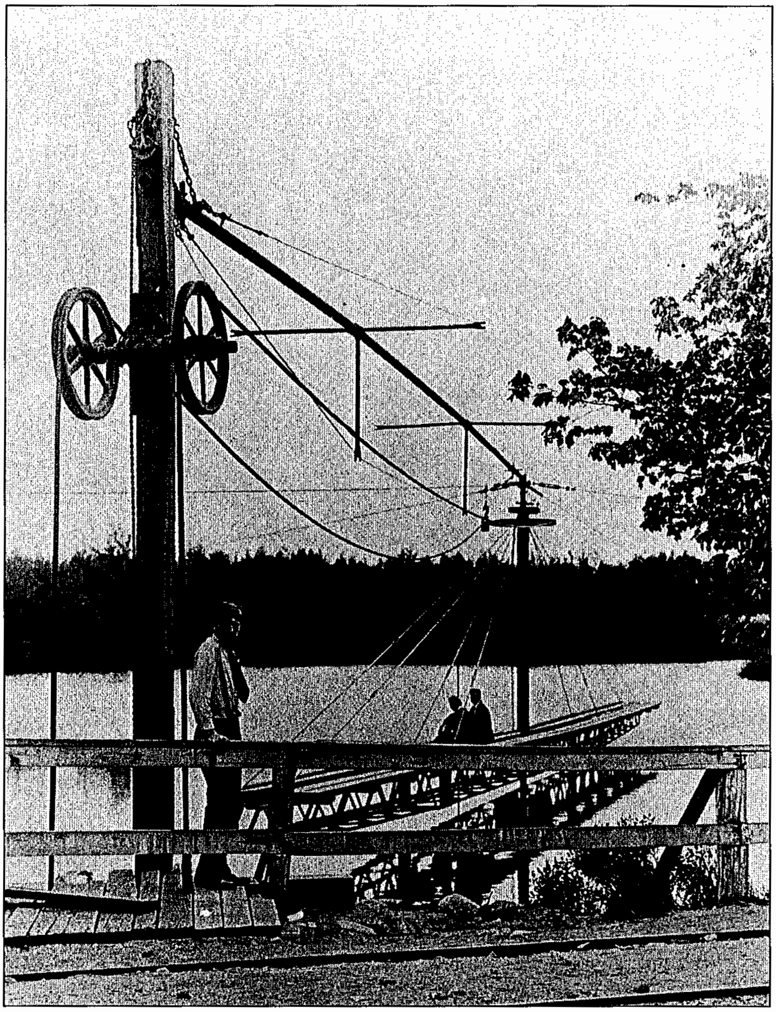

FIGURE 19. Rope drive for steel boom (circa 1920).

Throughout its lifetime, the rotating boom has been used to calibrate current meters. During World War I, Major Victor E. Edwards (an 1883 WPI graduate) used the boom to conduct drag tests on artillery shells. These studies proved to be valuable in his subsequent studies of artillery shell ballistics at the Aberdeen Proving Grounds in Maryland. Students also used current meters in available flow channels (see Figure 21).

Hydroelectric Power

Besides the great strides being made in the automotive, aviation and petroleum industries, the turn of the century saw the use of water turbines changing from driving machinery via belt and gear drives to driving electric generators. Arguably, the first hydroelectric station had been placed in operation at Appleton, Wisconsin, in 1882. Power transmission using step-up and step-down transformers had been achieved in Great Barrington, Massachusetts, in 1886. "Large-scale" hydropower saw its

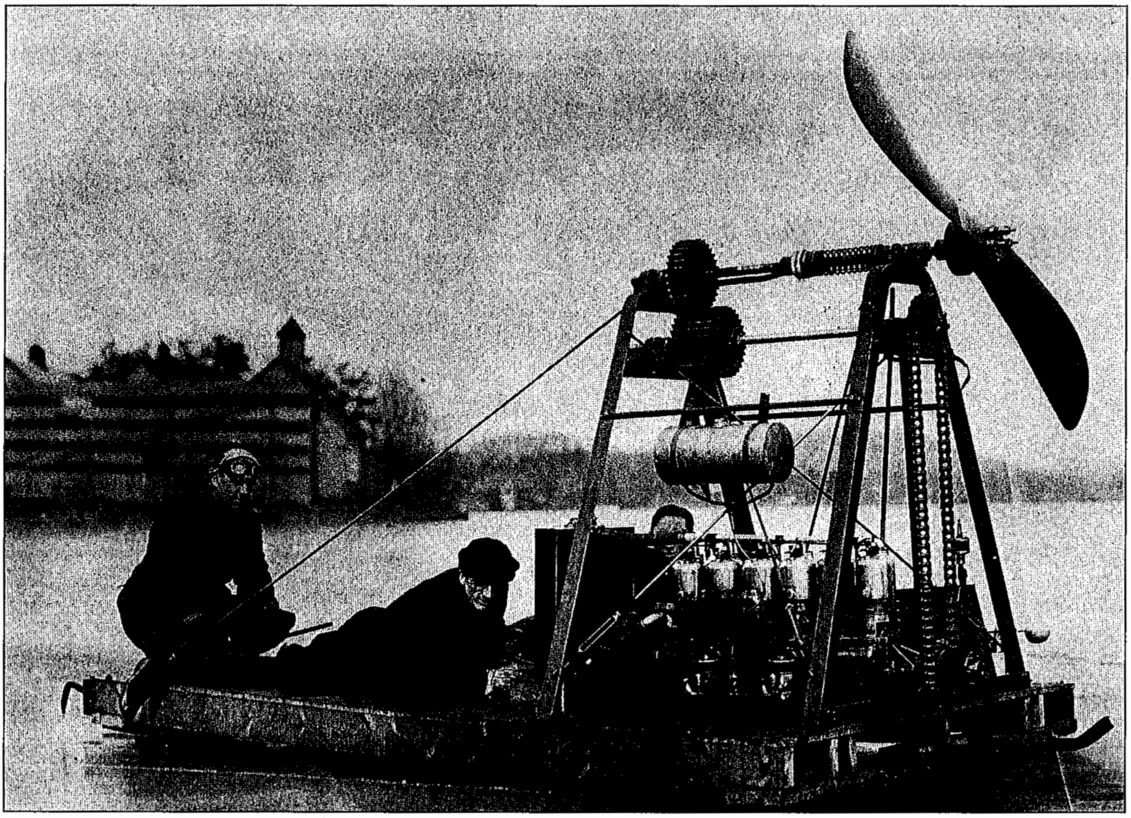

FIGURE 20. Testing propellers using an ice boat (circa 1915).

birth in the Niagara Falls development in 1895. Around the same time the transmission of power on small grids began. By 1900, electric transmission was at 40,000 volts and would increase to 110,000 volts by 1923.

Field testing of hydro turbines used both for power and electric production increased at that time. Allen's creative mind saw the need to accurately measure the flow of water during these tests. Based on the results of the Holyoke flume tests and the head on the turbine, he invented a flow recorder (see Figure 22) that gave continuous flow readings.

By 1910, Allen had conducted almost one hundred tests on hydro turbines and had published an ASME paper in 1910 on the "Testing of Water Wheels After Installation."[9] His turbine testing experience ranged from tests at the famous Holyoke turbine test flume, at hydroelectric power plants throughout the Northeast and at paper mills in Maine. At this time, the relatively low flows were measured using current meters or weirs. His concern for installed water-wheel efficiency was always on his mind. He frequently mentioned the term "fair setting" in his writings on installed turbines. In his mind, "fair setting" meant there was more to proper turbine operation than testing the turbine in the Holyoke Test Flume. Minimizing approach head losses, efficient draft tubes, regular wheel inspection, clean racks, efficient gate operation and all other "hydraulic common sense" plant characteristics taken for granted today encompassed his concept of "fair setting." He frequently showed plant operators and owners the misconceptions they had relative to efficiency when operating wheels at wide open gate or maximum speed to produce maximum power.

The size of hydroelectric turbines in the early 1900s increased exponentially due to the high demand from electric-intensive industries, such as chemical and steel. Urban centers were increasing in size, and electricity for lighting homes and streets was in great demand. In the 1890s, unit sizes were in the 500

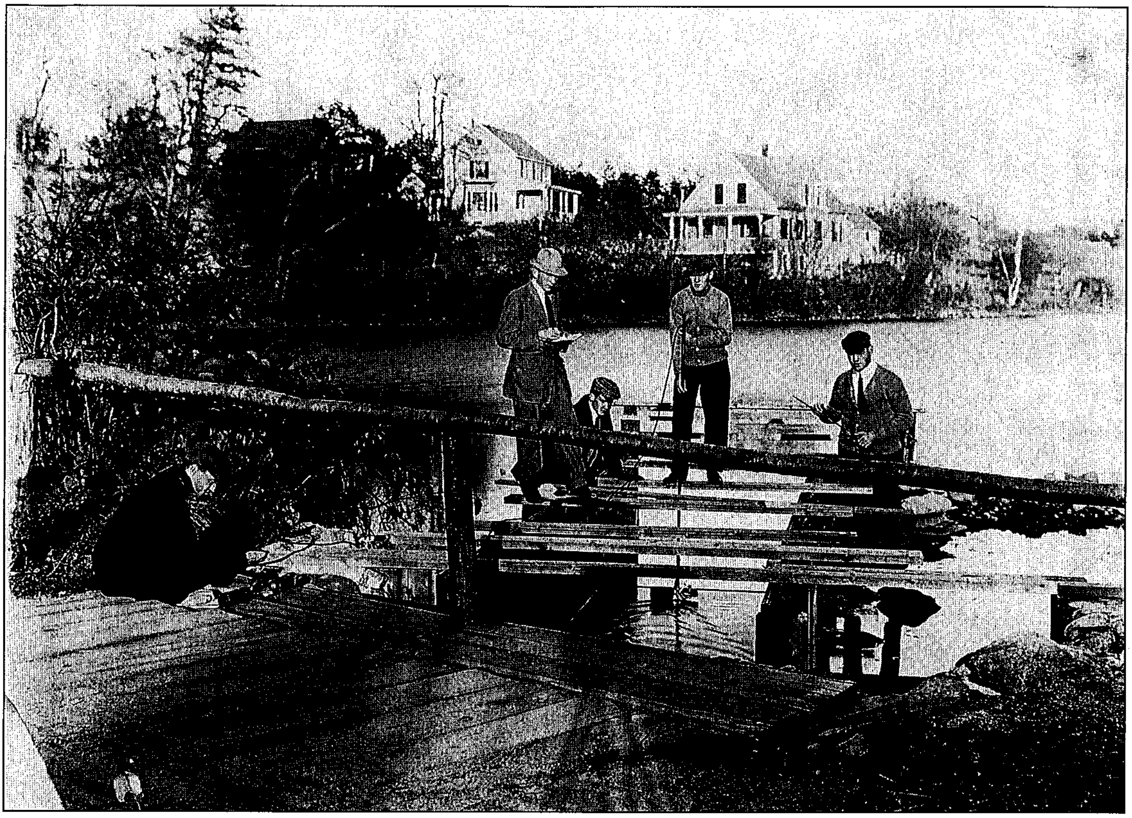

FIGURE 21. Students measuring current (1911).

horsepower range. By 1901, 10,000-horsepower units were being considered for Niagara, and ten years later the figure approached 20,000 horsepower. Another decade later, units 140 times the size of the 1890 units were being considered.

Besides the need for electric power, the power of hydro turbines increased due to technical advances in turbine designs. The work started in the late 1800s by Francis in Lowell (and Pelton and Doble on the West Coast) was continued. Blade designs were improved and efficiencies increased. As the steel industry grew, construction techniques also improved. All these factors and the relatively low cost of hydropower contributed to the sizable growth in this industry.

Although it may seem that Allen was doing mostly field tests, the laboratory building was being utilized fully for student activities, and for testing by Allen and his staff and other WPI faculty. By 1908, the facility was considered too small, and a "low head lab" (the Water Wheel Testing Laboratory) was built across the street from the existing facility. Built with funds supplied by Alden, this new building was erected on the site of the old grist mill. It was 70 feet long by 15 feet high and 36 feet wide for half its length and 24 feet wide for the other half. A portion of the building was used for a machine and repair shop. The building contained a large copper-lined wooden flume in the basement where two vertical 15-inch Hercules water wheels were used to power a jack shaft motivating a combined rope and belt drive apparatus.

Alden Hydraulic Laboratory & Early Field Testing

Allen approached research in an applied manner that would be followed by the laboratory during its existence. The other qualities that set the tone for the laboratory were his variety of work (demonstrating his grasp of engineering fundamentals), his Yankee thrift and the loyalty of his clients (showing the respect he earned in his work).

For example, in 1906, Allen was contacted by a paper manufacturer in Millinocket, Maine, to test turbines used to power grinders that reduce wooden logs to pulp. The company was so satisfied with Allen's work, he tested 13 turbines for this company during his career. Some of the later tests involved turbines used to produce electricity.

Early field testing was not limited to turbines. The large use of water in paper manufacturing and its accurate metering for the purpose of billing were problems that had been studied by Herschel in the late 1800s at the Holyoke Power Company. In 1908, the same company hired Allen to measure the flow rate in different diameter pipes. The tests were made at seven different paper mills by using a pitometer, invented by Edward Shaw Cole in 1896, and traversing pipes ranging from 8 inches to 24 inches in diameter. Some of the tests were to check the accuracy of flow meters, while others were checks on hydraulic turbines used to power machinery. These tests also indicated the fact that Allen remained current with the technology of his time.

On October 16, 1908, Herschel visited the Hydraulic Laboratory. During the tour he noticed many valved pipe fittings sticking out of the downstream end of his Venturi meter (see Figure 9). He asked, "What have you got on my meter, a bunch of parasites?" Allen replied by inquiring if Herschel knew what went on inside the pipe. Herschel's reply was that the water velocity slows down as the pipe diameter increases. Allen assured him this was true for the average velocity. "But what about the velocity distribution across the pipe diameter?" asked Allen. Herschel replied, "I don't know." At which time, Allen informed Herschel of the velocity traverse data that had been obtained downstream from the Venturi meter's smallest diameter.

Allen followed in Herschel's footsteps, testing in the Holyoke paper mills. He also did work for the Proprietors of Locks and Canals in Lowell where James Francis had performed pioneer studies on turbines and basic hydraulics some six decades earlier. At one of the largest textile mills of its time, Allen tested a 72-inch Swain turbine.

From 1900 to World War I, Allen conducted some one hundred and fifty different field tests on various types of equipment. He was held in high esteem as a hydraulic engineer, and his services were highly sought after throughout the United States and Canada. His testing covered all six New England states, New York, Pennsylvania, North Carolina, Georgia and Alabama, in addition to the Canadian provinces of Ontario, Nova Scotia and numerous locations in Québec. During the same time period, he carried his teaching load at WPI, guided research at the Hydraulic Laboratory (which included seventy-eight senior theses). His reputation, and that of the Hydraulic Laboratory, were growing as was his knowledge of the multitude of turbines and hydraulic equipment he tested.

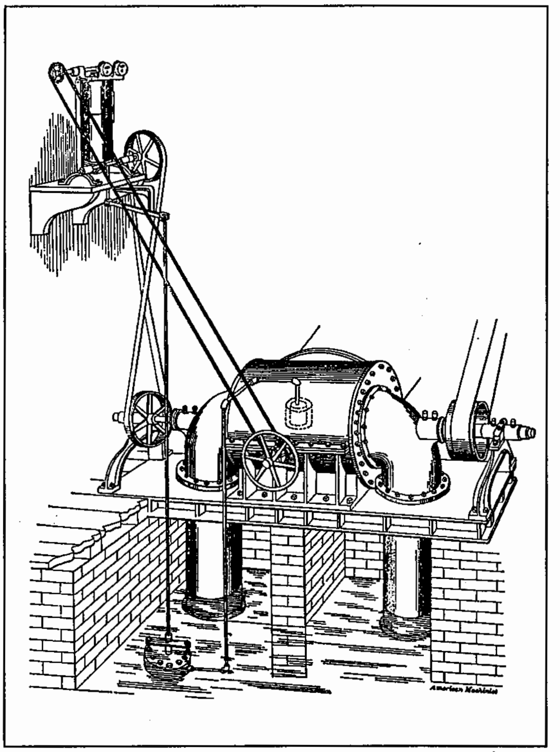

FIGURE 22. A double-cylinder flow recorder connected to a turbine.

Two decades after its start, it was obvious that the WPI Hydraulic Laboratory was a success in terms of its practical academics and the impressive contributions made by its staff, particularly Allen, in the area of applied research and field testing. The laboratory had become famous and on May 1915, in honor of the laboratory's founder and benefactor, the WPI Trus-

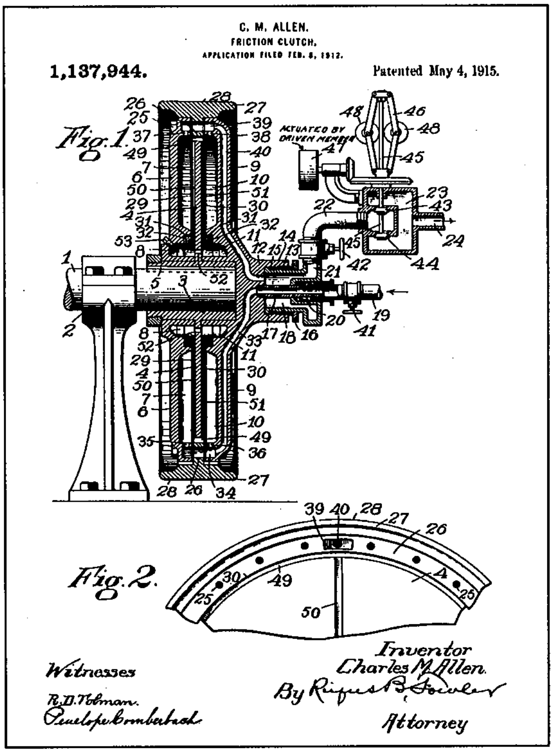

FIGURE 23. Allen's clutch.

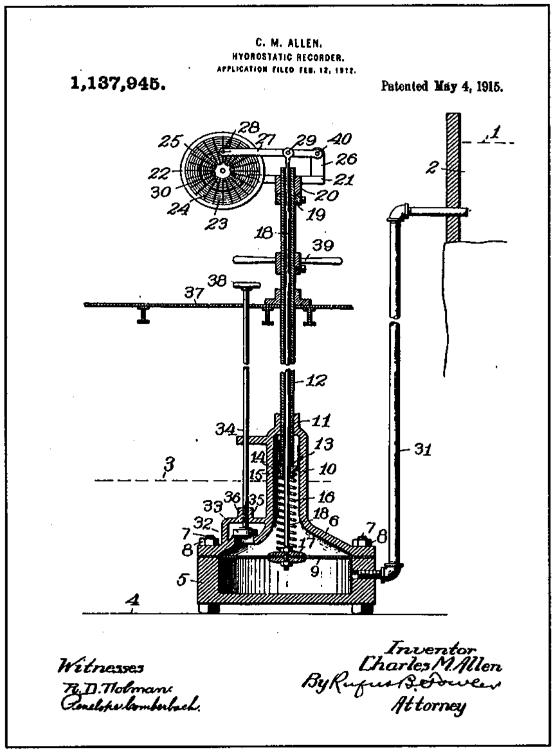

FIGURE 24. Allen's hydrostatic recorder.

tees voted to change the name of the laboratory to the Alden Hydraulic Laboratory.

In the same year, Allen received two patents from the U.S. Patent Office. One was for a clutch (see Figure 23) operated by hydraulic power. This device resembled the Alden dynamometer where the applied pressure to the plate in the dynamometer was regulated by a balanced valve actuated by a centrifugal flyball governor. The other patent was for a hydrostatic recorder (see Figure 24) to be used to record pressure variations on a flat rotating paper chart.

Growth of Cities, Industry & Electric Power

As the United States entered the new century, it was becoming an industrial giant. When Teddy Roosevelt was elected President in 1904, he expressed concern about electric power monopolies and the waste of what was thought of as unlimited natural resources. The first Reclamation Act was passed in 1902 and amended in 1906 to provide for the sale of electricity from federal projects for municipal purposes. Dams were reaching new heights, causing various hydraulic challenges in the areas of outlet controls, erosion below spillways and flood prediction.

In 1902, the Bureau of Reclamation was formed, and Roosevelt Dam in Arizona and Pathfinder Dam in Wyoming were well under construction. On the Susquehanna River, Holtwood Dam would be completed about 1910. Holtwood is notable because it is a very substantial eastern dam across a major river. This overflow dam had a downstream protective apron, but there was no stilling basin, the lack of which would cause erosion problems over the years. Also, there was apparently little consideration for migrating fish passage.

Larger water impoundments and transmission works for water supply were under active planning or construction. Flood control works were implemented in areas such as New Orleans, where the Sewerage and Water Board was formed in 1899.[10] A. Baldwin Wood, a remarkable engineer, was hired and worked 55 years for the Water Board, developing many inventions that eventually helped alleviate flooding problems. His high-capacity pumps for lifting water over the levees are notable.

In the early 1900s, threats to public health such as yellow fever, cholera and typhoid fever were concerns, and these concerns involved both water supply and disposal of sewage.

By 1914, Worcester's population had grown to 166,000. Arguably, more machine tool builders, machinists, mechanics and metal tradesmen were in Worcester and its suburbs than anywhere else in the United States. A partial list of products from Worcester and Worcester County included steam engines, railroad steam engines, saws, steam pumps, optical goods, cutlery, shuttles, gauges, drills and woodworking equipment. Other products included corsets, envelopes, railroad cars, grinding products, textiles and textile machinery, insurance-related businesses and lunch-car diners.

These developments set the stage for the activities of the WPI Hydraulic Laboratory through World War I.

GEORGE HECKER *was appointed Director of the Alden Research Laboratory (ARL) in 1975, when it was part of WPI, and became President in 1986 when ARL was separately incorporated. Prior to joining ARL in 1971, he worked for Stone & Webster in Boston and for the Tennessee Valley Authority before that. With more than 35 years of experience in solving flow problems using physical models, analyses and field studies, he has published widely and has served on many national professional committees. He has degrees from Yale and the Massachusetts Institute of Technology.*

ALBERT G. FERRON *was employed at ARL for 35 years. He also was an Adjunct Associate Professor of Mechanical Engineering at WPI. Upon his retirement from ARL in 1992, he was Vice President of the Flow Meter Calibration Section. Currently, he is employed at the University of Massachusetts Medical School in Worcester, continues as an Adjunct Associate Professor in WPI's Department of Civil & Environmental Engineering and is active in many community projects.*

BRUCE J. PENNINO *is Professor of Civil Engineering Technology at Springfield Technical Community College. Formerly, he was a Research Engineer at ARL for many years. He has a B.S.C.E. from Bucknell University and a M.S.C.E. from Colorado State University. He has over 30 years of civil and hydraulic engineering experience, and is a registered professional engineer in Massachusetts.*

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