FROM RULE OF THUMB TO SCIENTIFIC ENGINEERING:

James B. Francis and The Invention of the Francis Turbine

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MONOGRAPH SERIES OF THE NEW LIBERAL ARTS PROGRAM

The New Liberal Arts (NLA) Program of the Alfred P. Sloan Foundation has the goal of assisting in the introduction of quantitative reasoning and concepts of modern technology within liberal education. The Program is based on the conviction that college graduates should have been introduced to both areas if they are to live in the social mainstream and participate in the resolution of policy issues.

The New Liberal Arts Program has led to significant, new courses and course changes in many colleges and universities. MIT Press and McGraw-Hill are jointly publishing an NLA series of books. These monographs are planned to provide teaching/learning materials for other educational developments. A complete list of the monographs can be found on the last page of this book.

NLA Monograph Series

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TABLE OF CONTENTS

Foreword

From Rule of Thumb to Scientific Engineering: James B. Francis and the Francis Turbine is one of a series of monographs arising out the Princeton Summer Seminars on "The Engineer's Experience and the New Liberal Arts" conducted in 1987, 1988, and 1989 by David P. Billington, Michael Mahoney, Robert Mark, and John M. Mulvey under the auspices of the Alfred P. Sloan Foundation. The seminars brought together faculty from liberal arts colleges for intensive work on the development of curricular materials in engineering to be integrated into courses at their institutions. Although the materials selected in the first instance suited to the particular needs and opportunities of these courses, the seminar pursued several overarching themes:

· **Engineering (taken here to be the same as technology) has its own set of guiding ideas, different from those of the natural sciences.** Although liberal arts college students can comprehend those ideas without prerequisite college-level study of science or mathematics, they should nonetheless carry out simplified numerical studies which convey the quantitative nature of modern technology. Moreover, because engineering aims ultimately at artifacts—at structures, machines, processes, and systems—rather than words, students must see these objects of their study as well as hear and read about them. Hence, the seminars emphasized the development of visual materials in the form of slides, graphics, and models.

· **Engineering is an evolving social process conditioned by and in turn acting on politics, economics, and cultural traditions.** Analyzing this process can best be approached through studies in the history of technology.

· **Engineering is a human activity, which often reflects the thoughts and feelings of individual engineers, whose lives and works deserve study.**

When set in the context of these themes, several of the resulting projects seemed to promise interest and effectiveness among students and faculty at liberal arts colleges in general, and with further support from the Sloan Foundation the authors devoted additional time in 1989–1990 to putting them in final form for distribution in the New Liberal Arts Monograph Series. As the product of successful classroom experience each monograph is designed to be used directly by students. In addition, the authors have tried to provide guidance for faculty who might wish to adapt only portions of it into their own courses or simply inform themselves about the subject.

Arnold Pacey warned in *The Maze of Ingenuity* that "every technical innovation has social consequences—almost all technology is concerned with bringing about changes in society—and to train engineers in the twentieth century universities as if engineering is simply a matter of pipes, electronics, concrete and mathematical calculation seems little short of irresponsible." In the spirit of the New Liberal Arts Program, this monograph and its companions eloquently demonstrate the converse of Pacey's proposition, namely that to train liberal arts students as if pipes, electronics, concrete, and mathematical calculation had nothing to do with changes in society is equally irresponsible.

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Preface

James B. Francis

James B. Francis (1815–1892) was a British-born engineer who helped to shift engineering in America from a craft to a scientific base. He linked engineering firmly to experimental inquiry of a scientific nature. He was associated with America's most important early center of textile manufacturing, Lowell, Massachusetts. In its early stages the factory system relied mainly upon water power, and cotton textile manufacturing was at the cutting edge of the industrial revolution. Francis was one of the foremost figures in the development and effective use of water power at Lowell and elsewhere.

An understanding of Francis's work and the Lowell context provides important insights into the Industrial Revolution in America. It was at Lowell that we can find one of the origins of a style of technology and labor relations which helped to humanize the industrial revolution; this style involved relatively high wages and a higher level of decency and dignity for working people made possible by an advanced, labor-saving technology. The city of Lowell became, for a time, an "ideal" industrial community which attracted visitors from all over the world. It allegedly showed that the industrial revolution need not be associated with the degradation of labor.

Idealism or Cynical Realism?

Whether the labor system reflected a genuine idealism or a cynical realism has been long debated. It is useful to compare the work of Francis C. Lowell and Henry Ford. The work of both marked milestones in the development of technology and labor relations. We find a similar paternalism toward labor and a linkage of higher wages and shorter working hours in the systems of technology developed by Lowell and Ford. In both cases, however, workers had to form unions and strike to obtain the full benefits of the advanced technologies which they implemented. Henry Ford gave his system the imprecise term "mass production," and we can see in the work of Lowell one of the roots of the tradition that led to Ford's mass production. The work of both contributed to a technological style that developed in America from 1814, when Francis Cabot Lowell's first textile mill began production, down to 1914 when Henry Ford gained widespread publicity for offering five dollars for an eight-hour day.[1]

Both Ford and Lowell stood for highly productive technologies that attracted attention because they were advanced for their age and associated with relatively high wages for workers. The technologies of textile and automobile manufacturing have little in common, except for the fact that they used power intensively. Indeed, the intensive use of power and the development of labor-saving technologies have been among the major themes in the American version of the industrial revolution.[2]

Many historians have attacked the myth of an idyllic relation between labor and management in American industry. This monograph will not attempt to resolve the important social issues involved in this debate. It will, however, shed light on an important dimension of the technological and labor systems that evolved in America in the period since 1814. James B. Francis, in particular, helped to develop the large-scale use of water power at Lowell. The history of higher productivity through the substitution of power for labor is an important and neglected part of the story of the industrial revolution in America, but no claim is made here that it is the whole story.[3]

Purpose of This Study

This study shares the basic goals as the other monographs in this series. It is hoped that it, like the others, will provide useful collateral studies for undergraduate students. The story of Lowell and its novel labor system is often included in undergraduate surveys of American history, as well as courses in a variety of disciplines which appeal to students who are not science or technology majors. This study will supplement the usual textbook coverage with additional materials which provide an understanding of the water power technology used at Lowell and the role of engineers in producing power and developing technologies for industry. It will also help students understand the relationship between engineering, power, and productivity in the early days of the city of Lowell, when that city foreshadowed, for a time, a new and vibrant vision of what the industrial revolution might be like.

The Underlying Technology

Though the labor system at Waltham and later at the city of Lowell has attracted a good deal of attention, the underlying technology is seldom made clear in the textbooks. An assumption of this series is that understanding the technological foundations is important for a full understanding of history. One of the aims of this study, therefore, is to make clear some elementary but important engineering facts and relations. Because of this it should also be of use in giving some preliminary insights into hydraulic engineering in courses for freshman engineers.

Though the primary audience is undergraduate, it is hoped that this work may be relevant for anyone interested in the history of technology. It is a case study of the "interactive model" of the relations of science and technology. The most fundamental of claims of the interactive model is that engineering is an autonomous community, co-equal with the basic sciences, with its own creative methods and its own intellectual history. In particular, the interactive model rejects the idea that technology is just applied basic science.[4]

Technological knowledge is quantitative. Underlying all the enormous complexities of engineering, there are certain very simple quantitative relations. These can be understood with no more background than elementary arithmetic. I do not claim that nothing is lost in such a simplification. But understanding just a few fundamentals is enough to illuminate and enlarge the student's understanding.

Work of an Engineer

James B. Francis provides a remarkable case study of the work of an engineer. Though Francis was not a founder and only arrived in the city of Lowell some 20 years after the death of Francis C. Lowell, he nevertheless played a critical role in the further evolution of the system in place on his arrival. He redesigned the hydraulic system at Lowell, and helped to introduce and further develop an important new water motor, the turbine. Francis helped make turbine testing something of an exact science and he invented a new type of turbine named after him. Francis is important not just for what he did, but for his methods. He was passionately determined to base engineering on experimental knowledge. In this he helped to set a path for engineering development which generations of engineers have followed. Much of Francis's experimental work was devoted to the measurement of the flow of water. Sometimes this was in connection with power production by turbines, at other times it related to the canal system which distributed water to the manufacturing companies at Lowell, and at other times it involved metering the amount of water used by the various textile factories at Lowell. And it was in measuring water that Francis made some of his most notable (and still useful) contributions to engineering.

Francis was very skeptical of all mathematical theory. One of Francis's most lasting achievements was an empirical formula for determining the flow of water, which was derived from experiment. It still figures prominently in reference works in engineering.[5] It is best seen as a contribution to engineering theory, a theory that is akin to that of the physical sciences, but distinct from them in a number of ways. The differences may be manifested in a lesser idealization in engineering theory and greater generality of the physical sciences. In either case the differences reflect the fundamental goals of engineering and scientific communities, particularly the fact that engineering communities rank doing above knowing while the communities of basic science rank knowing above doing.

ACKNOWLEDGMENTS

I would like to thank David Billington for his friendship, help, and guidance. Michael Mahoney read and made helpful suggestions on two earlier incarnations of this paper, and I am grateful for his assistance. I have enjoyed and benefitted from my association with others involved with the Sloan New Liberal Arts Program, including Alfonso M. Albano, J. Nicholas Burnett, William Case, Newton H. Copp, Christopher Nevison, Lawrence Owns, Robert B. Prigo, and Andrew Zanella. To all, thanks for more things than I can enumerate here.

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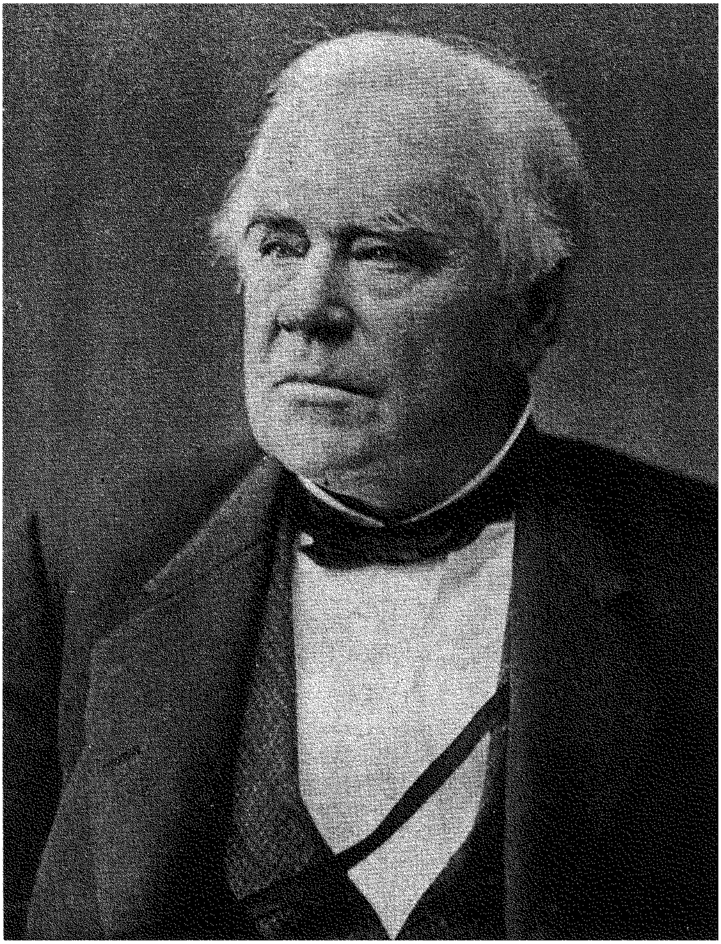
[2] H. J. Habakkuk, American and British Technology in the Nineteenth Century, the Search for Labour-Saving Inventions (Cambridge, U.K.: Cambridge University Press, 1967) is a pioneering economic study which stressed the labor-saving bias in American technological development, but he does not deal with power. On industrial power see Louis C. Hunter, A History of Industrial Power in the United States, 1780-1930, volume One: Waterpower (Charlottesville, 1979). There have been a number of studies of the rise of mass production in America: Hounshell, From the American System to Mass Production provides a useful starting point for the study of this important historical development.

[3] The high wages came at a social price, and historians have discussed wages, working conditions, and related issues in a number of excellent studies. For Lowell the student might begin with Thomas Dublin, Women at Work, The Transformation of Work and Community in Lowell, Massachusetts, 1826-1860 (New York: Columbia University Press, 1979) and Hannah Josephson, The Golden Threads, New England's Mill Girls and Magnates (New York: Duell, Sloan and Pearce, 1949). An enthusiastic contemporary defense of Lowell in 1845 was made by Henry A. Miles, Lowell, As It Was, And As It Is (Lowell: Nathaniel Dayton, 1846, which has been reprinted by Arno Press in 1972 as part of a series "Technology and Society," edited by Daniel Boorstin).

[4] Statements of the interactive model may be found in Barry Barnes, "The Science-Technology Relationship: A Model and a Query," Social Studies of Science, 12 (February 1982): pp. 166-171 and Edwin T. Layton Jr., "Mirror Image Twins: The Communities of Science and Technology in 19th-Century America," Technology and Culture, 12 (October 1971): pp. 562-580. Studies of technology as knowledge include Edwin T. Layton, Jr., "Technology as Knowledge," Technology and Culture, 15 (January 1974): p. 41, Walter G. Vincenti, What Engineers Know and How they Know It, Analytical Studies from Aeronautical History (Baltimore: Johns Hopkins, 1990).

[5] Leonard Church Urquhart, Civil Engineering Handbook (New York: McGraw-Hill, 3rd edition, 1950), pp. 337-345 presents Francis's weir formula. From the context it is clear that the work of Francis is the most fundamental. Subsequent formulas make relatively small changes to adapt the basic Francis formula to somewhat different situations.



Courtesy of National Museum of American History, Smithsonian Institution

James B. Francis (1815–1892)

CHAPTER 1

Introduction: Quantitative Fundamentals

Though history is not just numbers, numbers are an essential part of history, particularly the history of engineering. Engineering knowledge is mainly expressed in quantitative terms. And a few quantitative facts shed much light on several historical questions. In this introduction we will describe six formulas that played an important role in the location and the evolution of the Lowell hydraulic system and the work there of James B. Francis. They can be briefly stated (see box next page).

The Historical Importance of Numbers

Numbers tell us nothing by themselves. They must be combined with social facts to have historical importance. The power of a fall of water, determined by equation (1), can help answer questions such as, "why was the city of Lowell located where it was?" and "why was Lowell one of the largest manufacturing centers in the United States prior to the Civil War?"

To answer the historical questions, we begin with the fact that the developers of Lowell (called the "Boston Associates") needed a large Q and a large H, and they discovered these conditions at the falls of the Merrimack where they founded the city of Lowell. Lowell, with 13,940 gross horsepower, was one of the largest early textile manufacturing centers in America; and it was the model upon which other large centers in Northern New England were patterned. Thus the leadership of the city of Lowell was based on a combination of mechanical power, on the one hand, and technological and business leadership, on the other.

To use the power of a small stream simple arrangements are often sufficient. To use the enormous power available at the falls of the Merrimack, a complex hydraulic system was needed, including dams, canals, and other hydraulic structures. The large manufacturing companies established at Lowell paid substantial sums to lease

Quantitative Relations for Understanding Waterpower

Power is fundamental to understanding all kinds of engineering issues. Where **Q** is the quantity of water flowing per unit of time, which we shall call simply the **flow** (in cubic feet per second), and **H** is the fall of the water in feet (or its "head" see FIG. 1), **w** the weight of water in pounds per cubic foot, and **P** stands for power in foot pounds of work per second:

(1) $$P = Q\,w\,H$$

Since the time of James Watt, the basic unit of power has been the horsepower. Watt defined one horsepower (Hp) as 550 ft. lbs. of work per second:

(2) $$Hp = QwH/550$$

The quantity of water flowing in a canal is another engineering fundamental. Where **Q** is the flow of water (as in equation 1 above), and **A** is the cross sectional area in feet squared, and $\mathbf{V_m}$ is the average or "mean" velocity of flow in feet per second, then the flow in a canal or other channel in cubic feet per second is given by:

(3) $$Q = V_m A$$

Any rational policy of power production requires the measurement of the amount of power produced by a power source (or "prime mover"). Where $\mathbf{P_r}$ is the rotary power of a turbine in foot pounds per second, **T** the thrust or load in pounds, and $\mathbf{V_r}$ the rotary speed[1] of the prime mover in feet per second, then the power produced is expressed by:

(4) $$P_r = V_r\ T$$

Efficiency is another key engineering idea. Where **e** is the efficiency, and P_r is the actual power given in equation (4), and P the power of the falling water given in equation (2), the efficiency of a turbine or other power source is given by the ratio of the power realized to that potentially available:

(5) $$e = P_r / P$$

The flow (Q) into a water wheel was important for understanding Francis's work. Water is admitted to water wheels and turbines through a rectangular opening (or openings) called a "weir." Where **Q** is the flow as before and H is the distance between the crest of the weir and the surface of the water in the canal (see FIG. 2) this **H** is therefore different than that in equation (1). **L** is the length in feet of the weir (which can have more than one rectangular opening in the direction perpendicular to the flow) and **n** the number of sides of these openings, then the flow of water over the weir is given by the Francis weir formula:

(6) $$Q = 3.33\,(L - 0.1\,nH)\,H^{3/2}$$

FIG. 1

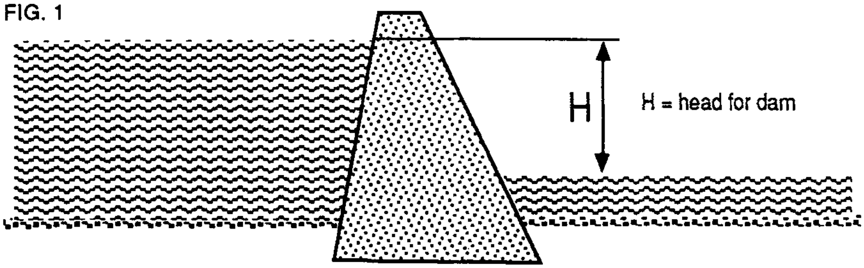
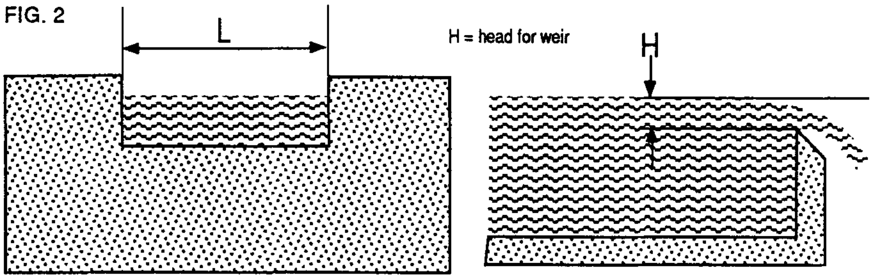


FIG. 2



FIGS. 1 and 2 Hydraulics engineers use "H" in two ways. It is usually apparent which is intended — FIG. 1 shows H for the head in a dam and FIG. 2 shows H for the head in a weir.

parts of the waterpower available. Equation (3) is that used for measuring the flow of water in a canal, such as those used to distribute the water to the mills at Lowell. In order to manage a hydraulic system such as that at Lowell, a method was needed to measure the flow of water in order to design and operate the system rationally, and also to ensure fairness in the distribution of water among a number of large manufacturing companies. Equation (3) provided the basis for measuring the flow of water in the canals that distributed the water to the manufacturing companies at Lowell.

Mean Velocity

Although equation (3) is simple, determining the mean velocity is not. This is because the water does not move uniformly but rather it is divided into many separate streams or layers, each moving with its own speed. This speed varies in rather complex ways with the depth of the stream and the distance from the sides and bottom, where the speed is slowest. Many other factors influence the velocity of water, including the shape of the channel, the difference in the height of the water from the beginning to the end of the channel, the amount of friction generated by the flow of the water, and even the wind. All of these factors could influence the mean velocity of the water and all had to be taken into account.

Efficiency

Lowell and other hydropower manufacturing centers in America grew rapidly in the nineteenth century. This meant increasing demands for power. Engineers such as Francis therefore were concerned with efficiency. By increasing the efficiency of the water wheels or turbines, Francis could extract more power from the existing supply of water. Efficiency is given by the fifth formula. Efficiency in Francis's time was often given the descriptive name, "coefficient of effect." We will use the modern term, "efficiency." It is the ratio of the actual power realized at the shaft of a water motor and the power potential of the falling of water (which is given by equation 2).

To determine the efficiency of a water motor, Francis needed to know its actual output of power. This had long been a matter of guesswork, but by Francis's time a precise measurement of power was possible. A device that measures power output is called a dynamometer. Francis used the fourth formula to determine the actual output of power of a water motor by means of a dynamometer.

To determine the efficiency of a water motor Francis needed not only to determine the power output by equation (4), but the potential power in the fall of water used by the water motor. This can be calculated by equation (2) where the horsepower is determined by QwH/550. The problem for Francis was that though H and w could be measured accurately, there was no known way to determine the volume of flow (Q) accurately at that time. Francis therefore set out to derive an equation that would measure Q. Once this was done he could make turbine testing (and hence the management of a large water power system) a matter of precise, quantitative data. This can be seen as part of a programmatic goal adopted by Francis and other engineers of making all engineering rest upon exact knowledge.

The Weir Formula

Since the inlet to a water motor was called a weir, the formula that Francis determined was called the Francis weir formula and is given by equation (6). This formula had several uses. It was needed in determining the input of a water motor, and this, with the output enabled him to calculate the efficiency of the water motor by equation (5). There were other uses for this formula also. Francis used his weir formula as a part of his method of measuring the mean velocity of flow in a canal, according to equation (3).

Additional information, including some quantitative data, is needed to put these five equations into perspective. For example, why was New England the leading section in manufacturing, particularly factory production, down to the Civil War? Why did New England lose this leadership rather rapidly after the Civil War? Clearly a part of the answers to these questions lay in a fact of New England geography. The land is undergirded by hard rock which has faulted (that is, huge sections of bedrock have slipped in relation to adjoining sections); further, the faulting took place in a step fashion in New England, but this pattern is highly unusual, and no other section of the eastern United States has the potential for hydropower that New England has. When these facts are combined with another, that the rainfall is abundant, the result is that New England has numerous waterfalls which early industrialists seized upon to provide power for factories.

The Merrimack River

No river in New England is more ideally suited to industrial development than the Merrimack. It was often called "the hardest working river in America," in the middle years of the nineteenth century. (The three largest manufacturing cities, Lowell, Lawrence, and Manchester had over 40,000 gross horsepower.) It has a substantial flow and it falls through a number of discrete steps. The Town of Lowell was founded at one of the largest of these, a fall of about 35 feet at a place some 20 miles from Boston. The cotton to be converted into cloth had to be imported by ship and the finished product had to be shipped out, so a connection with a major port, such as Boston, was critical. Before the founding of Lowell a canal had already been built which provided cheap transportation linking it with Boston.

Steam Power

Changes in power technology help to explain why New England lost its industrial leadership after the Civil War and why Lowell lost its position of leadership in manufacturing. Down to the 1850s the cost of steam power was considerably greater than water power. Thus, steam engines in America were first used for transportation and to supply power where there was no waterpower. But the cost of steam power declined after about 1850, due in part to the appearance of very efficient Corliss steam engines.[2] Steam power grew more rapidly than waterpower, and surpassed it just before 1870. In that year the census showed that water produced 48.8 percent of the industrial power (1,130,431 horsepower) while steam produced 51.8 percent (1,225,379 horsepower). The rate of increase of steam was very rapid after 1870. In the following decade steam as a source of industrial power grew by 30 percent while waterpower for industry increased only by 8.4 percent.[3]

New England was rich in waterpower, but lacked coal for steam engines. The rest of the country lacked New England's endowment in waterpower, but coal was widely distributed. The rapid expansion of textile manufacturing (especially in the postwar South) caused cut-throat competition and Lowell and other New England textile centers became the sites of sick industries with social problems rather than glamorous pace-setters at the cutting edge of technological and social change.

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[1] There is a conceptual difference between speed, the time rate of change of position without regard to direction, and velocity, the time rate of change of position in a particular direction. Velocity has both magnitude and direction, speed has magnitude but not direction.

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[3] U.S. Census, 10th Census, 1880, "Reports on the Water-Power of the United States." pp. xii. See also Hunter, Waterpower, p. 212, table 9, p. 283.

CHAPTER 2

The Lowell Context

Early Training

On November 22, 1834 James B. Francis arrived at the bustling industrial city of Lowell. Born in Southleigh, England, May 18, 1815, Francis had had only a brief formal education (to age fourteen) before his father, John Francis, called him home to begin his apprenticeship as an engineer and to work on a small railroad in Wales that the father managed. Engineers in Britain and America at that time were trained mainly by on-the-job experience combined with self-study. James Francis showed an aptitude for hydraulic engineering. He worked on canals and harbor works associated with his father's railroad. Subsequently he gained further hydraulic experience while employed by the Great Western Canal in England.

The young Francis immigrated to America in 1833, at the age of only 18. It was probably because of his experience on his father's railroad that Francis was retained by Major George W. Whistler, a West Point graduate, who had become one of America's leading railroad engineers. The owners of the factories and hydraulic works at the growing industrial city of Lowell wanted a railroad to bring cotton from Boston to Lowell. The Machine Shop at Lowell had made and sold textile machinery and it now ventured to produce railroad locomotives.

Whistler was invited to come to Lowell in 1834 to help with the railroad. Francis followed Whistler and he was actively engaged in the design and manufacture of railroad locomotives at the Machine Shop until Whistler left in 1837. Francis was then offered the position of engineer with the hydraulic works at Lowell. He jumped at the chance, and spent the rest of his life in the design, construction, and management of the largest and most important hydraulic system in North America.[1]

Francis made important contributions to the development of the water power that drove the looms and spindles at the Lowell mills, and indirectly at many other places. Just how important his work was can be inferred from the fact that when he retired in 1885, his friends, who included many of the second generation of directors, presented Francis with a handsome set of silver, with the praise that to his "eminent ability and wisdom" the "marked success of the Lowell manufacturers has been largely due."[2]

Although the city of Lowell was already famous when Francis arrived, he had an influence, not only at Lowell, but, through his publications, consultation, and professional activities, wherever waterpower was used. He was the most important American engineer in the field of waterpower. To understand this context we need to examine the events leading to the founding and rapid growth of the city of Lowell prior to the arrival of James B. Francis.

Successful Industrialism

The city of Lowell was relatively new; the first mill started operation in 1823, about 11 years before Francis arrived. But it was already the most important textile manufacturing city in America, and its technological and labor styles were widely copied, in textile centers in northern New England and elsewhere. The city of Lowell became a showplace visited by many Europeans; it demonstrated to the satisfaction of individuals as diverse as Charles Dickens and Davey Crockett that industrialism could be successfully adopted without degrading the work force or undermining the character of free citizens of a Republic. [3]

The city was named after an American merchant, Francis Cabot Lowell (1775-1817). On an extended visit to Britain in 1810-1812 he decided to transfer the cotton textile industry and the factory system to America. While he was impressed, like most American visitors, with the technology used in the production of textiles by the factory system, Lowell was also repelled by the wretched social and moral conditions of the working classes in major British textile centers. His emphasis, like those of Americans of that epoch, was upon the decay of morals, but this included family disintegration and the gross exploitation of women and children by employers.

American visitors were especially repelled by the city of Manchester, where coal-powered steam engines drove textile factories and polluted the air which deposited its soot on the factories. Here American visitors found the "dark Satanic mills" deplored by the British poet William Blake. American visitors were repelled by immorality and the gross exploitation of children, who, in words of one American clergyman, were "cast destitute, helpless, and orphans," in a place which provided "exhibitions of the most disgusting and loathsome forms of destitution."[4]

Francis C. Lowell thought that the evils of the British system of textile manufacturing could be eliminated in America. With the assistance of Paul Moody, an inventor and engineer of genius, Lowell adapted British textile technology to make it more productive and power intensive. Moody's labor-saving inventions allowed Lowell to adopt a novel labor system, first instituted at Lowell's earliest textile mill at Waltham, near Boston, which started production in 1814. The "Waltham System" was associated with relatively high wages, the virtual elimination of child labor, and strict moral supervision of the operatives. Lowell sought to avoid the formation of a permanent working class by recruiting young farm women to work for a few years at his mills. This system was further elaborated by Lowell's followers, the "Boston Associates" at the city of Lowell, and it had an enormous influence on the factory system in America.[5]

Use of power in previously undreamed of quantities lay at the heart of Lowell's system, especially as it was further expressed in the city named after him. Lowell's original idea for more efficient textile manufacturing centered upon the idea of what is now called a vertically integrated plant or "flow production." As one of Lowell's associates noted, " Mr. Lowell adopted an entirely new arrangement in order to save labor, in passing from one process to another; and he is unquestionably entitled to the credit of being the first person who arranged all the processes for the conversion of cotton into cloth, within the walls of the same building. "[6] This system, combined with many other labor-saving technologies, foreshadowed Henry Ford's "mass production" in some important ways.[7]

The Power Loom

The critical invention which allowed Lowell to implement his vision involved the perfection of the power loom. With an automatic loom he could integrate spinning (which was already mechanized) with weaving (which was still a handicraft industry).[8] In adopting a loom driven by inanimate power in place of the hand loom, Lowell tacitly built upon America's abundant water power. Though the power loom and integrated production were Lowell's starting point, Lowell and Moody did not stop there. They invented or improved upon labor-saving machinery which allowed the factories to run faster and turn out a greater product with fewer employees.[9]

After Lowell's premature death in 1817, his friends and followers, the Boston Associates, sought to carry out his plan by building a large waterpowered textile-manufacturing city that dwarfed the pioneering factory at Waltham.[10] They did so by purchasing the property and charter of an old canal company, The Proprietors of Locks and Canals, which controlled the 35 foot fall of the Merrimack River. The company had been created in 1792 to build a canal and locks which allowed river traffic to by-pass the falls.

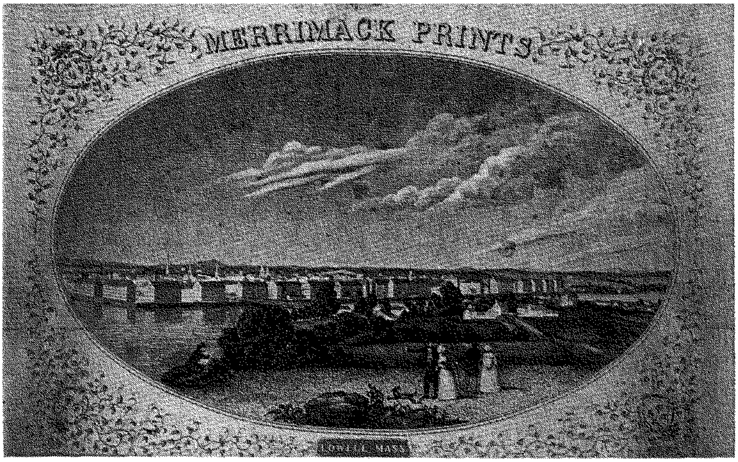
Upstream from the falls of the Merrimack the Boston Associates placed a dam 950 feet long which diverted virtually all the river water to their canal, the Pawtucket, which ran approximately parallel to its former bed, but at some distance south of it. They built feeder canals to distribute the water of the Pawtucket canal to the textile mills that were built in the new manufacturing city. This allowed almost the entire power of the river to operate factory machinery.

Industrial Developers

The Boston Associates organized the Merrimack Manufacturing company to carry out Lowell's ideas on a large scale. They purchased, besides the water power and works of the old canal company, a great deal of land in and near their new city in 1822. The city was named after Lowell, since his vision continued to inspire their efforts. They started work on the first mill and residences in that year. The first waterwheel for this first factory started to turn on September 4, 1823.

The Boston Associates were eager to sell land, water rights, and machinery to new textile companies which they helped to organize. The high profits attracted stockholders, and the promoters were well rewarded for their efforts. By 1845 it was thought by many that the city of Lowell had reached the limit of the water available. By 1845 Lowell had ten large manufacturing corporations employing 5,870 women who lived in over 500 boarding houses. In addition they employed 1,255 males, who were also provided with houses and apartments.The ten textile companies together had 31 mills, plus dye houses and print works.[11]

Lowell was, in some sense, an "ideal" industrial community. Many visitors were impressed by the unquenchable thirst for knowl-



Courtesy of Museum of Textile History, North Andover, MA

FIG. 3 – Lowell portrayed as an ideal community, 1858

edge of the women workers. They used subscription libraries, attended lectures, and wrote, edited, and published a magazine, the Lowell Offering. Self-help and self-education were encouraged by employers, who assisted their employees in making Lowell a remarkable place in its first generation. Real wages declined with increasing competition in the 1840s, and following several spontaneous strikes and agitation for a 10-hour day, Sarah G. Bagley organized a union for women workers in 1844. Though intended to be an ideal city in some sense, idealism was increasingly at odds with profits, and when the crunch came profits tended to win out.[12]

Increased Productivity Through Water Power

In discussing early industrialism at Lowell and elsewhere, it is essential to recognize the intensity with which power was used. Britain was not well-endowed with water power, and the early factory system in Britain was associated with rather modest use of water power compared to the standard adopted at Lowell and elsewhere in America. Even the largest British textile factories used 100 horsepower or less, a small amount by Lowell standards.[13] The higher wages and improved working conditions in America were made possible, in some significant degree, by the lavish use of waterpower in America as compared with Europe.

It has been estimated that the Waltham technology developed by Lowell and Moody increased the productivity of labor by more than 300 percent as compared to the original British technology. The output at Lowell by 1855 was more than 160 percent higher per worker than it had been at Waltham between 1810 and 1820.[14] As Francis wrote, "the machines used in manufactories are usually great consumers of power; the ability of a machine to turn off the greatest quantity of work with the least manual labor, and in the least time, has been the point mainly considered..."[15] The use of labor-saving machinery (supported by an ample supply of inanimate power) became one of the central themes in American economic and technological development.[16]

Half the Power of France at Lowell in 1855

The power available at Lowell was enormous for the middle of the nineteenth century. Francis noted that not long before 1855 the total "useful effect derived from waterpower in France was about 20,000 horsepower."[17] The horsepower available at Lowell averaged about 10,000 horsepower (about half that of France) for the ten large textile corporations and a machine shop, or an average of nearly 1,000 horsepower for each manufacturing company.[18]

Ten thousand horsepower was an average, the amount of water power varied with the season, with considerably less available at low water because both H and Q diminished. Even so, the use of power at Lowell was very remarkable for its age, and goes far to explain why the conditions of labor at Lowell in its early years differed so much from those prevailing in Europe.

The power leased to the Lowell companies was less than 10,000 horsepower because the quantity leased was determined by the flow at low water. In 1845 the Lowell corporations leased 91 "millpowers" (one millpower was approximately 100 horsepower), the equivalent to a flow of 2,348 cubic feet per second of water falling 33 feet, or by equation (2) : $QwH/550 = 2348 \times 62.33 \times 33/ 550 = 8{,}781$ gross horsepower. The net power equivalent may have been about 5,500 horsepower (assuming an efficiency of the waterwheels of a bit less than 63 percent).

By 1855 after Francis had reconstructed the hydraulic system, the companies at Lowell leased 139.7 millpowers, or power equivalent to a flow of 3595.93 cubic feet per second falling 33 feet. By equation (2) this gave a gross horsepower of $3595.93 \times 62.33 \times 33 / 550 = 13{,}448$. In 1855 Francis estimated the actual efficiency of the waterwheels and turbines at Lowell at 2/3 (or 66.7 percent efficiency). This gives a net horsepower available at the Lowell mills of almost 9,000 horsepower

(8,965.8 horsepower). In fact Francis was conservative both as to the efficiencies of Lowell turbines and the actual flow at low water. The actual power consumption was higher than the leased power. It varied with rainfall, but averaged about 10,000 net horsepower.[19]

People Power Equals Only 1/10 the Power of a Horse

To form an idea of what this amount of power really meant, we can compare this inanimate power with that produced by people. According to several estimates, a 35 year old European working ten hours per day produces about 1/10th horsepower above that needed to support the body's metabolism. Humans can produce more power under special circumstances, but 0.1 horsepower is an accepted average.[20] Thus the minimal power guaranteed by the Proprietors of Locks and Canals to the ten textile corporations (about 8,781 gross horsepower in 1845 and 13,448 gross horsepower in 1855, or net horsepowers of about 5,500 and 8,965 respectively) was equal to the work of about 55,000 humans in 1845 and about 90,000 humans in 1855. Since there were 7, 125 men and women employed at the 10 Lowell companies in 1845, and 13,187 in 1855, this means that in 1845 there was about .77 horsepower per worker in 1845 and about .66 horsepower in 1855. The human power was therefore multiplied about seven times.[21] The immense increase in available power accounts for much of the increase in productivity at Lowell.

REFERENCES

[1] The date of Francis's arrival, along with other historical details, is given in a brief historical memoir of Lowell prepared by Francis. (James B. Francis, "Locks and Canals, Sketch of Its History," in "Records, 1866-1879," volume "H," [a note book], pp. 109-137. [the date is given on p. 120]). Francis Engineering Papers, Proprietors of Locks and Canals Office, Boott Mills, Lowell, Massachusetts. See also, "James Bicheno Francis," Dictionary of American Biography, s.v. and William E. Worthen, "Life and Works of James B. Francis," Contributions of the Old Residents' Historical Association, V(1894): 227-242.

[2] On the tribute to Francis, see G. S. Green, and J. W. Adams, and W. E. Worthen, "James Bicheno Francis, Past President and Honorary Member," Proceedings, American Society of Civil Engineers, 29 (1893), pp. 74-87 (quote on p. 77).

[3] John F. Kasson, Civilizing the Machine, Technology and republican Values in America, 1776-1900 (New York: Penguin Books, 1977): 15-16. describes the revulsion felt by many Americans at the immorality and exploitation, and urban pollution and crowding at major British textile centers such as Manchester. He credits Francis C. Lowell and his "Boston Associates" with a genuine concern to develop a new labor system compatible with the ideology of "republicanism."

[4] Quoted in Ibid., p. 61.

[5] Robert F. Dalzell, Jr., Enterprising Elite, The Boston Associates and the World They Made (Cambridge: Harvard University Press, 1987) emphasizes the Boston Associates goal of a secure elite position for themselves, but stresses their goal of public service. The two interpretations are not wholly incompatible; the social status of the Boston

Associates was certainly cemented by their reputation as benevolent employers concerned for moral issues.

[6] Appleton, Introduction of the Power Loom, p.14.

[7] On "mass production" as used to describe Ford's assembly-line production and also its general use, see Hounshell, From the American System to Mass Production, pp. 1-13. Hounshell is concerned with the tradition of metal cutting industries and the degree to which they did or did not use interchangeable parts. A broader use of mass production was suggested by Alfred D. Chandler, The Visible Hand: The Managerial Revolution in American Business (Cambridge, Mass.: Harvard University Press, 1977), pp. 240-299 suggests the importance of continuous flow and a high rate of throughput for understanding mass production. Chandler's emphasis upon integrated plant (p. 241) is very relevant to Lowell's innovations in this direction.

[8] Appleton, Introduction of the Power Loom, p. 9.

[9] David J. Jeremy, "Innovation in American Textile Technology during the Early 19th Century," Technology and Culture, 14 (January 1973), pp.40-76, esp. figures 10.1 and 10.3. Moody invented a "fault detection" mechanism in which the treads were connected to light drop wires which fell when a thread broke. The fall of the drop wire released a spring-loaded apparatus which turned the machine off. This allowed one worker to supervise many machines.

[10] The leaders were Patrick Tracy Jackson and Nathan Appleton, but others were involved. The story of these men and the business and corporate history of Lowell has been told in Dalzell,, Enterprising Elite, The Boston Associates and the World They Made.

[11] Henry A. Miles, Lowell, As it Was, and As It Is, "Technology and Society," Arno Press reprint collection (Arno Press: New York, 1972), pp. 48-57.

[12] On labor and working conditions see Arthur L. Eno, Jr., Cotton Was King, A History of Lowell Massachusetts (Lowell: Lowell Historical Society, 1976): pp.118-126, Bernice Selden, The Mill Girls (New York: Atheneum, 1983): pp.117-180, and Dublin, Women at Work, pp. 86-182.

[13] In Britain an exploitive labor system was combined with relatively modest amounts of power. See, Richard L. Hills, Power in the Industrial Revolution (Manchester: Manchester University Press, 1970), p 113. Arkwright's West Belper Mill, one of the largest in England, had water wheels which provided about 80 horsepower. Arkwright built a cotton mill at Tutbury in 1781; when it was sold in 1831 its three water wheels produced 70 horsepower. As Hills has noted: "Through the greater application of iron, one hundred horse[power] wheels had been made by 1820, and mills of this size remained the largest in the cotton industry for many years (p. 113). A typical Lowell mill (there were 31 of them in 1845) averaged close to 300 horsepower. The machine shop leased only 3.3 millpowers out of 139.67 in 1880. On water power at Lowell see U.S. Census, 10th Census, 1880, "Reports on the Water-Power of the United States," pp. xii, 78-83.

[14] David Jeremy has provided data indicating that textile manufacturing after 1813 using the technology developed by Lowell and Moody at the pioneering textile factory at Waltham near Boston saved three and a half times the labor of Samuel Batchelder's New Ipswitch mill for the period 1810-20 (where the technology was similar to that employed in Britain). The Batchelder mill processed 25,000 pounds of cotton annually with a work force of 48 (thus producing 520.83 pounds of cotton per worker per year), The Boston Manufacturing Company at Waltham processed 450,000 pounds of cotton with a work force of 264 persons in 1820 (thus producing 1,704.55 pounds of finished cotton cloth per worker). The Waltham manufacturing complex therefore processed 3.27 times as much cotton per worker in that year as the New Ipswitch mill. (See Jeremy, "Innovation in American Textile Technology," p. 73.) In 1855 the ten Lowell companies processed 35,880,000 pounds of cotton with a work force of 13,187, Or 2,721 pouns of cotton per year per worker; this increase (almost 160 percent) understates the

increased producitivity, since Lowell in 1855 also produced printed calicos and woolen carpets. (See Eno, When Cotton Was King, p. 256, Appendix B.)

[15] Francis, Lowell Hydraulic Experiments, p. xi.

[16] Habakkuk, American and British Technology in the Nineteenth Century, the Search for Labour-Saving Inventions was a pioneering economic study of the labor-saving bias in American technological development.

[17] Francis, Lowell Hydraulic Experiments, p. ix The estimates for France and other countries were probably "ball park" estimates. For though the flow of rivers could be measured, the power realized by a waterwheel was more difficult to determine. The method (e.g., by means of a dynamometer) will be discussed below. It is probable that the power output of small country mills were not accurately measured, but only estimated. It is notoriously the fact that England was much less well equipped with water power than France or New England, and had to turn to steam earlier when it was still quite expensive. British textile factories traded labor for inanimate power, just as American textile factors on the Lowell pattern traded power for labor.

[18] The figures on power allocated to the Lowell mills in 1855 is from James B. Francis, Lowell Hydraulic Experiments, second edition (New York: D. Van Nostrand, 1868), p. x. See also Hunter, Waterpower, pp. 159-160. One of the first to point out the continued importance of water power in America at a time when Britain had been forced to shift to steam (because waterpower was in short supply) was Peter Temin, "Steam and Waterpower in the Early Nineteenth Century," Journal of Economic History, 26 (1961): 187-205.

[19] Francis, Lowell Hydraulic Experiments, p. x gives figures for 1855, and he gives his results in horsepower, except when referring to leased power. Because the mill power was a measure of both net and gross horsepower, it is inherently ambiguous. Its definition also varied over time. I have determined the value of the millpower by using Francis's data in his Lowell Hydraulic Experiments. His data indicated that a flow of 3595.9 cubic feet per second falling 33 feet, giving 13,448 gross horsepower as equal to 139.37 millpowers, which gives a value for the millpower of 96.49 gross horsepower. When applied to the 91 horsepower leased prior to 1845, the result is 8,780 gross horsepower. Assuming the same coefficient of 2/3 for the relation of gross to net horsepower gives 5,857 leased net horsepower for 1845, which provides an upper limit. I further assume that the flow for the 91 millpowers was 91/139.37 part of the flow of 3595.9. or 2,348 cubic feet per second. It should be emphasized the the leased millpowers were leased or guaranteed horsepowers, and not the actual power realized. They were important economically in determining productive capacity at low water. But for eight months of the year the flow was above the low water levels, and the actual horsepower was the leased power plus the "surplus" power used.

[20] E. S. Krendal, "Man and Animal-Generated Power," In Theodore Baumeister et. al., Marks' Standard Handbook for Mechanical Engineers (New York: McGraw-Hill, 1978), p. 162. For a discussion of the problems of determining the measurement of human work, see Eugene S. Ferguson, "The Measurement of the 'Man-Day,'" Scientific American, 225 (1971): 96-103.

[21] Francis's estimates tend to be very conservative. He estimated the average efficiency of a Lowell breast wheel to be only 0.60, while Boyden thought that such a wheel should capture two thirds of the power of the falling water, or an efficiency of 66.7 percent. My figured of 5500 net horsepower from a gross horsepower of 8,781 is based on an efficiency of 62.64 percent. These power estimates are based on leased horsepower, a legal fiction rather than an actual flow. The actual flows were considerably larger. I believe the apparent decline in horsepower per worker is a result of underestimating the efficiency of the watermotors in 1855. Francis estimated an overall efficiency of only 60 percent, though there were many turbines in use getting about 80 percent efficiency. If we assume that 70 percent, then the net horsepower in 1855 was 9,414 and horsepower per worker was about 0.71.

CHAPTER 3

Francis and the Lowell Canal System

Chronic Water Shortages

Though Francis was only 22 years old when he moved from the machine shop to the hydraulic works at Lowell in 1837, his outstanding abilities soon marked him for leadership. He was thrust into power as Chief Engineer and Agent (or manager) of the Locks and Canals Company in 1845 at age 30 in the midst of a developing crisis both of competition from without and inefficiencies within the city. The hydraulic system was not working effectively and there were chronic water shortages at some of the mills and bickering among the ten manufacturing companies. Francis had made a careful study of the problems of the hydraulic system, and he was in a position to present a comprehensive plan to the directors in 1845. They accepted with enthusiasm and gave him the formal authority to carry out his plan. This was a great honor for a young engineer, but also a great challenge, perhaps the greatest challenge of his life.

The Lowell companies were eager to expand, but the power leased to them was determined by the low water flow, and this put a limit on their future growth. The rainfall was beyond human control, but more water power could be allocated if the cycle of famine and glut could be evened out. In addition some mills, more remote from the main water supply (the Pawtucket canal), did not get the water they were entitled to receive, even when the water supply for the total system was adequate. To make matters worse, as Lowell had expanded, the water carried by the Pawtucket canal had increased in volume and velocity, leading to excessive energy losses through friction and other effects.

Evolution of the Lowell Canals

Equation (3) in Chapter 1 ($Q=V_mA$), shows that the flow in a canal (Q) is simply the product of its cross sectional area (A) and the mean velocity (V_m). If A stayed the same and Q increased V also had to increase. The friction was approximately proportional to the square of the velocity. Attempts to further increase Q in the early 1840s were to some extent defeated by increased friction (which prevented Q from increasing very rapidly). The canal system was simply overburdened and unable to handle the larger flows required by the increased use of water power.[1]

Francis's plan for the redesign of the Lowell canal system can best be understood in the context of the historical evolution of that system. The Boston Associates had begun with the Pawtucket canal, a transport canal of modest dimensions, which had been built in 1796 to allow boats to by-pass the falls of the Merrimack. The canal diverted water from well above the falls of the Merrimack (see map in FIG. 4) and discharged it into the Concord River (which flowed into the Merrimack). For more than half of its length, until it reached the Swamp Locks, there was little fall in the Pawtucket canal; after it passed the Swamp Locks it descended rather steeply through canal locks to the level of the Concord River.

Kirk Boott, the manager of the first mills, converted the old canal into a water power system. He removed the old locks on the first part

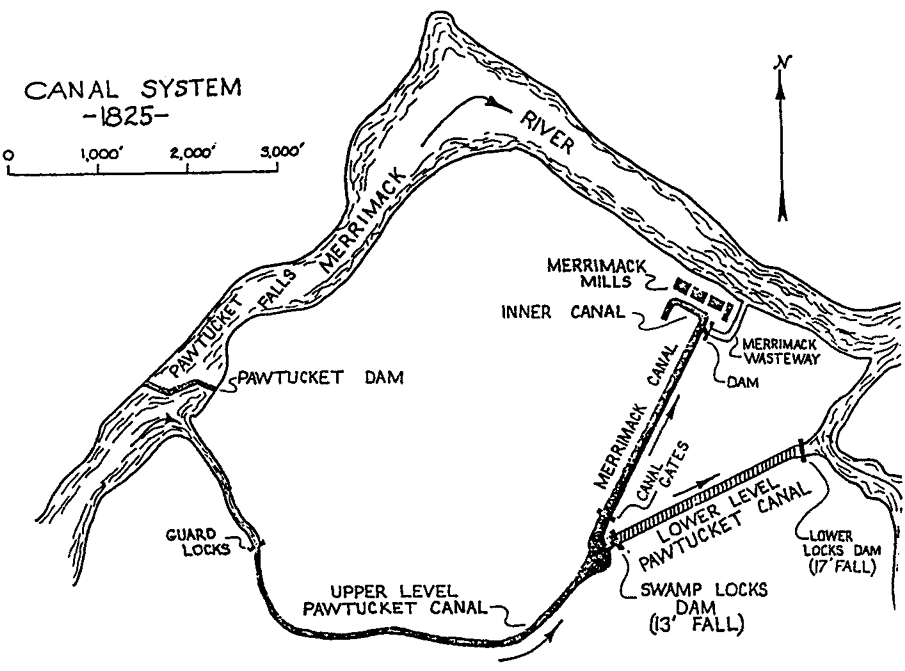


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FIG. 4 – The Lowell canal system in 1825

of the Pawtucket canal and built a dam 15 feet high at the Swamp Locks. Though it was chiefly a dam, a canal lock was incorporated into the structure at one end, so that the old canal could still be used to transport materials for the mills at Lowell. Boott enlarged the Pawtucket canal. It was somewhat irregular, but it approximated a width of about 60 feet, and a depth of 8 feet along much of its course to the Swamp Locks. The Pawtucket was enlarged by Francis after 1847, to a more rectangular shape and a depth of 10 feet. The Swamp Locks created a large reservoir, the Swamp Locks Basin. This stored water which could be carried by smaller feeder canals to textile mills located close to the old river bed. Because of the new Swamp Locks dam, the Pawtucket canal retained almost the full head of water of the Merrimack throughout most of its course, from the Merrimack to the Swamp Locks.[2]

Since the Swamp Locks were some distance inland from mills located near the old bed of the the Merrimack River below its falls, Boott built a new canal, the Merrimack, in 1822-1823, which carried water from the Swamp Locks Basin of the Pawtucket canal to the first of the new factory complexes, the Merrimack company whose mills were located near the old river bed in order to use the maximum fall of the water. This system worked well for the early mills, but it was not designed to handle the enormous flow of water needed 20 years later. In particular the Merrimack canal was not wide or deep enough for later needs, and its excess velocity caused friction losses.

Spectacular Growth

Had the enormous growth of Lowell been foreseen by Boott, he might have made his main canal, the Pawtucket, wider and evolved a more rational system for the feeder canals. But the spectacular growth of Lowell was not foreseen. One of a group of the Boston Associates on visiting the site of the future city of Lowell in 1821 had remarked that a town of twenty thousand might be located there within the lifetimes of those present, but this was apparently not taken very seriously at the time.[3] In 1845 the population was in fact almost 30,000, and the town was still growing; Lowell was a spectacular success beyond the fondest dreams of its founders.[4]

The hydraulic system had grown piecemeal without a rational long-range plan. As new mills were build additional canals were constructed to supply them with water. Thus by 1845 they were trying to feed ten large manufacturing companies with a canal

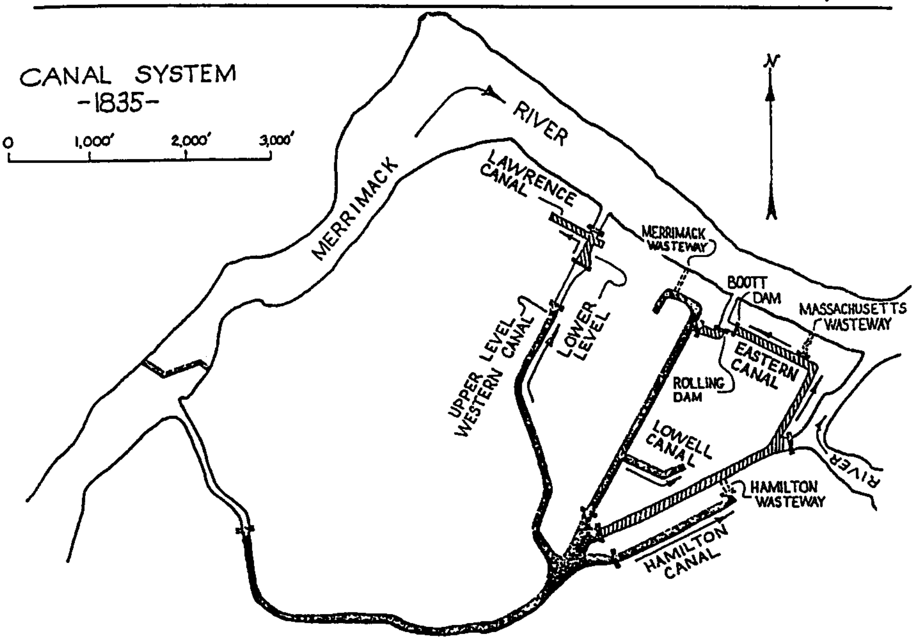

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FIG. 5– The Lowell canal system in 1835

system that was really adequate for only half of the mills in place. In addition to the Merrimack canal which fed the Merrimack mill, the Hamilton canal was constructed from 1825 to 1826. It provided water for two new mills at different levels, the Appleton mills on higher ground, and the Hamilton mills at a lower level (see FIG. 5). The Lowell canal, the shortest, took its water from the existing Merrimack canal to supply the Lowell Mills. The Hamilton and Lowell canals were in place by 1828 to supply four sets of mills, the Merrimack, Lowell, Appleton, and Hamilton complexes of mills.

Continued growth added more complexity to the hydraulic system (as shown by FIG. 5). By 1836 several additional canals had been added. The Western canal (built in 1831-1833) angled from the Pawtucket to supply three mills upstream of the Merrimack mill: the Tremont and Suffolk Mills on higher ground and the Lawrence Mills at a lower level. The Eastern canal (built 1835-1836) took its water from further down the Pawtucket canal and at a lower level. It supplied the Massachusetts and Boott mills. The Middlesex company was exceptional: its mills were the only ones to draw water power from the Concord River as well as from the lower Pawtucket canal which was fed by the discharge of the Hamilton, Appleton, and Lowell Mills. The establishment of the ten companies did not end the expansion; the companies built new mills and enlarged existing mills, leading to ever larger demands upon the water supply.

Francis Increases the Leased Waterpower

Though Francis's comprehensive plan was complicated in its details, his strategy was simple. Francis proposed changes that would even out the cyclical flow of water, enabling him to increase the leased waterpower (based on average low water flow) by nearly two thirds. Francis proposed to add additional canals to make the distribution of the water fairer, while reducing losses due to friction. He also proposed to improve the metering of the use of water, so that the amount that each company used could be determined precisely to ensure greater fairness.

Francis met the challenge of inadequate low water flow by upstream storage of water. The Proprietors agreed with Francis's farsighted plan and they purchased a woolen mill and other property that controlled the outlet to Lake Winnipesaukee, the largest lake in New Hampshire, and a chief source of water for the Merrimack River. Later, the Proprietors were able to purchase control of the outflow from three additional lake storage basins. As a result the water could be impounded in these lakes at high water and then used at low water. This raised the low-water flow dramatically, and allowed Francis to increase the guaranteed (or leased) waterpower from 91 to 139.37 millpowers, an increase of 65.3 percent, almost two-thirds (to 13, 448 gross horsepower, or almost 9,000 net horsepower).[5] Francis left a margin for error. The Lowell companies paid for "surplus" power at a lower rate. Thus whereas the Locks and Canals Company leased 8,965 net horsepower in 1855, when allowance is made for the larger flows at high water the actual average consumption in 1856 was more than 10,000 net horsepower. This figure, about 10,000 net horsepower, was more typical of the consumption of the Lowell mills than the leased (or guaranteed) power.[6]

Surpassed by Steam

Francis's plan of 1845 sustained the expansion of Lowell for almost 20 years, but continued growth led the manufacturing companies to purchase efficient Corliss steam engines, particularly after the Civil War. By 1880 the power available from steam at Lowell was greater than that from water: there were then 13,940 horsepower available from steam engines, as against the 10,188 horsepower provided by water power. Thus after Francis increased the water power that could be guaranteed by two thirds, the introduction of steam engines more than doubled the power potential of the Lowell mills to about 24,000 horsepower.[7]

The Northern Canal

The most conspicuous change produced by Francis was a large, new canal, the Northern. It was built in 18 months and completed in 1847; it was 4,400 feet long and as many as 1,000 men had been employed in its construction. This canal served two purposes: to reduce friction losses and to distribute the water more effectively. It increased the total cross sectional area through which water was fed to the feeder canals which supplied the mills. The cross sectional area for the Pawtucket was originally about 480 square feet, increased incrementally to 600 square feet after 1847. The Northern canal was 100 feet wide and fifteen feet deep, so its 1500 square feet combined with the enhanced cross section of the Pawtucket amounted to 2,100 square feet. This decreased the over all velocity of flow in the main Lowell canals and reduced the energy losses due to friction. Of almost equal importance, the new canal contributed to a better distribution of the water, especially to the mills that had been unable to get their fair share.[8]

The Northern canal was expensive to build. It cost over a half million dollars; about 4 percent of the total capital invented in all of the Lowell manufacturing enterprises in 1845 (twelve million dollars.)[9] The Northern canal paralleled the Merrimack River, through hard rock and difficult country. One section of the new canal traversed a ledge on the natural bed of the Merrimack. The canal was carried over this ledge on the massive "Great River Wall," a masonry structure which lifted the canal more than 33 feet above the river bed and enclosed the canal with massive masonry parapets. This structure was sufficiently impressive to became one of the main tourist attractions at Lowell.

Since the Northern canal brought water into the system at higher head, it reversed the flow of the Western canal which now increased the supply of water delivered to the Swamp Locks Basin. The Western canal had been a problem because of excess velocity; it was slowed down, and by supplying water to the Swamp Locks Basin, it served to slow down the Pawtucket canal and so lowered the excess velocity and hence the large loss of power due to the the friction caused by the water moving at high velocity.[10]

The Importance of the Canal Redesign

We can make a rough estimate of the impact of Francis's reworking of the canal system on the velocity of flow and friction in the main canals by the sort of "back of the envelope" calculation engineers often use, understanding that there are many things that influence the velocity of flow and friction that are not taken into account in such calculations. From equation (3) where $Q = V_m A$, if the flow Q was constant at the 3,593.9 cubic feet per second that Francis calculated for leased power in 1855, and the cross sectional area (A) of the Pawtucket was 480 square feet, then, the mean velocity of flow before 1845 would have been:

$$V_m = Q/A = 3593.9 \ / \ 480 = 7.45 \text{ feet per second}$$

At this velocity friction was a major problem. After 1847 the aggregate cross sectional area for the two canals rose (see FIG. 5) to 2,100 square feet (600 + 1500 = 2100) which led to a velocity:

$$V_m = 3593.9 \ / \ 2100 = 1.71 \text{ feet per second}$$

This is less than a quarter of the former flow (22.8 percent), with friction reduced to only 5 percent of its former magnitude ($[.228]^2 = .05$). This calculation assumes that the two canals behaved as one with the same mean velocity, a crude assumption useful for gaining a rough idea of the over all change brought about by Francis's reforms.[11]

An important purpose of the Northern canal was to ensure greater fairness in distributing the power. It provided water to those mills that found it difficult to get their allotted share with the old canal system. Also it delivered water directly to the Tremont and Suffolk mills. In addition, special feeders were added to supply those companies that had had especially difficult problems in getting their fair share of the water. Francis designed and built an underground extension of the Northern canal, the Moody street feeder, which supplied additional water to the Merrimack canal. Some of the surplus from this feeder was diverted by a smaller underground canal, the Boott Penstock, to remedy chronic water shortages at the Boott mills.[12]

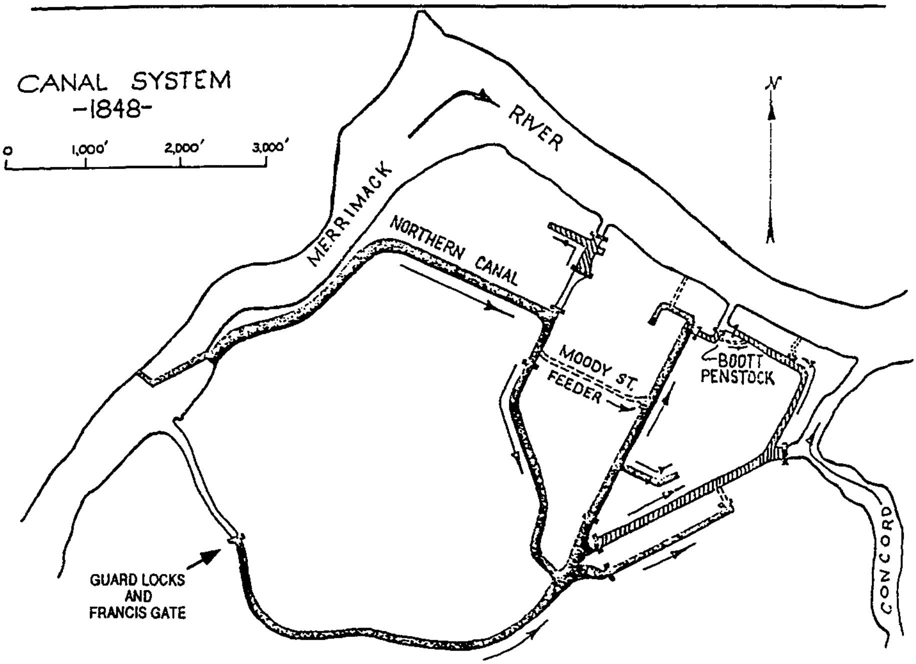

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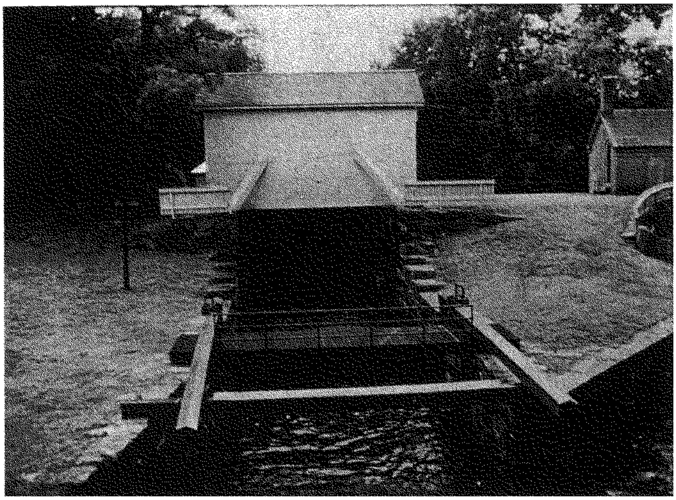
FIG. 6 – The Lowell canal system in 1848 with guard locks and Francis gate

Francis insisted that no power be drawn at night; thus the less-favored mills could better obtain their share if a large body of water was impounded at its fullest height at the start of each working day.[13] Francis also developed a new method of measuring the water used by each mill, to ensure fairness in water consumption.[14] (See Chapter 5 on the system for metering the use of water.)

Planning for a Big Flood

It is perhaps inevitable that Francis is most often remembered not for his extensive and sophisticated redesign of the entire hydraulic system, but for a simple structure, his guard gate on the Pawtucket canal. This gate saved Lowell from very severe damage and possible destruction with attendant loss of life in two floods, in 1852 and 1936. Francis, as part of his planning for the restructuring of the canal system in 1845, had gathered historical data on rainfall and water level including information on floods. He became aware of the fact that a major flood had occurred in 1785, more than a half century before the founding of Lowell.

The existing guard locks on the Pawtucket canal would not be tall enough or strong enough to halt a flood of similar magnitude, with



D. P. Billington

FIG. 7 - The Francis guard gate on the Pawtucket canal

potentially catastrophic consequences. To protect the city of Lowell and its inhabitants against the danger of another flood of similar size he built, in 1850, a massive timber portcullis gate 27 feet wide and 25 feet high, which was suspended over a groove in the lock in such a way that it could be quickly lowered in place in case of need. (It had to be suspended in the air in order to allow canal traffic to use the canal in normal times.) It was located behind the existing Pawtucket canal gates, and the sides of the canal were built up, setting the flood gate into a sort of dyke.

Within two years, in April 1852, there was a flood even greater than that of 1785. In the earlier flood the crest had been 13.5 feet above the top of the dam; in 1852 the flood crest was 14.3 feet, well above the top of the canal gates. The Francis gate was lowered, and was (at 25 feet) quite enough to contain the flood. Francis's gate undoubtedly saved the city of Lowell from severe flood damage and probable loss of life. The Boston Daily Advertiser ran an article which praised Francis for his decision, "to take measures to guard against what every one considered, a very remote contingency, by what many considered a useless expenditure of money." Had Francis not built the gate, "every vestige of the old guard gates would have been carried away, and a mighty and uncontrollable river would have swept though the heart of Lowell, destroying everything in its course."[15]

The public's reaction was not misplaced. The public safety is one of the engineer's most fundamental obligations. This was Francis's largest single contribution to public safety, but he was also involved in developing sprinkler systems for the mills to provide better fire protection, as well as a safer system of construction based on iron pillars and beams to replace the older wooden ones. He was also interested in fire safety in public theaters.

The guard gate was a simple device. But determining that the gate should be built at all was a result of his painstaking gathering of data combined with good judgment. These were the hallmarks of Francis's style of engineering.

REFERENCES

[1] Though V was the critical term in equation (2), there was a small change in head with changing velocity, called the velocity head. The loss of head and hence velocity was due to what is called friction head, or conversely, a loss in velocity head. In a canal there is an incline associated with the velocity; a lower velocity has less incline and hence less of a difference in the height of the water from one end to the other of the canal.. The loss of head due to friction is called the "friction head." Both velocity head and friction head loss are proportional to the square of the velocity. Increased friction reduced velocity and consequently the head associated with the higher velocity. For our purposes it is sufficient to deal just with the velocity changes. (See J. W. Murdock, "Mechanics of Fluids," in Baumeister, Marks' Standard Handbook for Mechanical Engineers ,pp. 42-43.)

[2] Historic American Engineering Record (Patrick M. Malone), Selections From the Lowell Canal Survey (Washington, D.C.: Historical American Engineering Record, 1976) p. 5. (hereafter cited as HAER, Lowell Canal Survey). The later depth (10 feet) of the Pawtucket is the one given in U.S. Census, 10th Census, 1880, "Reports on the Water-Power of the United States," p. 79.

[3] Appleton, Introduction of the Power Loom, p. 19.

[4] On the size and success of Lowell in 1845 see Miles, Lowell, As It Was, And As It Is, p. 19.

[5] Francis Lowell Hydraulic Experiments, p. x.

[6] There are two accounts of Francis's reforms of the Lowell hydraulic system. Patrick M. Malone's survey of the Lowell canal system first appeared as Historic American Engineering Record, Selections From the Lowell Canal Survey (Washington, D.C.: Historical American Engineering Record, 1976), (hereafter cited as HAER, Lowell Canal Survey); this work was reprinted as, Patrick M. Malone, The Lowell Canal System (Lowell: Lowell Museum, 1976). An enlarged version of this study if contained in Patrick M. Malone and Larry D. Lankton," Water Power in Lowell, Massachusetts," Ms. submitted in support of H.R. 14689 to the Subcommittee on National Parks and Recreation of the House Committee on Interior and Insular Affairs, August 19, 1974. Another survey is in Hunter, Waterpower, pp. 205-227,

251-291. I have drawn from the works of both Malone and Lankton and that of Hunter in this chapter.

[7] U.S. Census, 10th Census, 1880, "Reports on the Water-Power of the United States," pp. xii, 78-81. See also Hunter, Waterpower, p. 212, table 9, p. 283. This gives the depth of the Pawtucket as 10 feet. The increase in depth had to be made incrementally, because the Pawtucket could not be closed off without halting production. It could be drained on Sundays and trash removed. Any significant reshaping of the canal had to be done bit by bit on Sundays.

[8] The 480 square feet cross sectional area was for the Pawtucket on the assumption that its dimensions approximated 60 by 8 feet. The 2,100 figure is based on the new canal, the Northern having dimensions of 100 feet wide by 15 feet deep with a cross section of 1500 feet. Francis enlarged the Pawtucket also. Its depth reported in 1880 was 10 feet. Hence the cross sectional area of the Pawtucket rose from about 480 square feet to about 600 square feet, for a total for both canals of 1500 + 600 + 2100

[9] Miles, Lowell, p. 59.

[10] Worthen, "James B. Francis," p. 235-236. H.A.E.R., Lowell Canal Survey. pp 9-15.

[11] The "friction head" is $v^2 / 2g$, where g is the gravitational constant. (See J. W. Murdock, "Mechanics of Fluids," in Baumeister, Marks' Standard Handbook for Mechanical Engineers ,p. 43.) Friction is a complex subject, and this calculation is an approximation at best, but it illustrates the general magnitudes involved. The difference in head (as between the Pawtucket and Northern canals) has also not been taken into account. Since the deepening of the Pawtucket had to be spaced out over time, the changing cross section by year has not been taken into account; even the final figure, 600 square feet, is approximate, since there were major inequalities in the breadth of the canal. Francis apparently removed some of the boulders that had produced narrows at places in the old canal, and gradually got a more rectangular section. The 1880 census gives no figure for breadth because of the many inequalities that remained even then. The flow was by no means constant, even though the mean low water flow had been increased. The flow at high water would have been considerably larger than 3593.9 cubic feet per second. Naturally, Francis in working out the detailed designs would take more factors into account than are noted here.

[12] Ibid., pp. 16-21 and figures 3 and 4.

[13] Malone, Lowell Canal System, pp 16-18. The less favored mills were best able to get water when it was at it highest, and suffered disproportionate losses when the head declined, as it had been doing in afternoons in periods of low water..

[14] These will be discussed in chapter 5, below.

[15] Quoted in Malone, Lowell Canal System, p. 15.

CHAPTER 4

Turbine Inventions

Improved Water Motors

Francis wanted to increase the efficiency of the water wheels used at Lowell. Though he began experiments on alternate water motors in 1844, he was very busy from 1845 to 1848 with the redesign of the canal system, and his friend and colleague, Uriah A. Boyden (1804-1879) had the honor of introducing the Fourneyron turbine (a French innovation) at Lowell. The arrival of the turbine inaugurated a period of intensive hydraulic experiments. Boyden made important improvements in the Fourneyron Turbine, both in its design and in developing improved methods of turbine testing. Francis assisted Boyden in his testing, and after 1848 he assumed full responsibility for designing and testing turbines at Lowell. Francis was creative and original, but in the case of turbines he clearly built upon foundations laid by Boyden.

The water wheels completed at Lowell from 1823 through 1844 were examples of craft-based technology. Paul Moody, who long survived Francis Lowell, had built large large breast waterwheels to power the the first Lowell mills. These were variations on the overshot waterwheel which received the water slightly below their highest point rather than at its crest. The breast was a curved housing within which the wheel was set which help prevent the loss of water through its lateral movement or splashing. These waterwheels were the final products of a long, craft-based evolution of traditional water wheels. They had an average efficiency of about 60 percent, which was high for a craft technology. The wasted 40 percent, however, left room for improvement by a science-based technology.[1]

The Tall Water Wheels

The first company, The Merrimack Company, was the only one to utilize the full fall of thirty-three feet. In building large water wheels more than 33 feet high, Moody pushed the traditional technology to (and perhaps beyond) its limits. A problem with overshot and breast waterwheels was that the wheels had to be as high or higher than the fall of water they sought to utilize. Smaller vertical waterwheels were easier to design and maintain, because they and the water they carried weighed much less. After it was realized that the tall waterwheels at the Merrimack mills were less than completely satisfactory, the company built new feeder canals which delivered water to two sets of mills, one higher than the other. The 33 foot fall was divided into two falls of 14 and 19 feet.

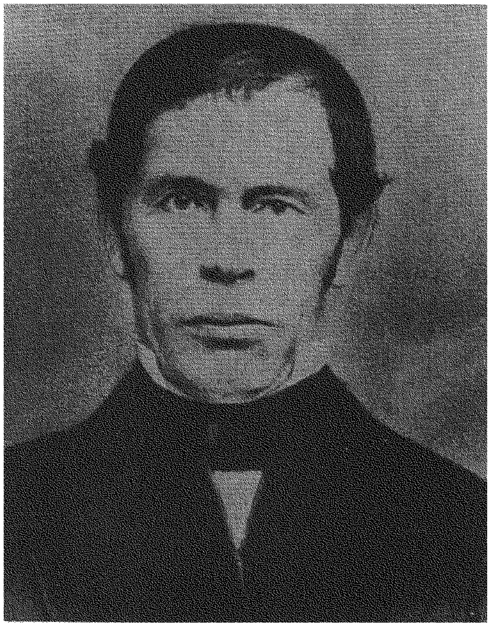
An additional problem came with high water when a rise in the downstream water level (called "backwater") could flood the wheel pits and bring the waterwheels to a stop. Thus another avenue of approach to the power shortage was to adopt water motors that would be less influenced by backwater, such as the "reaction wheels" invented in America.

In February 1844, Francis was making preparations for testing novel water motors. He built a model breast wheel and he tested it along with several of the reaction wheels then available in America.[2] Francis knew that American reaction wheels, while not very efficient, were able to work in backwater. He was well informed concerning European developments and he probably knew about the invention of "ideal" water motors called turbines in France.[3]

Turbines, like reaction wheels, were enclosed in water-tight cases and operated by the pressure of the water; their vanes therefore were not directly impeded by backwater as were those of traditional vertical wheels. The only loss for turbines in backwater was that due to the decrease in head caused by the rise in the downstream water level. Turbines had the added attraction of achieving efficiencies approaching 80 percent, about a third higher than that of breast water wheels and twice that of most reaction wheels (which typically achieved efficiencies of about 60 and 40 percent respectively).

Uriah Boyden, Turbines, and Reaction Wheels

Boyden's built his first turbine for the Appleton Company and completed it in 1844 and tested it in early 1845. It was an improved version of the turbine invented by Benoît Fourneyron in France. This first turbine was a small one which developed only 75 horsepower; it got an efficiency of 78 percent, about what Fourneyron got with his turbines. In 1846 Boyden designed three large turbines for the Appleton Company which produced 190 horsepower each at an efficiency of 82 percent. Subsequent Boyden turbines averaged about 86 percent efficiency. Boyden designed a large number of turbines used at Lowell and elsewhere in New England.



Courtesy of National Museum of American History, Smithsonian Inst.

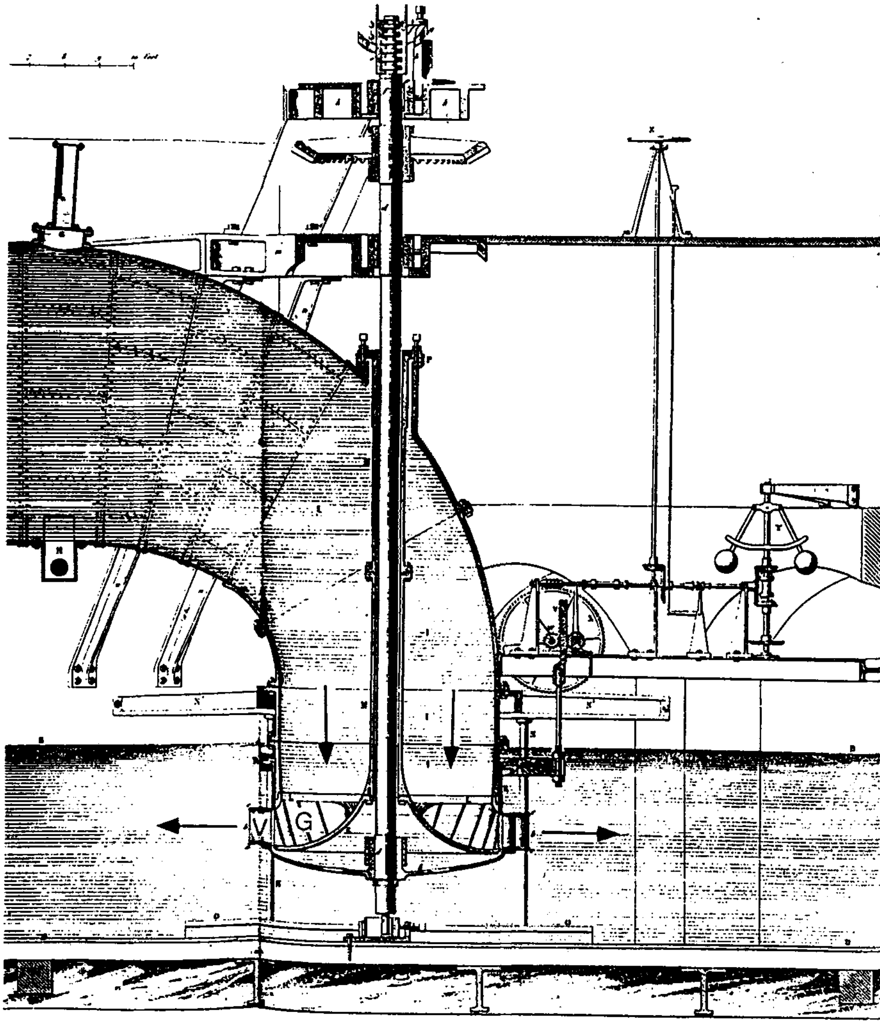
FIG. 8 – Uriah Atherton Boyden (1804-1879)

By 1848 Boyden turbines had proved themselves. On Francis's recommendation the Proprietors of Locks and Canals bought out the local right to Boyden's patents early in 1849, and then Francis undertook to design, build, and test turbines for the Lowell companies. His invention of the Francis turbine and his improvements in turbine testing, notably his weir formulas are probably the achievements for which Francis is best known today. The Lowell mills today stand as derelict reminders of the glories of a past industrial epoch, while improved Francis turbines are the most important water motors in the world today.[4]

To understand Francis's work on turbines, it is necessary first to understand Boyden's accomplishments. Although well versed in the European literature on the turbine, Boyden borrowed a number of important ideas from the American craftsmen who designed and built reaction wheels. A notable case in point was the scroll or scroll-casing. Because Boyden never acknowledged his indebtedness to others, Francis was not fully aware of just how much he owed to craft-based inventions.

An American Reaction Wheel by James Rumsey

The American reaction wheel was invented by James Rumsey (1743-1792), who improved upon European proposals for reaction mills and other devices utilizing the force of reaction.[5] His work was the basis of a very vigorous American tradition of reaction water wheels which usually converted less than 40 percent of the power potential of the water into useful work, thus being less efficient than the traditional breast waterwheels used at Lowell. But reaction



Francis, *Lowell Hydraulic Experiments*, plate V

FIG. 9 - Francis's Tremont turbine is a Boyden-Fourneyron outward flow turbine. Water flows down through the fixed guides (G) and out through the rotor vanes (V), thus causing rotation of the shaft.

wheels were very cheap and so they became in the early nineteenth century the most common form of water motor in a nation which lacked capital and had a surplus supply of water power.[6]

Although the craftsmen have had some important insights, improvements often depended upon rule of thumb or fortunate accidents. Two of the ablest reaction wheel improvers were the Ohio millwrights, Zebulon and Austin Parker, who invented a spiral duct (called a scroll) to conduct the water to their reaction wheel as a result of just such an accident, when a board happened to fall into their reaction wheel pit in such a manner as to give a rotary motion to the water approaching the wheel, a rotation that had the same direction of motion as that of the reaction wheel. The Parker's scroll was widely imitated; it sometimes increased the efficiency of reaction wheels to about 60 percent, but results were not always predictable.[7]

French Engineers: Borda and Carnot

The turbine, in contrast, was the product of deliberate efforts in France to make engineering scientific. It was, however, not simply an application of physical science to technology. Rather, the turbine emerged from efforts by engineers to develop their own theories, using experimental and theoretical methods inspired by the natural sciences. Among the methods used in these sciences were those of abstraction and idealization, whereby the scientist constructed a simplified model of a system based on an analysis of the essential factors influencing its operation.[8]

A French engineer Charles de Borda (1733-1799) developed a powerful model of a generalized water wheel in 1767. His emphasis was upon how water wheels lost energy rather than how the water transferred energy to the water wheel. His work was continued, extended, and popularized by another French engineer, Lazare Carnot (1753-1823). The work of Borda and Carnot led to the discovery of three conditions needed for the highest efficiency which were clarified and stated clearly by Carnot as: (1) entrance without shock, (2) exit with minimum velocity, and (3) operation with least possible friction.[9]

It was clear to Borda and Carnot that water wheels (such as the undershot wheel) lost much power through the impact or "shock" of the stream of water upon the vane of the water wheel. "Shock" was a sudden change in velocity leading to a loss in the energy communicated by the water to the vane of a water wheel.[10] A second loss came when the water left the wheel with an appreciable velocity, the principle loss in overshot and breast waterwheels, such as the ones used at Lowell. These still had higher efficiency compared with undershot wheels because there was much less shock at entrance. But they could not increase their efficiency much above 60 percent without losing unacceptable amounts of power by being slowed down. (They approached 100 percent efficiency as the power output and velocity approached zero.)

The New Physics of Energy

The ideas of Borda and Carnot were not immediately accepted. This may appear puzzling from our modern perspective. We take the concept of energy for granted. In terms of energy, the conditions for ideal operation of a water motor amounted to saying that energy losses should be eliminated or cut to a minimum. This is a truism. But this is only the case in the framework of the concept of energy and certain correlates, such as work, power, and energy conservation. None of these ideas had been formulated when Borda and Carnot wrote. Since their ideas appeared to be in conflict with the existing consensus in science, they were rejected.

It was not until after 1820 that the concepts of energy and its correlates were formulated and widely accepted. Borda and Carnot, though not without scientific interests, were primarily engineers guided by the desire to design more efficient water wheels. Thus, they were led to reject the prevailing scientific orthodoxy. Their contributions to the scientific revolution associated with energy were therefore indirect. The physics of energy was formulated by a number of leading scientists, notably William Thomson (Lord Kelvin) (1824-1907), perhaps the most important pioneer in this area. Other physical scientists made important contributions. Hermann von Helmholtz (1821-1894) helped establish the doctrine of the conservation of energy, and Rudolph Clausius (1822-1888) coined the terms "energy" and "entropy." In this as in many cases in the history of technology, the attempt to develop improved artifacts has contributed to important new concepts in basic physics.[11]

Tangent Entry of Water

As the concepts of energy, work, and power were clarified, engineers began to think about how to realize Borda's and Carnot's conditions for an "ideal" water motor. In the case of entrance without shock, the basic solution was obvious and expressed by several engineers; to minimize shock at entrance the water would enter parallel to (or tangent to) the moving vanes of the water motor. This, however, left unsolved the fundamental design problem of how to achieve tangent entry in a real water motor.

Similarly, the early experience with reaction mills of various sorts suggested how exit with minimal velocity might be achieved. In reaction wheels the water was discharged in a direction opposite to the motion. Clearly, if the velocities were the same and tangent to the wheel, but opposite in direction, then the two velocities would cancel out, and water would have no absolute velocity at exit. But though reaction wheels suggested this strategy, their designers did not know how to realize this condition to a reasonable approximation in a real water motor, nor was it immediately obvious how the friction associated with turbines might be substantially reduced.[12]

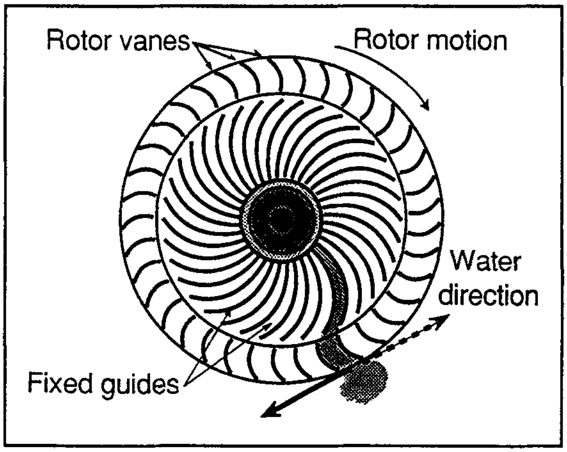


FIG. 10 – In the ideal case the water should leave the turbine in a direction tangent to the wheel motion, but in the opposite direction. If the velocity of the water is equal to the tangential speed of the rotor, but in the opposite direction, the two cancel out with no loss in energy.

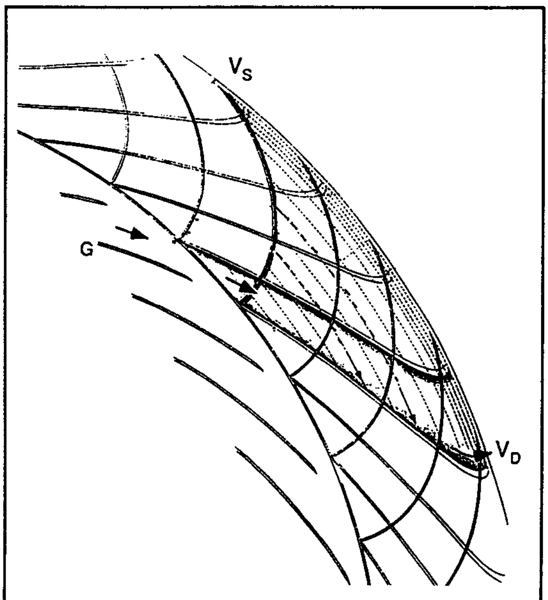
Though the theory of Borda and Carnot did not tell engineers how the conditions of an ideal motor might be achieved, it led engineers to ask the right questions. Understanding the conditions of maximum efficiency gave French engineers clearly defined criteria which allowed them to design an ideal water motor. The term "turbine" came, for a time, to mean such ideal water motors incorporating the criteria of Borda and Carnot in their design.[13]

The Fourneyron Turbine — An Early Standard

Benoît Fourneyron's turbine became the most widely used turbine (in the sense of an ideal water motor) in America, prior to the maturing of the Francis turbine in the 1860s and after. Fourneyron's analysis of the problem was more elegant and more successful than that of other, earlier turbine designers. He was also an outstanding practical designer, so that he was able to embody his theoretical insights into a very useful, working design of a device that diffused rapidly though France and Europe in the 1830s and, by the 1840s, to America as well.[14]

The most critical problem that Fourneyron solved was that of entrance without shock. Though tangent entry of the water with respect to the moving rotor vanes was clearly the key, the problem remained, however, how to realize this in an actual design. We can think of this as two problems: first, how to direct the water at a predetermined angle, and second, how to determine the angle for tangent entry of the water into the rapidly rotating rotor vanes. Fourneyron introduced fixed guide vanes which determined the angle of the water entering the rotor of the turbine. Fourneyron arranged his turbine with the guides at the bottom of a vertical penstock (an iron pipe used to admit water). The rotor vanes were located circumferentially around these guides, and there was a small gap between the guides and the rotor to allow the rotor (or "runner") to move freely without touching the fixed guides (see FIG. 10).

Fourneyron then solved the problem of determining the angle of the guides that would direct the water flow at an angle tangent to the moving rotor. If the vanes did not rotate, determining the angle of tangent entry would be simple. The problem was difficult precisely because the rotor did move. This rotation caused successive points along the rotor to move in a circular direction in successive small intervals of time, thus changing the angle of tangent entry for water moving through the guides into the moving rotor vanes. Fourneyron found a mathematical formula which told him how to determine theoretically the necessary angles of guide vanes for tangent entry into a rotor of any given rotary speed and size. Boyden and Francis used Fourneyron's formula, but they also determined the angle of tangent entry and in addition, the shape of the water's path through the rotor by simple geometric methods, based upon their calculation of the size and speed of the rotor (see FIG. 11). Fourneyron also found a mathematical formula



adapted from: Francis, *Lowell Hydraulic Experiments*, plate VI

FIG. 11 – Tangent entry of water the Tremont turbine was accomplished by Francis's graphical method. Starting with a static rotor vane V_s, and allowing for its rotation, Francis was able to plot the dynamic shape of of moving vane V_d. The guide (G) could then be shaped to make a straight line flow tangent to the moving rotor vane V_d.

for the problem of exit with minimal velocity, that is, for directing the water at exit in a direction contrary to that of the turbine rotor's motion and approximately tangent to the outer circumference of the turbine. Fourenyron's design methods did not allow him to approach this ideal situation very closely, and excess velocity at exit was a source of significant loss of energy and hence of efficiency for the Fourneyron turbine.[15]

These advances allowed Fourneyron to approximate the conditions of Borda and Carnot. His theory treated the turbine as a "black box." He assumed that if he could control the angles of entrance and exit that he could ignore the precise geometry of the vanes, so long as they described smooth curves and there were no sharp bends. Fourneyron's three-part monograph on his turbine which he published in 1834 became a classic upon which almost all subsequent work on turbines was founded.[16] Several efforts were made to import turbines into America, particularly by Ellwood Morris of Philadelphia, who published the results of his tests upon turbines.[17]

$200 for Each Percentage Point Improvement

Uriah Boyden read Fourneyron's papers and all other extant literature on turbines before he built the first turbine at Lowell in 1844. He was able to make some significant improvements in Fourneyron's original design. His turbines were costly; he spared no expense in increasing their efficiency. He cannily drafted an agreement with the Appleton and other companies by which he received a substantial fixed fee, plus $200 for each percentage point of efficiency over 78 percent. Boyden had perfected his design by about 1848, thereafter his turbines usually got efficiencies in the range of about 85 to 88 percent.[18]

Boyden claimed to have achieved 93 percent efficiency for a turbine designed and built for the Atlantic Cotton Mills at Lawrence, near Lowell. The owners claimed that this was too much, and the turbine was then tested with great care by James B. Francis in 1854, who used his own more accurate weir formula in order to determine that the efficiency was actually 88 percent. This was unusually high for Boyden, but reflected steady improvements in Boyden's design methods. Boyden's ability to improve the efficiency of his versions of the Fourneyron turbine from 78 percent in 1845 to 82 percent in 1846, and finally to an average of 86 percent after about 1848 was a remarkable achievement.[19]

There can be no doubt that Boyden had a very deep understanding of turbine design, an understanding which he was, however, somewhat reluctant to part with. Boyden was secretive and never published any of his turbine discoveries. He was obliged to share his knowledge of his turbine with Francis by the terms of the purchase agreement reached with the proprietors of Locks and Canals in 1849.[20] But he provided the absolute minimum he felt necessary. Francis had to infer Boyden's rules for constructing turbines from the actual turbines.[21]

Boyden, however, liked Francis and enjoyed dropping him occasional hints. He was generous in providing critiques of Francis's plans for turbines. On January 14, 1854, Francis asked Boyden's opinion of a turbine he was designing. Francis made a note on the conversation: "Mr. Boyden remarked 'and this,' he says, 'is one of the secrets of the art.'" What Boyden then told Francis was that the turbine blades should be so designed that the water "in passing through the wheel, moves more rapidly on the [one] side [of the vane] than on the [other]."[22] This was a critical insight and one that was not widely appreciated by engineers until after the invention of the airplane when the remarkable similarity of a turbine blade to an airfoil was made manifest.

Flow Like an Airplane Wing

The vanes of a turbine are like the wing of an airplane, in which the air travels faster on the top, more curved, side of the wing than on the bottom, more linear, side. The result is a difference in pressure which produces lift on the wing. This follows from the Bernoulli theorem, whereby, to conserve energy in a streamline, an increase in kinetic energy (velocity) must be accompanied by a decrease in the energy involved in producing pressure.[23] So higher speed means lower pressure, and lower speed higher pressure.

Turbine vanes are geometrically more complex than aircraft wings, but they operate very much like airfoils in that differences in pressure on opposite sides of turbine vanes caused the rotation and the power of the turbine. In 1856 Boyden revealed to Francis (as part of his dispute with the Atlantic Cotton Mills) that in his design methodology he routinely calculated the pressure exerted by the water as it moved inch-by-inch along the vanes; that is he calculated the pressure on both sides every few inches and by subtraction determined the pressure exerted at each point.[24]

Fourneyron's turbine was called a reaction turbine, because it acts according to Newton's third law of motion.[25] As the work of Borda, Carnot, and Boyden demonstrated, this may be true, but it is not very helpful for the designer of turbines. An accurate physics description of how an engineering artifact works does not always capture those things that are most critical for design. Scientific explanations left out such things as the angles of entrance and exit of turbines, and the way pressure is exerted on turbine vanes and all of those insights that were later codified in aeronautics and then applied retrospectively to turbines.

These latter insights were the products of engineering research, research which aimed at an understanding of how to design engineering artifacts, and in this case the design approach led engineers such as Boyden to anticipate the modern treatment of turbine vanes as similar to airfoils and, in modern times, to use aeronautical terms, such as "lift" and "drag" in analyzing them.[26]

Boyden might have produced a turbine theory of considerable value. (He was asked to produce such a paper by the editors of a leading technical encyclopedia.) He failed to do so. He was reluctant to publish his discoveries. One reason for this was that he was hampered by his excessive distrust of all mathematical theory. Boyden's skepticism seems to have reinforced Francis's own prejudices against theory. To Boyden (as to Francis) the only valid scientific understanding must come from observation and experiments involving observation. In a remarkable passage in his private papers, Boyden wrote:

> Unlike most other machines, [turbines] operation, that is, the acting of the water in the wheels is done out of sight, and there seems to be no means of comprehending the cause of a failure, but by such abstruse investigations as caused such men as Sir Isaac Newton and Leonard [sic] Euler to fall into great absurdities.[27]

Because of his extreme skepticism Boyden missed a great deal that he might have learned from both Newton and Euler. When modern turbine theory was developed in Germany in the early twentieth century it was built around Euler's theory, for example.[28]

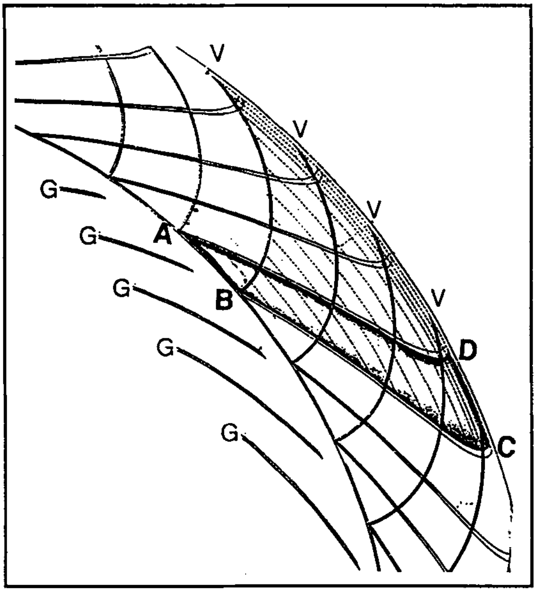
Lubricated Bearings

Despite blind spots, Boyden's improvements in the Fourneyron turbine were remarkable. Boyden's sought, for example, to reduce friction effects, one of the issues which Fourneyron had failed to address adequately.[29] Fourneyron's turbines rested upon a lubricated bearing upon which the shaft of the turbine moved. The bearing was constantly under water, and adequate lubrication was difficult.

One of Boyden's improvements was a novel system of suspending the turbine from above, eliminating the immersion of the bearing, thus avoiding a major source of corrosion and allowing regular lubrication and maintenance. Boyden reduced the friction in the bearing dramatically. He gave his suspended bearing a novel shape: it consisted of a number of circular flanges or collars (often seven) projecting from the shaft. These moved in grooves in the supporting bearing, which was coating with a low-friction metal. This arrangement reduced friction by increasing the bearing surface area and making frequent servicing easy. Boyden also made all internal passages as smooth as possible, for example eliminating projecting bolts or rivets by using flush rivets or bolts.[30]

Boyden and Francis had a qualitative understanding of the flow of water that was far ahead of their time. They understood that water (and other fluids) flows in thin layers and when this smooth flow (now called "laminar flow") was disturbed this smooth flow could change to turbulent flow (in which the water ceased to flow in parallel layers and broke into circular eddies, a change that reduced the work that the water could do). In order to avoid disturbing the water, Boyden used a method of tracing out the absolute path of the water (that is its path relative to the ground) as it flowed through a turbine in two dimensions. Boyden apparently got the idea from the Parker brothers. The basic idea of tracing out the absolute path of water in a water motor was published by an American critic of James Rumsey, William Waring. It is likely that Waring's idea was the source of this idea in the American tradition of the reaction wheel.[31]

Some of Boyden's most original turbine improvements were apparently suggested by his application of the Bernoulli theorem to the graphical plots of the absolute path of the water in passing through a turbine. This was the source of Boyden's insight that velocity differences on the opposite sides of a turbine vane caused the pressure on the vane that explained how turbines work. He saw that by altering the geometry of the absolute path of the water (which he could do in the design of the turbine vanes), he could control the pressure of the water on the vanes and velocity of the water in his turbines.



adapted from: Francis, *Lowell Hydraulic Experiments*, plate VI

FIG. 12 – Absolute path of water for a Francis's Tremont turbine, a Boyden-Fourneyron type outward flow turbine. Water enters at A-B with the rotor moving and exits at D-C, following a nearly straight flow path.

Boyden (and following him, Francis) used these insights in order to design turbines in which the absolute path of the water was very nearly straight (see FIG. 12) over most of its path and in which the speed changed uniformly while the water exerted a constant pressure on the turbine vanes. They realized that any bending of the stream of water or any sudden change in velocity tended to produce turbulent flow with a significant loss of power due to the random motions of the water. In these and other insights, Boyden and Francis anticipated some important insights of the modern science of fluid mechanics and the modern art of turbine design.[32]

The application of the Bernoulli theorem to the plot of the absolute path of the water led Boyden to a fundamental invention, the diffuser. It was well known that water speeds up in a converging nozzle, such as that on a garden hose. Boyden exploited the converse effect, that water tends to slow down when moving through a diverging passage. One of the most persistent sources of energy losses in turbines was the excess velocity of the water at exit. Boyden fixed a device to the outlet of his turbines which created a diverging channel through which the water flowed after leaving the turbine rotor. This device, the diffuser, served to reduce the excess velocity of the water at exit, thus reducing enery loss and increasing efficiency. This idea was so new that the commissioner of patents claimed that the term "diffuser is not a technical term as applied to water wheels," and at first refused to grant Boyden's patent.[33]

Accelerated Spiral Motion

Boyden's careful attention to the patent literature led him to invent a cup-shaped Penstock to give the water an accelerating spiral motion prior to its entrance into the guides. This was a version of the scroll invented previously by Austin and Zebulon Parker. Boyden's scroll produced a spiral motion in the water and thus prevented (or limited) shock produced by the impact of the water with the guides. Boyden also bent the leading edge of the guides to be approximately parallel to the flow of the water entering the guide vanes, the further to facilitate a smooth flow of the water and eliminate shock. Boyden's scroll was a more effective use of the principle of the scroll than that of the Parker brothers' who used the scroll as a substitute for guide vanes. They failed to realize that the best effects are achieved when both the scroll and guide vanes were used together.[34]

REFERENCES

[1] The chief rivals to overshot and breast wheels were undershot water wheels (vertical wheels in which the water impinged upon the wheel at its base) and "tub mills" (horizontal water wheels mounted in a cylindrical wooden housing to prevent the loss of water). Few undershot wheels got over 30 percent efficiency, and tub wheels seldom did better than about half this (or about 15 percent).

[2] On the work of Fourneyron and Boyden see below. Francis had a special breast wheel built by the Lowell machine shops and he tested this water wheel on February 28, 1844. He tested other water wheels using a Prony Dynamometer on March 10 and 12, 1844. Francis had been collecting advertising and other descriptions of patent reaction wheels, and he tested one of them "Dummers Wheel" in late March and April of 1844. On the design and testing of this breast wheel, see "Table Showing the Speed of the Extremity...of the Machine Shop Water Wheel," (memo with tabulated test results and diagram), February 28, 1844, and the summary, titled, "Summary of the Experiments on the preceding pages, made at Lowell, Mass., in 1844 on the Breast wheel in the Machine Shop of the Proprietors of Locks and Canals," (otherwise undated), and "Experiments on Drummer's Wheel," March 31, 1844, Records 1837-65," notebook A, Francis Engineering Papers.

[3] The term "turbine" has gone through a variety of meanings. It is from the Latin word for "top," and turbines are indeed much faster than traditional water wheels. As initially used by Claude Burdin its primary meaning was a very rapidly rotating water motor of high efficiency. The term "turbine" was used by Fourneyron and others to mean an "ideal" (e.g., one of the highest possible efficiency), based on the theoretical studies of Charles de Borda and Lazare Carnot (discussed in the text). In France the term was soon applied to any water wheel with a vertical axis (and a horizontal wheel). This usage was never applied in America where reaction wheels could have either a horizontal or a vertical axis. The term "turbine" has lost its meaning of an "ideal" or highly efficient water motor. The term "turbine" is now seen as any motor which operates by the "dynamical" effects (e.g., changes in velocity ,volume, and pressure) of a fluid (which might be steam or burning gases in the case of a jet plane). Turbines are seen as part of a broad category of machines, "turbomachines," which are all machines that operate by continuous rotation. The opposite of a modern turbine is a piston engine working by positive displacement.

[4] In his own lifetime Francis was best known for his redesign of the Lowell hydraulic system. The Francis turbine is not mentioned in his principal memorial biography

prepared by three former presidents of the American Society of Civil Engineers (See Green, Adams, and Worthen, "James Bicheno Francis.") Green et al. emphasize his hydraulic work at Lowell and elsewhere; they mention, for example, his method of operating head gates by means of screws, the nuts of which were driven by a turbine (p. 75). One of the three authors of this biography, William E. Worthen, had been a hydraulic engineer at Lowell when Francis shifted from the machine shop to the hydraulic works in 1837. Worthen, a long-time friend of Francis, wrote a longer and much more detailed biography of Francis, which mentioned (in less than a page) his work in the introduction and testing of turbines, but did not note the Francis design of turbine (the Francis Turbine). See Worthen, "Life and Works of James B. Francis," pp. 227-241 (p. 233).

[5] Edwin T. Layton Jr., "James Rumsey, Pioneer Technologist," West Virginia History, 48 (1989), pp. 25-32.

[6] "Hydraulics," Scientific American, 6 (April 26, 1851): 256. See also Edwin T. Layton Jr,"The Most Original," American Heritage of Invention and Technology, 2 (Spring 1987): 53-56.

[7] Edwin T. Layton Jr., "Millwrights and Engineers: Science, Social Roles, and the Evolution of the Turbine in America," in Wolfgang Krohn, Edwin T. Layton Jr., and Peter Weingart, eds., The Dynamics of Science and Technology (Dordrecht, Holland: Reidel Publishing Company, Sociology of the Sciences, Yearbook no. 2, 1978), pp. 66-67.

[8] Layton, Jr., "Mirror Image Twins," pp. 562-80. Galileo constructed an early example of an idealized model of a technical situation (the flow of a river, in the context of flood control). Galileo represented the flow of water in a river by a mental model of balls rolling down an inclined plane. (See Richard Westfall, "Floods along the Biscenzio: Science and Technology in the Age of Galileo," Technology and Culture, 30 [October 1989], pp. 879-907.)

[9] Carnot held that "...the means of producing the greatest effect... is not to apply a wheel whose blades receive the impact of the fluid. In fact two good reasons prevent us from producing the greatest effects in this way: the first is ... because it is essential to avoid all percussion whatever; the second is, because after the impact of the fluid there is still a velocity which it retains and it is a pure loss ... In order to make the most perfect hydraulic machine ... the true knot of difficulty lies therefore, first, in making it so that the fluid loses absolutely all its movements by its action upon the machine or at least that it retains only precisely the quantity necessary for escaping after its action; second, in making it lose all of its movements by insensible degrees, and without percussion...the form of the machine would be of little consequence; for a hydraulic machine which fulfills these two conditions will always produce the greatest effect." (see Ibid., p. 241). Elsewhere Carnot noted the importance of friction effects. Quoted in Terry S. Reynolds, Stronger than a Hundred Men, A History of the Vertical Water Wheel (Baltimore: Johns Hopkins University Press, 1983): 241.

[10] Shock produces turbulence, the situation where the water moves in all directions more or less randomly; clearly for power purposes it is best if the particles of water all move parallel to the direction of the motion of the stream. Other losses associated with "shock" were inelastic collision, and splashing. In inelastic collision the kinetic energy is transformed into heat energy. Splashing, in an open water wheel of traditional type, causes some of the water to leave the wheel, while carrying an appreciable amount of energy in its motion.

[11] Donald S. L. Cardwell, "Some Factors in the Early Development of the Concepts of Power, Work, and Energy," British Journal for the History of Science, 3 (June 1967), pp. 209-224, who emphasizes the role that the work on the turbine (and other prime movers) led French engineers to formulate the modern scientific concepts of work, energy, and power. This is a dramatic example of technology influencing basic science. For an overview of the interplay of science and technology in the energy revolution, see Donald S. L. Cardwell, From Watt to Clausius, the Rise of Thermodynamics in the Early Industrial Age (Ithaca: Cornell University Press, 1971), in which the role of the steam engine and its technology in producing a scientific revolution are emphasized.

[13] In modern times "turbine" had changed its meaning; now a turbine is any prime mover that operates by continuous rotary motion.

[14] Norman A. Smith, "The Origin of the Water Turbine and the Invention of Its Name," History of Technology, 2 (1977), pp. 215-259.

[15] There were several versions of this formula in use at the time of the invention of the Francis Turbine. The ones employed most frequently for the Fourneyron type turbine can be found in modern texts expressed in terms of velocity triangles and vector analysis, methods we will not use. Students with the necessary background might wish to examine the mathematical conditions of of entrance and exit as presented in modern texts, such as Robert L. Daugherty and Joseph B. Franzini, Fluid Mechanics With Engineering Applications (New York: McGraw-Hill, seventh edition, 1977), pp.156-159, 489-490 figure 6.10.

[16] Benoît Fourneyron, " Mémoire sur l'application en grand, dans les usines et manufactures, des turbines hydrauliques ou roues á palettes courbes de Bélidore," Bulletin de la société d'encouragement pour l'industrie nationale, 33 (January 1834): pp. 4-17, (February 1834): pp. 49-61, (March 1834): pp. 85-94.

[17] Ellwood Morris, "Remarks on Reaction Water Wheels Used in the United States and on the Turbine of M. Fourneyron," Journal of the Franklin Institute, 3rd ser., 4 (November 1842): 289-304, and the same author's "Experiments on the Useful Effect of Turbines in the United States," Journal of the Franklin Institute, 3rd ser., 6 (December 1843): 377-379. Morris found efficiencies for reaction wheels of less than 40 percent. Fourneyron and following him Morris used a weir formula that underestimated the input of water, and hence made claims to higher efficiencies than were warranted. It is not certain whether Boyden used the same weir formula, but his work too had to be corrected using the more accurate weir formula of James B. Francis (see below).

[18] Francis, Lowell Hydraulic Experiments, pp. 2-3. Boyden claimed to average 86 percent efficiency for his later turbines..

[19] The best source is Francis, Lowell Hydraulic Experiments. Francis was very careful to give Boyden full credit for all his inventions. Useful secondary accounts may be found in Arthur T. Safford and Edward Pierce Hamilton, "The American Mixed-Flow Turbine and its Setting," Transactions of the American Society of Civil Engineers, 85 (1922): 1251-1255, and John R. Freeman, "General Review of Current Practice in Water Power Production in America," The Transactions of the First World Power Conference, 5 vols (London: Percy Lund Humphries,n.d.[1924]) vol. 2, pp.376-378. and Edwin T. Layton Jr., "Scientific Technology, 1945–1900: The Hydraulic Turbine and the Origins of American Industrial Research," Technology and Culture, 20 (January, 1979), pp. 64-89. On the disputed turbines for the Atlantic Cotton Mills, see below.

[20] James B. Francis, memorandum, December 1, 1848, volume A-19, file 96, Proprietors of Locks and Canals Papers. It should be noted that the superior efficiency was not the only advantage. All traditional water wheels can be brought to a halt by an increase in the downstream water level (usually called "backwater"). This had been a chronic problem at Lowell as elsewhere in periods of high water. The turbine, as a pressure engine enclosed in a metal casing continued to operate when under water (there was a small loss in power due to the shorter head). In addition the turbine also provided more uniform power than breast wheels and they were much more compact.

[21] Francis, Lowell Hydraulic Experiments, p. 44.

[22] James B. Francis Memorandum, January 14, 1854, volume 18, file 96, "Turbines," Proprietors of Locks and Canals Papers.

[23] The Bernoulli theorem for a frictionless, incompressible fluid takes the form $p/w + z + V^2/2g$ = constant, Where p is fluid pressure (e.g. lb/ft^2), s stands for specific weight (e.g., $lb./ft^3$.), w is elevation above an arbitrary plane, and g is the gravitational acceleration (=32.2 feet per second). It assumes that energy is conserved in a streamline. If there is no change in elevation, then an increase in pressure will produce a decrease in velocity and an increase in velocity will produce a decrease in pressure.

[24] [Uriah A. Boyden], "Process of obtaining the equations for computing the numbers...of the Atlantic Cotton Mills," January 31, 1856. Boyden had to provide this data because Francis was appointed by the court to test the turbine to settle a legal dispute between Boyden and the Atlantic Cotton Mills.The memorandum begins, "The numbers in the thirty-fifth column represent comparatively, estimated differences of pressures of the water on opposite sides of the floats" (Boyden called the vanes "floats") (Vol. A-4, Proprietors of Locks and Canals Papers). Boyden did not use this to calculate the power of a turbine, but to proportion the vanes so that the pressure (and the velocity) changed in a uniform manner, to minimize any disturbance that might produce turbulent flow with consequent loss of power.

[25] Newton's third law of motion was, "To every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts." (Quoted in Isaac Newton, Mathematical Principles of Natural Philosophy, 2 volumes, translated into English by Andrew Motte in 1729, with further revision by Florian Cajori [Berkeley: University of California Press, 1962], I, p. 13).

[26] See for example Dennis. G. Shepherd, Principles of Turbomachinery (New York: Macmillan, 1956), pp. 151-219. The analogies between flight and turbines did not become widely known until the early twentieth century. See for example: Bruno Eck, "The Characteristic Coefficients for Hydraulic Machinery," Mechanical Engineering, 49 (May 1927): 518-520. Rumsey's early reaction wheels were improvements in "Barker's Mill" a device similar to common rotary lawn sprinklers. In these devices the water "reacts" at its exit, so that the more power, the greater the velocity of exit. Such devices are inherently inefficient, since they cannot approximate the condition of exit with minimal velocity. That is why they make good lawn sprinklers: the excess kinetic energy in the water at discharge serves the useful purpose of spreading it over a wide area. To lump these devices with vaned turbines is scientifically correct, in that both use the force of reaction, but they use it in different ways, and the detailed mechanisms of their operation, which designers need to know, are not illuminated by treating both as reaction turbines (in the modern sense of "turbine" as any rotary power source).

[27] "Article on Turbines written for the 'American Cabinet,'"n.d. Papers of Uriah Atherton Boyden, National Museum of American History, Smithsonian Institution, Washington, D.C. The sort of "absurdities" was not specified in this paper, but in his translation of a paper by Euler he was critical of what he considered excessive idealization and abstraction. Both are essential for the development of any mathematical theory.

[28] See for example the modern use of the Euler turbine equation in modern textbooks such as Shepherd, Principles of Turbomachinery pp. 49-61, 65, 125, 196, 282.

[30] Francis, Lowell Hydraulic Experiments, pp. 5-6 and plate 1,e.

[31] William Waring, "Investigation of the Power of Dr. Barker's Mill, as improved by James Rumsey, with a description of the Mill," Transactions of the American Philosophical Society, 3 (1793), plate 4, figure 3. On the Parker brothers, see Edwin T. Layton, "Millwrights and Engineers," in Wolfgang Krohn, Edwin Layton, and Peter Weingart, eds., The Dynamics of Science and Technology (Dordrecht, Holland, 1978), pp. 62-81.

[32] Francis, Lowell Hydraulic Experiments, plate VI.

[33] On the Bernoulli theorem and the diffuser, see Daugherty and Franzini, Fluid Mechanics, pp. 86-87, 223-226, 482-484. On Boyden and the patent commissioner see Edmund Burke to James Buchanan, May 22, 1847, copy, with other patent correspondence in "Letters Received, 1840-1849," Boyden Papers.

[34] Ibid., pp. 3-4. On the Parker brothers' scroll see Layton, "Millwrights and Engineers," pp. 62-63, 66-67.

CHAPTER 5

Hydraulic Experiments

An Empirical Investigation

Francis gained world fame as a result of his efforts to make engineering practice rest upon exact, experimental data. In all of his hydraulic studies, Francis showed a strong bias toward direct empirical measurement and a deep-seated skepticism of all mathematical theory. As Francis later wrote to a younger engineer,"I fear I have a habit of doubting purely theoretical deduction in an unreasonable degree."[1]

An example of Francis's experimental methods was his research on Boyden's diffuser. Francis was intrigued by this novel and useful device, and he incorporated it in some of the turbines he designed for Lowell companies. He did a series of experimental investigations of Boyden's diffuser. The behavior of the diffuser depended upon a mathematical theory, the Bernoulli theorem. Quite characteristically, Francis avoided the usual mathematical expressions of the Bernoulli theorem, and he found ways of conducting his investigation in an entirely empirical manner.[2] He went back to Bernoulli's own original formulation which had been purely verbal, ignoring the mathematical and theoretical development of Bernoulli's ideas by Leonhard Euler and others. He showed, by experiment, that Boyden's diffusers added to the effective head. (That is the excess velocity which the diffuser checked, could be seen as a savings in the head by the amount needed to produce the velocity saved.)

Francis's experiments revealed that Boyden's diffuser added about 3 percent to the power and efficiency of Boyden's turbines. Francis used his knowledge of diverging underwater tubes to design diffusers for four large 700 horsepower turbines he designed for the Merrimack Company. Such powerful turbines were possible at the Merrimack Company because it was the only one to use the full 33 feet of head available at Lowell; even so these were very large turbines, with a diameter of 104.25 inches. The fact that a single

Lowell company used in excess of 2,800 horsepower was eloquent testimony of how power-intensive the Lowell factories had become.[3]

Turbine Testing with the Prony Dynamometer

It is almost impossible to overstate the importance of precise measuring instruments in the rise of modern engineering. Measuring devices were needed to determine accurately those things that were most important in creating a rational basis for the design and operation of all manner of engineering artifacts. For power sources (or prime movers) of all sorts it was crucial to determine how much power they actually produced. One of the most important measuring instruments for prime movers was the dynamometer, which measures the output of power from any prime mover.

One of the most important dynamometers, particularly for water motors, was the dynamometer invented by a distinguished French engineer, Gaspard F. C. Riche de Prony (1755-1839); Prony developed it in 1826 and used it to test Fourneyron's turbine in 1833.[4]

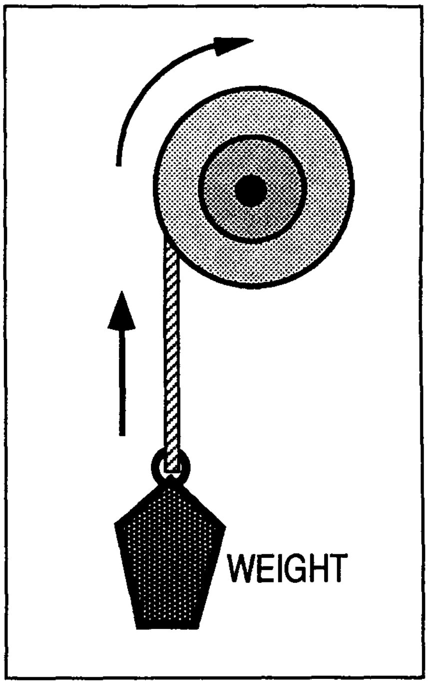


FIG. 13– Rate of doing work is similar to the functioning of the Prony dynamometer

The operation of the Prony dynamometer is analogous to a shaft which can lift weights by means of a rope which winds itself around the shaft (see FIG. 13). The thing to be measured is power, that is, the rate of doing work. If we attach a weight to the free end of the rope and allow the shaft to lift the weight by its rotation, its rotary power P_r is the product of the downward force of the weight T and the velocity by which this weight is lifted V_r. This situation is similar to that expressed by the fourth formula from the first chapter:

$$P_r = V_r T \qquad (4)$$

The Prony dynamometer operated by converting the power of a machine into friction and measuring the amount of friction. The Prony dynamometer consisted of a friction brake attached to a lever arm. The brake could be pressed tightly on an iron wheel fixed to the shaft of the turbine, converting the rotary power of the shaft into friction (see FIG. 14). It measured the friction by a method analogous to weighing something in a scale (like those used to weigh patients in doctor's offices). That is the pressure of the brake on the wheel attached to the shaft of the turbine was counterbalanced by weights at the end of a lever arm. This pressure of the brake on the wheel was equivalent to the power output of the turbine. The Prony dynamometer was very simple in principle, but very difficult to use accurately, a problem which Boyden and Francis both addressed.

Turbine Testing by Boyden

Uriah A. Boyden not only designed the first turbine at Lowell in 1844, but, assisted by Francis, he tested it with a Prony dynamometer in January and February, 1845. He continued to test all of his turbines, and he carried turbine testing to new heights. Francis picked up turbine testing where Boyden left it. He continued to improve the methods and apparatus used, but he was always careful to give Boyden credit for his innovations in testing as in turbine design.

Boyden borrowed some of his testing ideas from the same American millwrights who had invented the scroll, the Parker brothers. They had done much to improve the accuracy and ease of using the Prony dynamometer. The intense mechanical vibrations produced when the friction brake pressed tightly against the metal ring mounted on the shaft of the turbine made accurate measurement difficult. The Parker brothers mitigated the problem of dynamometer vibrations by attaching a device called a "dash pot" to the lever arm.

The dash pot, a perforated piston mounted in a water-filled cylinder, served to dampen the vibrations of the lever arm. Boyden used the same device in his own turbine testing. In turn James B. Francis borrowed the idea from Boyden, without being aware of its origins. Boyden almost never gave credit for ideas that he borrowed, in sharp contrast to Francis, who took painstaking care to acknowledge the source of his ideas.

Boyden made at least two contributions to turbine testing that were apparently his own inventions. To eliminate the errors in making measurements he employed several observers, each making frequent observations of just one instrument. Francis was one of the observers in Boyden's early tests. The use of multiple observers helped cancel out inevitable small errors. Francis followed Boyden's practice to minimize observational errors, though this increased the costs of testing.

Boyden's Hook Gauge

Boyden's most important contribution to turbine testing, however, was his hook gage. The depth of water was one of the most fundamental variables in all hydraulic experiments. The problem with measuring the depth of water with a graduated rule or rod was that capillary effects due to the surface tension of water (which cause water to rise in narrow tubes) distort the measurements. Boyden had the idea of using a hook to measure the depth of the water from below its surface, avoiding most of the capillary distortion. The gage consisted of a scale with a vernier caliper attached to a rod with a hook at the end. Francis called Boyden's hook gauge, "an instrument of inestimable value in hydraulic experiments."[5]

In Francis's hands Boyden's hook gauge was capable of very high precision. When the point of the hook reached the surface level from below it did not go through; but rather it produced a slight bulge in the surface of the water. Francis discovered that by making observations with specially arranged lighting (e.g., light beamed from the

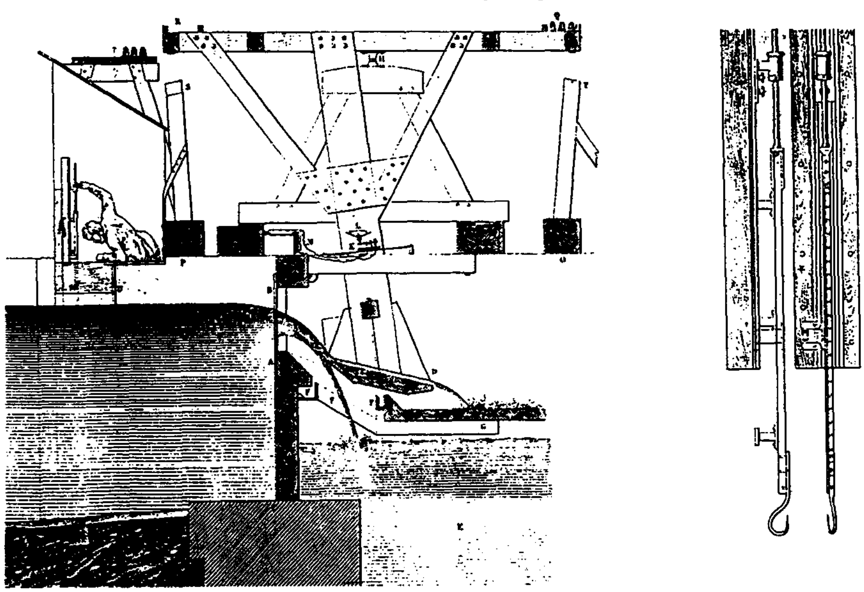


FIG. 14– Boyden hook gauge — from Francis, *Lowell Hydraulic Experiments*, Plate XIII

side, when the wooden box in which the gauge was mounted was partially darkened), these slight distortions could be made visible, and the true depth read by slightly lowering the hook so the bulge disappeared. This technique allowed Francis to achieve a truly remarkable accuracy of measurement for that time of one ten thousandths of a foot.[6]

Design and Testing at Tremont

Francis began to design and test turbines soon after his employers purchased Boyden's patent rights. Francis conducted the first test of one of his own turbines in February 1851 at the Tremont Mills at Lowell. The water power (P) available (as previously indicated) was the product of the weight of the water and the distance through which it fell, as in our equation (1), P= QwH, where Q was the flow in cubic feet per second, w the weight of a cubic foot of water (62.4 pounds), and H the head (or height) through which the water fell. For the Tremont Turbine, Francis's first test showed Q equal to 139.42 cubic feet per second, and the height equaled 12.86 feet. Thus, the gross water power, P, available was:

$$P = (139.42)\ (62.4)\ (12.86) = 111,870 \text{ cu.ft/ sec}$$

This is equivalent to 203.4 horsepower. The calculation depended upon an accurate measurement for the flow which led Francis to his studies of flow of water over weirs.

To measure the actual power generated, Francis caused the brake of the Prony dynamometer to be pressed against the iron wheel mounted on the turbine shaft, generating a friction force T, causing the shaft to slow down to the velocity V_r. The product of T and V_r gave the power. In the first test the weight in the scale was 1443.3 pounds, and this slowed the shaft velocity to 0.894 revolutions per second (or 53.62 revolutions per minute). To calculate the speed, we need distance traveled times the time.

The radius of the wheel to which the brake was fixed was 10.83 feet, so that one revolution equaled a distance of $2\pi r = (2)\ (\pi)\ (10.83) = 68$ feet. The velocity of the circumference of the wheel was:

$$V_r = (0.894)\ (68) = 60.9 \text{ ft / second}$$

From which the net rotary power delivered by the turbine's shaft could be calculated by equation (4):

$$P_r = TV_r = (1443)\ (60.9) = 87{,}762 \text{ ft-lbs per second}$$

which corresponds to 159.56 horsepower.

The efficiency (e) was measured by equation (5), showing that the efficiency was the ratio of the actual to the potential power: $e = P_r / P$. (To calculate this efficiency it is not necessary to convert foot-pounds per second into horsepower, but it is essential that P_r and P have the same units). Thus the efficiency, e, was:

$$e = 87{,}761 \ / \ 111{,}870 \ = 0.784$$

The Ninety-two Experiments

Francis made a total of ninety-two experiments on the Tremont Turbine, an enormous effort which testified to his determination to achieve the highest accuracy possible. He varied the key parameters such as the load of the brake, the velocity of the shaft, and the gate opening (e.g., the amount of water flowing into the turbine). Francis found that the efficiency varied with its speed and load from zero (when the load equaled 4080 pounds, just enough to bring the turbine to a halt) to its maximum speed (when it ran free with no load), 1.78 revolutions per second. The top speed was:

$$V_{max} = (1.78)\ (68) = 121 \text{ feet/ second}$$

Francis found that the maximum efficiency was achieved in his thirtieth test, when the turbine rotated at about half its maximum speed, where the ratio of net to gross horsepower (the efficiency) equaled 0.794 or 79.4 percent. This occurred where the velocity equaled:

$$V = (0.851)\ (68.3) = 58 \text{ ft/second}$$

The friction force (=the weight in the scale) (T) at this velocity was 1525 lbs and therefore the net mechanical power transferred to the shaft was: $P_r = (1525)\ (58) = 88300$ ft-lbs/sec. The gross power of the fall of the water in this experiment was a bit less than that in the first test. It equalled P= 111, 220 ft-lbs/sec. The ratio of these gave the efficiency (equation 5):

$$e = P_r \ / \ P = 88{,}300 \ / \ 111{,}220 = .794$$

The Francis Weir Formula

The validity of the determination of efficiency with the Prony dynamometer depended upon the experimenter's ability to measure the input. Though Prony had shown how to measure the power output, he lacked an accurate means of measuring the input (the flow of water, Q and the fall H). Boyden had made it possible by the hook gauge to determine the head, H, with great precision. But existing formulas for Q were not accurate. The formulas most commonly used underestimated the flow of water (Q) so that all of the early tests of turbines overestimated the efficiency.

The formulas for measuring the flow of water through a weir were deduced from theory, and failed to take into account all the things which influenced the actual flow into a turbine. As Francis commented after reviewing the literature:

> The result, however, of these numerous labors, is far from satisfactory to the practical engineer. On a careful review of all that has been done, he finds that the rules given for his use, are founded on the single natural law governing the velocity of fluids, known as the theorem of Torricelli; omitting, in consequence of the extreme complexity of the subject, all consideration of many other circumstances, which it is well known, materially affect the flow of water through orifices.[7]

Francis determined an accurate weir formula by experimental inquiry. It has become an important part of engineering knowledge and continues to appear in engineering handbooks and is used in a variety of contexts other than turbine testing.[8] Though it is a law-like relationship, and determined scientifically, it differs from physics in several ways. In particular, Francis's formula lacks the generality so characteristic of physical laws. With slightly altered conditions, slightly different formulas have to be used. Francis's formula is the first to be listed in engineering works, and the others can be considered variations upon it. But a physicist would prefer a general equation applicable to all such flows. Such a general formula can be constructed, but it lacks the specificity so important for engineering. That is, it lacks the accuracy of specific formulas intended to suit the particular conditions of engineering work. Francis's weir formula is therefore an example of engineering research leading to scientific knowledge that is the peculiar concern of engineers.[9]

The Theorem of Torricelli

Francis carried his rejection of theory to an extreme. All weir measurements started with the theorem of Torricelli, a mathematical expression which Francis was apparently unwilling to reproduce, adding an element of obscurity to his derivation of his weir formula.[10] This theorem, attributed to one of Galileo's followers, was and remains one of the most useful, if inevitably approximate expressions in hydraulics. It expresses the velocity of the water (V) as a function of g, the acceleration due to gravity (= 32.2 ft./sec^2), and the head (H), or height though which the water falls. The usual expression is $V^2 = 2\ gH$ or

$$V = \sqrt{2gH}$$

In the case of the flow over weirs, hydraulic engineers had long accepted a modification of the theorem of Torricelli, by which the flow was just two thirds of that predicted for free fall in Torricelli's formula. Francis refers to this equation only obliquely, without giving the formula. It was: $V = 2/3 \sqrt{2gH}$, where V is the velocity of the water, and g and H are as above. The total flow was determined by our equation (3), $Q = V_m A$. In this case the cross sectional area A was the product of L (the length of the passages admitting water in the weir), and of H, the fall, so that $Q = (HL)V_m$.

Francis wanted to know the mean velocity V_m, which, of course varied in a channel with depth. The velocity at any given depth below the top surface, z, would therefore be $V_z = \sqrt{2gz}$. By this line of reasoning the velocity should go from zero at the surface (where z=0) to $\sqrt{2gH}$ at the bottom of the weir (see FIG. 2 where z = H). The mean value must be between these two extremes and produces the following formula (which Francis did not give in his derivation) for the flow:

$$Q = HL\ 2/3 \sqrt{2gH} = (2/3 \sqrt{2g})\ LHH^{1/2} = CLH^{3/2}.$$

Q is the flow, the thing Francis wanted to determine, and C is an unknown constant.

Francis's skepticism stood him in good stead here. He did not take the value of $2/3 \sqrt{2g}$ as given and instead he introduced "C" a constant coefficient whose value was to be determined experimentally, and L is the length of the weir and H its depth. Francis's unwillingness to accept anything on faith might seem like unreasonable skepticism. Francis wanted every term to be determined by experimental measurement. It turns out that for rather subtle reasons, the figure for $2/3 \sqrt{2g}$ is inaccurate in the context of weir flow.

The accuracy and value of Francis's formula, therefore, depended upon his determination to measure every relevant quantity by precise empirical observation. He was assisted in this by Uriah

Boyden, who suggested a form of the equation suited to empirical testing:

$$Q = C\,(L - b\,nH)\,H^{a}$$

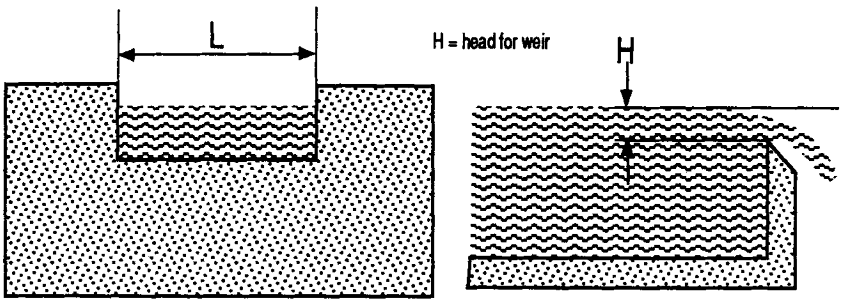


FIG. 2 (repeated)– L is the length of the weir, H is the height or head of the weir

This expression related Q, the flow to be determined by the formula, to the length (L) and the height (H) of the weir and n, the number of vertical sides to the weir (a weir could have more than one rectangular opening), and the unknown constant coefficients, a, b, and C which Francis wanted to determine experimentally.[11] The term "a" was the exponent (3/2 in the expression given above) which Francis assumed to be unknown in order to determine it experimentally. The term "b" was simply a constant coefficient needed to get an accurate formula for measuring Q, the volume of flow.

Francis did experiments to determine the value of a, b, and C. The expressions a and b were relatively easy to determine experimentally, by comparing the flow in two different weirs which gave the same Q. The nice thing about this method is that a and b could be determined independently by any set of matched experiments in which the volumes were the same.

These experiments, done in 1851, led to the result that a should be 1.47 (close to the theoretical 1.5, which Francis found more convenient to use in most cases) and b should be 0.05. Francis found that b could be rounded off to 0.1 without appreciable error. Francis now could determine C experimentally, having determined the values of the other terms in Boyden's equation (Q,L,H, N, a, and b). His result, as determined by the arithmetical mean of 88 experiments in 1852, was C=3.33.[12] Thus the Francis weir formula took the form:

(6) $$Q = 3.33\,(L - 0.1\,nH)\,H^{3/2}$$

Fairness in Water Distribution

The weir formula proved to be very useful in many contexts. Indeed, Francis relied upon it in determining his method of metering the water used by the various companies at Lowell. Francis's work in measuring the flow of water in the various Lowell canals was necessary in order to determine the amount of water used by each of the Lowell companies. It was an improvement over measurements previously used and contributed to greater fairness in distributing the water to the users.

In the case of the flow of water in the Lowell canals Francis rejected the prior work of three distinguished engineers retained by the Proprietors and consultants in 1841 and 1842 for precisely this task. One of these consultants, Charles Storrow, had been educated, in part, at French engineering schools and he admired French work and he published English translations of some of the most important French works on hydraulic engineering in 1835.[13] He was a very distinguished and able engineer and manager, and he was a major figure in founding and developing Lowell's twin hydropower textile center of Lawrence, just 12 miles down the Merrimack from Lowell.[14] After exhaustive experimental work Storrow and his colleagues concluded that a previously published French formula (which was based on theory) was sufficiently accurate to use as a starting point in the metering of the flow of water in the Lowell canals.

Francis rejected the prior work of Storrow and the other consultants who had provided a useful basis for the measurement of water at Lowell. His reasons were not stated, but this was probably due, at least in part, to Francis's extreme rejection of mathematical theory. (That is, the use of the formula deduced from theory.) Storrow's methods were successfully used at Lawrence, Lowell's neighbor, for many years. Also, Francis's method for metering the flow of water into each company also involved the use of a formula, his own empirically based weir formula.

Francis was one of the least vain of engineers; his preference for his own formula appears to have been based upon the fact that his formula and other techniques for measuring the flow in canals were founded on exhaustive experimental investigations, involving direct observation of the things to be measured.

Francis's preference for direct observation and measurement is strikingly demonstrated in his experiments to measure the water consumption of the Lowell companies. His method gave accurate results, and Francis developed simple techniques which allowed his method to be applied routinely in metering the consumption of water by the Lowell companies. In essence, Francis sought to determine the flow by our second formula in the first chapter: $Q = V_m A$. Since the cross sectional area was known, Francis had to determine the mean velocity in order to determine the flow. He chose a method of direct measurement, using weighted tubes almost wholly submerged in the canal, and observing the time they took to traverse a measured distance. Since the poles were nearly the same length as the depth of the canal to be measured, their velocity (apparently) gave a direct measurement of mean velocity.

He compiled tables so that his assistants could use a stop watch to measure the time the weighted tubes took to traverse a given distance. The assistant engineer could then look up the velocity in a table. But Francis had to determine various corrections to the directly measured quantities (of which his own weir formula was one of the most important). The tedious determination of correction coefficients reflected the fact that the weighted cylinders did not, in fact, directly measure the mean velocity.

The most important corrections arose from the fact that these tubes could not touch the bottom, so there was always a gap near the bottom that was not taken into account. Nor did Francis measure this depth directly, but assumed this to be known (though in fact it varied, due to inequalities in the original construction and the deposit of debris from the flowing water on the bottom of the canals). Francis also ignored the inclination of the tubes (that is, the angle they made with the surface). Francis's work in measuring the flow in canals was tedious and it had no lasting impact outside Lowell precisely because of his excessive skepticism of theory and his preference for direct observation.[15]

But while Francis's method of metering the flow of water in open channels has not had a significant influence, Francis relied increasingly upon another method, which he developed. He found that his detailed testing of turbines allowed them to be used as water meters. They had consistent performance patterns, and, for a given head and gate opening, used a predictable amount of water. This usage of water could only be determined by testing the turbines; but it was a turbine "characteristic," which was consistent, and such behavior could be applied for measuring the water consumption of other turbines of the same design and size working at the same head. This allowed turbines to be used as water meters, given data on gate opening, head, and the times of operation. Francis justified his tests of the Swain turbine (an improved version of his own Francis turbine) when two were purchased by the Boott Mills on the grounds that he needed to know its water consumption under various heads and gate openings in order to measure the amount of water being consumed.

Thus Francis measured the quantity of water Q used at one-quarter, one-half, and full-gate at a uniform fall of 17 feet.[16] It appears that Francis used both of his methods of measuring consumption for accuracy; the weighted tube measurements were still employed even after the simpler and more accurate method of using turbines as water meters had been developed.

Francis was an outstanding experimental researcher. His painstaking care and his patience were well rewarded. No one doubted that his measurements were accurate. They served their intended purpose very well. Francis's determination to base all engineering on precise, direct measurement was a remarkable success.

REFERENCES

[1] Francis to Luigi D'Auria, February 25, 1878, vol. A-16, Proprietors of Locks and Canals Papers.

[2] To compare the verbal discussion of the Bernoulli theorem and as applied to diffusers in Francis with the mathematical theory used to analyze the diffuser in a modern text, see : Francis, Lowell Hydraulic Experiments, pp. 209-217 and Shepherd, Principles of Turbomachinery ,pp. 153-157.

[3] Francis, Lowell Hydraulic Experiments, pp. 209-231, plates 22,23.These turbines were not the only ones used at the Merrimack mills; Boyden had designed a smaller one several years earlier for the Merrimack company's picking house. By comparison, the Francis turbines at Hoover dam generated 115,000 horsepower at 180 rpm under a head of 475 feet as will be noted below.

[4] Aubrey F. Burstall, A History of Mechanical Engineering (Cambridge: M.I.T. Press, 1965), p. 242.

[5] Francis, Lowell Hydraulic Experiments, p. 18.

[6] Ibid.

[7] Ibid. p. 71. Torricelli was a pupil of Galileo; his formula ($v^2 = 2gH$) can be seen as a modification of Galileo's law of fall for the general case of fluids. It is a very useful approximation.

[8] See for example Urquhart, Civil Engineering Handbook, 3rd edition, pp. 337-345.

[9] Galileo's law of fall is such a general formula. However it lacks accuracy for measuring to the flow of water until it has been modified to take various specific conditions of matter into account. On the question of the role of engineering science and its relation to basic physical science, see David Channell, "The Harmony of Theory and Practice: The Engineering Science of W. J. M. Rankine," Technology and Culture, 23 (January 1982), pp. 39-52, especially 51-52.

[10] I would like to thank David Billington for helping me understand these obscurities and I have followed his derivation in what follows.

[11] A weir may have more than one rectangular opening for water, hence Francis could have two, four, or six edges. When a fluid flows through an orifice there is a contraction which has the effect of narrowing the stream. In effect this was one of the things that Francis wanted to measure experimentally by using Boyden's formula.

[12] Francis's use of modified values of a and b is indicated on page 118. The modified values of a and b are given in column 15 of table XIII on p. 123. This was pointed out to me by David Billington, and I acknowledge his indispensable aid in understanding Francis's none-too-clear derivation. The theoretical value for $C = 2/3 \sqrt{2g} = 5.33$ which assumes that the water flows over the weir at a height H, but in reality the flow contracts vertically (see FIG. 2) such that its true height is less than H. In addition to contraction there are energy losses and Rehbocks formula accounts for these by a discharge coefficient $C_d = 0.611 + 0.08\ H/L$ where in nearly all cases the second term can be neglected so that $C = C_d (5.33) = 0.611 (5.33) \cong 3.33$ The term 0.1nH accounts for the lateral contraction. See F.M. Henderson, Open Channel Flow, New York, 1966, p.175

[13] Charles S. Storrow, A Treatise on Water-Works (Boston: Hillard, Gray and Company, 1835).

[14] On Storrow's life and accomplishments see "Charles Storer Storrow, " Engineering News 29 (February 16, 1893), p.147.

[15] Francis, Lowell Hydraulic Experiments, pp.146-208.

[16] Francis, James B., "Report on a Test-Trial of a Swain Turbine Water Wheel," Journal of the Franklin Institute, 3rd series, v. 69 (April, 1875), pp. 249.

CHAPTER 6

The Invention of the Francis Turbine

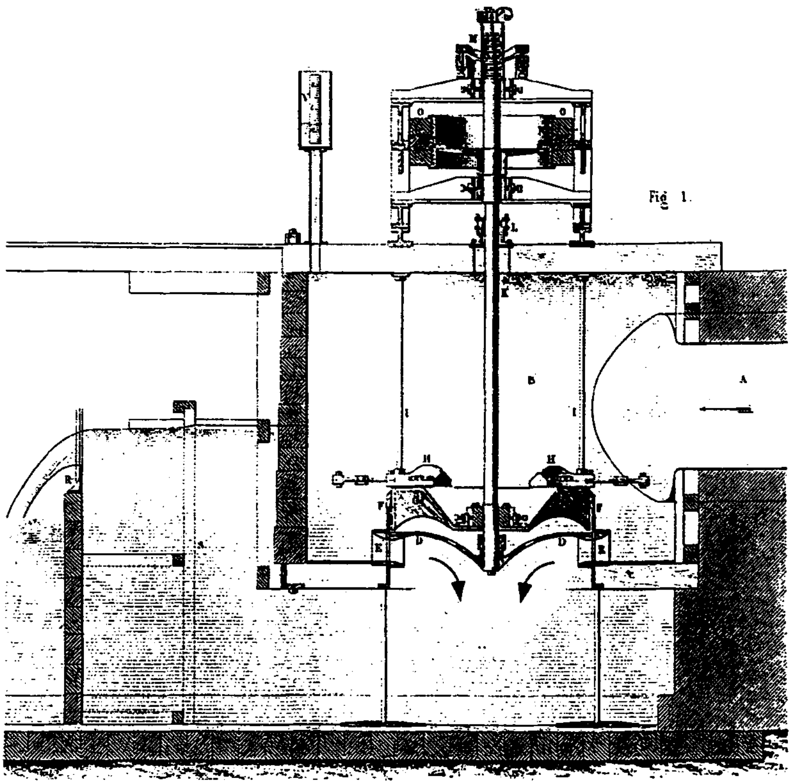
Large Flows at High Speed

Francis is best known for the Francis turbine which is today the most important means of utilizing the power of falling water at high heads and large flows. It is characterized by a flow that moves inward and downward. This flow pattern is sometimes called "mixed flow," and it is the defining characteristic of Francis turbines. The first full-sized Francis turbine was one that he installed and tested in October 1849 at the Boott Cotton Mills at Lowell. It developed 137 horsepower.[1] Fully evolved Francis turbines were built to generate electricity at Hoover Dam, and the first of these began to produce power in October 1936, almost exactly 87 years after that which Francis built for the Boot Mill. These turbines were rated at 115,000 horsepower.[2] The Francis turbine is one of the most versatile and efficient machines ever designed. Francis turbines are noted not only for their high efficiency, but also their ability to utilize very large flows at high heads and do so with a relatively compact and inexpensive turbine. The Hoover dam turbines had a rotor ("runner") diameter of only 14.25 feet, compared to 9.33 feet for the Boot turbine, a modest increase of 65.5 percent in this critical dimension for nearly a thousand times the power production. [3]

The Popular Howd Reaction Wheel

The Francis turbine combines the tradition of scientific engineering, which in turbine design began in France, with ideas developed by American craftsmen in designing reaction wheels. Indeed the Francis turbine can be seen as a hybrid of the scientific Fourneyron turbine and the rather crude reaction wheel invented by an obscure millwright, Samuel B. Howd.

In 1838 Howd designed the first radial inward-flow reaction wheel. It would be called a turbine today, but it was anything but an "ideal"motor. Though his reaction wheel was compact and cheap, Howd had no scientific justification for his design, and his reaction wheels were rather primitive, but very cheap, and consequently popular.



Francis, *Lowell Hydraulic Experiments*, plate VIII, figure 1

FIG. 15 – In the Francis mixed flow turbine water flows from (A) in through fixed guides (E) on through the rotor (D) and out directly below the rotor. The Prony brake (O) is on upper part of shaft with Boyden low friction suspension collar (M) above the brake.

Francis persuaded the Locks and Canals Company to purchase a a local right to manufacture turbines under the Howd patent in 1847, in order to make an improvement in Howd's design. When Francis began to design a small model turbine of what was later to become the Francis Turbine design, he called it the "U.S." turbine. His first major turbine, for the Boott Mills, was also labeled by Francis in his notebook as the "U.S. Turbine." Howd's reaction wheels had the brand name "United States Turbine."[4]

Laminar Flow in the Francis Turbine

Though Francis had a low opinion of the American reaction wheels, he wanted to design inward-flow turbines. As he commented, "I was led to this design by the consideration of the [absolute] path of the water in passing through the wheel."[5] Francis saw from the plot of the absolute path of the water that by reversing the direction of flow, from outward to inward, he could eliminate a major defect of the Fourneyron-type turbine. In a radial outward flow turbine such as that of Fourneyron, the path of the water inevitably widens, causing eddies and turbulence. In an outward flow turbine, the outer periphery of the rotor was inevitably greater than the inner circumference, and as the channels widened the water had to move laterally to keep the passages full, disturbing the smooth, laminar flow and leading to power losses. This spreading was made very clear by the graphic method of plotting the absolute path of the water which Francis learned from Boyden (see FIG. 12).

The plot of the absolute path of the water in the Tremont turbine showed a very considerable widening by the time the water left the turbine. By reversing the direction of flow (as in the Howd reaction wheel) Francis could hope to eliminate the loss of power due to the spreading and eddying of the water.

Francis no doubt hoped that a rational design would increase the efficiency of an inward-flow turbine based on Howd's patent. Francis, however, was aware of an inherent problem with a purely radial inward-flow turbine. As the water moved inward, the passages of the turbine narrowed, causing an increase in the velocity on the same principle as the converging passages of the nozzle of a garden hose. Francis realized how this inherent defect of the Howd turbine might be remedied. He saw that he could keep the inward flow principle and eliminate the spreading and also avoid excess exit velocity if the cross sectional area of the water's passage was not decreased. The acceleration of the water in a convergent nozzle was due to a decrease in the cross sectional area; but the area could be kept constant simply by increasing the depth of the passages to compensate for their narrowing. This implied that the flow instead of being purely horizontal, as in the Fourneyron turbine or Howd reaction wheel, would be both inward and downward. This "mixed flow" principle became the distinguishing characteristic of Francis turbines.[6]

A Stolen Idea

Francis told Boyden of his idea, which he planned to incorporate in the design of a new turbine for one of the Boott mills. These early turbines had flat top and bottom plates called "crowns," so that the idea was that the distance between the crowns should be greater on the inner periphery where the water was discharged than on the outer, or inlet, circumference. Boyden beat Francis to the patent office with the idea. Francis thought Boyden had taken his idea from him, and he prepared a memorandum dated April 15, 1848 to establish his own priority:

> I met Mr. Boyden on the street. I asked him if he did not think that making the distance between the crowns of the wheel greater on the inside periphery than on the outside was new... He replied that he had application then pending for patents for this idea... I was much surprised — the more so as I had explained to him some months ago that I intended to make the wheels for the Boott Mill with a greater height between the crowns on the inside periphery than on the outside — and the impression I got at the time was that he thought it would not answer and he gave me not the slightest intimation that he claimed it as his invention.[7]

There were important differences in detail between the inward flow turbines of Boyden and Francis. So it is possible that Boyden was thinking along the same lines independently, and chose not to tell this to Francis. But Boyden was shrewd and had made a fortune from his patents; it is quite possible that he did borrow the key idea from Francis, just as Francis believed. Francis's motives were professional; Boyden's goal was to make a profit. The world has accepted the priority of Francis because he published the details of his turbine, whereas Boyden published nothing about any of his turbines or design methods.

Francis, ever skeptical of theory, used the graphical plot of the absolute motion of the water as a principle method for use in turbine design. Any spreading of the water became evident in such a plot. A sudden widening of the path of the water indicated shock. Unfortunately, as Francis noted, his plot of the path of the water in the Boott turbine revealed a small mistake.

Francis called attention to this problem; he wrote "...the section of the stream just after it has entered the wheel, is sensibly greater than the section of the stream as it leaves the guides... causing shock...which implies a loss of power. This indicates a defect in the design"[8] (see FIG. 12). Such candor was remarkable; Francis was honest almost to a fault. The error is not terribly obvious from a casual inspection of the plot of the path of the water; had he taken no notice of the matter many readers would have missed it, or assumed that Francis had a reason for what he did. He also could have blamed others. In a letter to Boyden he wrote that the error was due to defective castings prepared by the machine shop.[9] As a result of this small error Francis got a maximum efficiency of 79.8 percent for the turbine he designed for the Boott mill.[10] A few years earlier this would have been regarded as adequate performance, but efficiencies well above 80 percent had become the norm by the late 1840s.

Though he could have designed more mixed flow turbines, and gotten higher efficiencies, Francis chose not to do so. He was an experienced engineer and realized that progress in technology was incremental. Francis was very busy with many pressing problems and he was happy to leave the further development of his idea to others. It is quite probable that he also realized that the companies that were beginning to manufacture and sell reaction wheels and turbines in a highly competitive market could produce cheaper turbines than the Lowell Machine Shop.

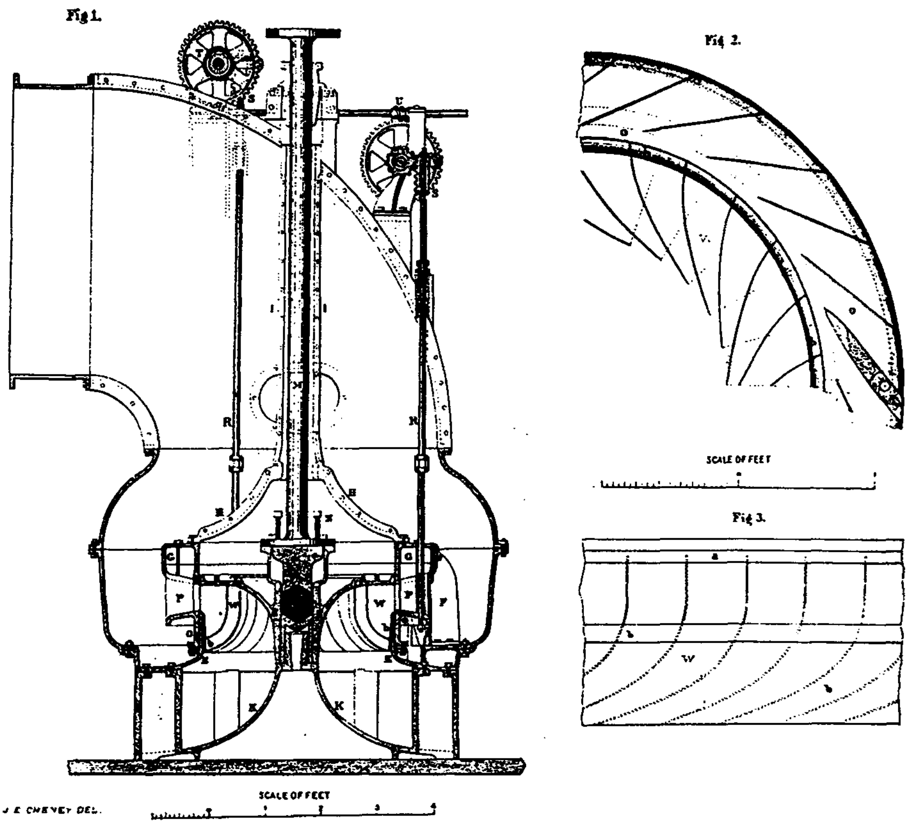
Improving the Francis Turbine

Francis thought further improvements depended on a lengthy process of development which would depend on cut-and-try. Indeed he concluded his 1855 discussion of his new turbine with the words: "nevertheless, the success attending this first essay on a large scale, of a center-vent water wheel, in which due regard has been paid to accuracy of construction and perfection of workmanship, guided by such light as the present imperfect theories can afford, ought to encourage us to hope, that, when it has received the same degree of attention as the [Fourneyron-Boyden] turbine, it will not be much behind that celebrated motor, in its economical use of power." [11]

Francis's expectations were fulfilled within a few years with the design of the Swain turbine. The Swain turbine, patented in 1860, was the first Francis-type turbine to be commercially and technically successful. Asa M. Swain was a former pattern maker employed at the Lowell Machine Shop, and he had had ample opportunity to examine both Francis's and Boyden's inward-flow turbines and to read Francis's account of his work.

Swain's Successful Turbines

Swain's turbines were not exceptional in their efficiency, but they were smaller and cheaper than Boyden-Fourneyron turbines of similar power. Swain achieved this by exploiting an inherent advan-



from *Journal Franklin Institute*

FIG.16 – The Swaine turbine

tage of the Francis design, its downward component of flow. Swain understood, in essence, that equation (2), $Q = V_m A$, could be applied to the turbine, and that Q could be increased without changing the diameter simply by increasing both V_m and A. This could be done by increasing the downward component of flow in a Francis turbine. By giving the water's path a much greater downward component of motion, Swain increased V_m by gravitational acceleration. He also increased the cross sectional area of the passages, A, by making the inlets deeper. Capacity (the ratio of Q to turbine diameter) is a key determinant of cost, a fact that millwrights understood very well.

These changes also allowed the rotor to have a smaller diameter because the vanes sloped downward, requiring less horizontal space. This meant that the surrounding guides and the penstock could also be smaller. By and large turbines cost is directly proportional to their size. A higher Q and smaller size (for a given horsepower) meant a lower capital cost per installed horsepower.

Beginning about 1868 ten Swain turbines were sold to Lowell companies and installed at Lowell mills. Other Swain turbines were sold at manufacturing centers in other parts of the country.[12]

The success in this and later attempts to exploit the Francis design depended upon a proper design of the turbine vanes which had a more complex shape in Swain's turbine. There was no theory available for this task, and much of the work was, as Francis realized, based on "cut and try" guided by intuition and experience. Francis concluded that "I have no doubt if the construction of such wheels had been continued [by Francis], still better results would have been obtained, by making small changes on the "Cut and Try" Principle."[13] Swain built himself a small dynamometer for an improvised workship in his home and thus was able to compare the performance of various models. He modified these models, changing the length and shape of the vanes, and other design parameters until he got good results.[14]

REFERENCES

[1] Francis, Lowell Hydraulic Experiments, table VI, pp. 66-67, experiment 33. This setting had a maximum potential head of 18 feet; with the same flow and efficiency at that head the turbine would have developed about 184 horsepower. This was Francis's second "Francis" turbine, the first was a model with straight vanes.

[2] L. N. McClellan, "Engineering Features of Boulder Dam and Power Plant," Electrical Engineering, 54 (June 1935): 585-586.

[3] W. M. White, "The Construction of the 115,000-HP Boulder Dam Turbines," Mechanical Engineering, 57 (September 1935), p. 539, table 1, and Francis, Lowell Hydraulic Experiments, p. 63.

[4] "U.S. Wheel Model," March 12, 1847 and "Model of U.S. Wheel with Straight Floats," March 24, 1847. After this first model, Francis designed his first "Francis" turbine for the Boott Mill. His preliminary calculations were titled, ""U.S. Wheels for Boott Cotton Mills," June 10, 1847. "Waste Book, 1847-47," #4, Francis Engineering Papers.

[5] Francis, Lowell Hydraulic Experiments, p. 55. Francis says the path according to his article 83, where he lays down his method for plotting the absolute path of the water (relative to the earth) as it passed through the rotating turbine vanes (see p. 39-43).

[6] For an incompressible fluid, the Bernoulli theorem gives a relationship between area and velocity for horizontal flow: $dA/A = -dV/V$. This implies that if the area increases the speed decreases, and conversely, if the area decreases the velocity increases. When the area, A, is kept constant, the speed will also remain constant. (See Murdock, "Mechanics of Fluids," in Baumeister, Marks' Standard Handbook for Mechanical Engineers, p. 43.)

[7] Memorandum, April 15, 1848, Proprietors of Locks and Canals Papers.

[8] Francis, Lowell Hydraulic Experiments, pp. 69, and figure 2, plate IX.

[9] Francis to Boyden, December 2, 1848, Boyden Papers. In this letter Francis summarized his design philosophy: "the considerations by which I have been principally guided...are, that the water should enter the wheel without shock and leave it with the least practicable velocity, that during its passage through the wheel, the water should suffer no sudden changes in velocity—and should also preserve as straight a course as practicable—as either a sudden change of velocity or direction, would be attended with eddies, which would a loss of force."

[10] Ibid., pp. 61-70, figure VI, pp. 66-67.

[11] Ibid., p. 69.

[12] For a brief review of the work of Swain and John B. McCormick (who further perfected the Francis design) , see John R. Freeman, "General Review of Current Practice in Water Power Production in America,", II, pp. 379-380. There is a wealth of information about the Swain turbine and Swain himself in the patent suit, "Swain Turbine and Manufacturing Company versus James E. Ladd," in U.S. Supreme Court Records and Briefs, Part III, 12 Otto, 235-533 (1880), pp. 129-136.

[13] Francis to D.H. Morrison, April 19, 1880, Vol. DB-10, Proprietors of Locks and Canals Papers.

[14] "Swain Turbine Co. v. Ladd," pp.130-131, 139-145, 147-148.

CHAPTER 7

The 115,000 Horsepower Francis Turbines at Hoover Dam

The Hoover Dam

The Francis turbine achieved its modern form through the efforts of a number of designers in the period 1868-1940. The Francis turbines installed at Hoover dam are remarkable examples of modern Francis turbines. First the setting, Hoover Dam, needs some explanation.

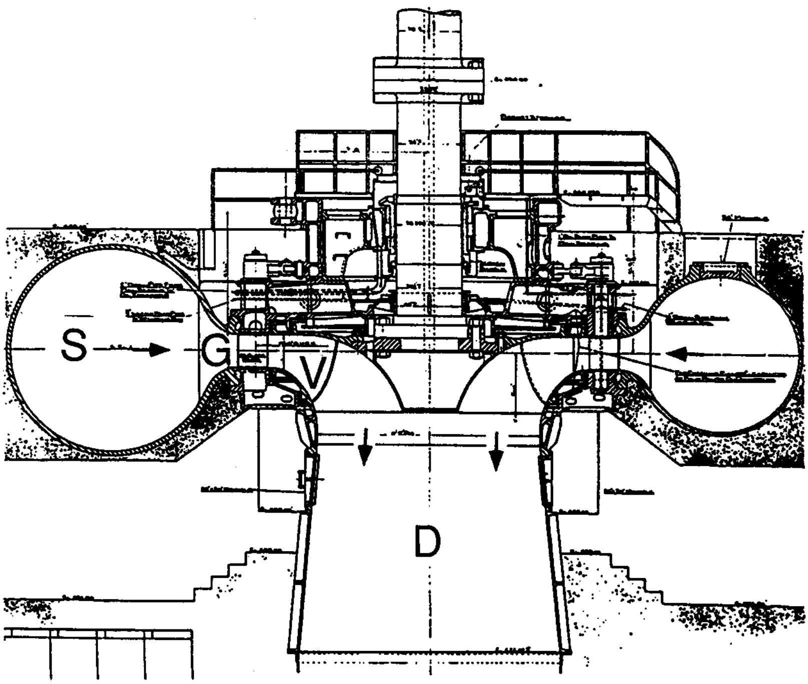
Hoover Dam, containing 3.25 million cubic yards of concrete, was the first structure to exceed the volume of the 4,000 year old Great Pyramid of Cheops (or Kufu) in Egypt. It is 726 feet high and was the highest dam in the United States when completed. It is 1,180 feet wide along its curving, arched crest, and 660 feet thick at the base tapering to 45 feet thick at the top. Hoover Dam created an artificial lake, Lake Mead, with an area of 227 square miles and a storage capacity of about 30 million acre feet of water, which is still the world's largest man-made reservoir. (One acre foot contains 43,560 cubic feet of water.)

Hoover is properly credited with the dam named after him. As Secretary of Commerce he had carried out long and difficult negotiations between the states of California, Arizona, and Nevada, leading to a 1922 interstate compact that made possible the construction of the dam. The act authorizing the dam was passed by Congress in December, 1928, a month after Hoover's election as President. Hoover arranged for financing, and construction started in 1931 under his administration. Hoover had the misfortune to be blamed for the great depression which developed after 1929, and his successor gave the structure the name "Boulder Dam," an injustice remedied almost a generation later, when Hoover received the recognition he deserved. No one did more to make the dam a reality than Hoover.

Construction, begun in 1931, was continued in the administration of Franklin D. Roosevelt. It not only provided jobs, but it was a technical wonder which aroused hope and enthusiasm in those dark days. It was finally dedicated by President Roosevelt in 1935. The installed capacity was 1,323.5 megawatts (or 1,774,813.5 horsepower; a megawatt equals1,000,000 watts, or 1,341 horespower) of electricity annually produced by Francis turbines and their electric generators. This electricity (and also the irrigation water) is split among the three states involved, but the lions share of the power was taken by Los Angeles. The electric power is sent to Los Angeles on a 287,500 volt high-tension line a distance of 270 miles.

Turbines with 115,000 Horsepower

The largest of the turbines at Hoover were the most powerful ever produced until that time. They were conventionally rated at 115,000 horsepower. The rating was based on the fact that the size and other design features of the electric generators limited the turbines to 115,000 horsepower. If the turbines could be operated with open



From E. M. White, "Construction of the 115,000HP Boulder Dam Turbines," *Mechanical Engineering*, Vol. 57 (Sept. 1935), p. 541, printed courtesy of American Society of Mechanical Engineers

FIG. 16 – Cross section of the 115,000 Hp turbine at Hoover Dam. Water flows in from the scrollcase (S) through the fixed guides (G), through the rotor vanes (V) and out the draft tube (D).

gates at a head of 590 feet, they would develop 158,000 horsepower.[1] Thus the gates admitting water to the turbine are used to limit the flow of water at high heads to keep output at no more than 115,000 horespower. As equation (2) from chapter 1 shows, the horsepower is dependent upon both the head and the quantity of the flow, and these can vary considerably.

The Hoover Dam turbines are able to operate under net effective heads varying from 360 feet to 590 feet, though most of the time the head fluctuates between narrower limits. For example, each of the 115,000 horsepower turbines uses a flow which varies with the net head. When operating at an effective head of 475 feet, the discharge has to be limited to 2323.2 cubic feet per second if the efficiency is 92 percent. Applying equation (1) from chapter 1 we can compute that for this flow the horsepower will be 115,000 under these conditions. That is, $Hp = QwH/550 = 2{,}323.2 \times 62.3 \times 475 / 550 \times .92 = 115{,}000$ Hp.[2]

Roots at Lowell

Though Hoover Dam and its power plant have important symbolic and social significance, what is relevant here is the fact that these enormously powerful Francis turbines clearly show their roots at Lowell. They have the inward-and-downward "mixed flow" characteristic of Francis turbines, though with larger inlets and longer vanes than Francis's first major effort. Their rotors are only 65.5 percent larger in diameter (14.25 feet) than those of Francis's Boott Turbine (9.33 feet). Like the turbines designed by Boyden and Francis, the rotor is suspended from above and the bearing surfaces are covered by the same type of low friction metal that Boyden and Francis used on their turbine bearings at Lowell.

Additional links to Lowell are the diffusers attached to the Hoover Dam turbines. The diffusers have a simpler shape (a truncated cone) than Boyden's original ones (two flared collars are needed for an outward-flow turbine such as the Boyden-Fourneyron design). One of the advantages of the Francis turbine is that a simple diffuser is highly effective. These cones were attached to ducts (called "draft tubes") which had to be bent around through a right angle, because of the height restrictions imposed by the need to empty into the tail water. But the draft tube-diffuser combinations at Hoover Dam are enormously effective; the water has a velocity of 25 feet per second on leaving the turbine, but only 5 feet per second on leaving the draft tube-diffuser. This respresents a loss of only one tenth of one percent of the gross horsepower due to the velocity of the water at discharge.[3]

The Hoover Dam Francis turbines also show their links to the early American millwright tradition of the reaction wheel, by their spiral scrolls. Those at Hoover Dam are larger (a diameter of 10 feet at the inlet from the penstock) than those used earlier, because of the enormous flows of water that they transmit. The diffusers at Hoover Dam are combined with draft tubes based upon the cylindrical draft tubes invented by the Parker brothers. Draft tubes allow turbines to be mounted above the tail water without loss of head, since the suction of the draft tube equals the "lost" head.

Scientific Data from Experiments

The greatest similarity between Francis's turbine work and that of the Hoover Dam turbines although not visible, is that every detail of these modern Francis turbines and their settings was based on scientific data, mostly gathered by experiments. Even the flanges and bolts of the scrolls were subject to elaborate investigation, resulting in greater strength at less cost. The designers of the dam and the turbine made extensive use of scale models, with many of these tests aimed at detecting and eliminating sources of turbulence. To this end, the Bureau of Reclamation tested models of the turbine blades, very much in the manner of the airfoils of aircraft. The water in the Hoover Dam turbines, like those of Francis, was designed to exert pressure at a uniform rate from its entrance to its exit from the turbine.[4]

Where the Hoover Dam turbines differed most markedly from those at Lowell was in the high head and enormous flows at Hoover Dam. Thus, while the turbines themselves are not wildly out of scale with its Lowell prototypes, other things were, from the immense dam down to the enormous ducts needed for handling the great quantity of water moving through the Dam. The flow handled by one of the Hoover Dam turbines was approximately the same as the base-line power leased for the entire Lowell manufacturing complex before Francis's reforms in 1845 (2,348 cubic feet per second). Even more striking was the difference in head, about 520 feet on the average at Hoover Dam, as compared to an average of 33 feet at Lowell.

A Modern Engineering Artifact

The Francis turbine is a modern engineering artifact, and Francis was a modern engineer. His work represented a clear shift from a craft to a scientific basis for engineering. This meant, among other things, reliance upon exact knowledge rather than rule of thumb. His redesign of the Lowell canal system, his weir formula, and his turbine testing were examples of work aimed at basing engineering design on precise quantitive data and reliable formulas derived by methods akin to those used in the sciences. He was also modern in that he published his findings, thus sharing them with the international engineering community.

Francis was modern also in that his work was guided and shaped by the needs of engineering, and of the needs of the corporations that employed him. He was not interested primarily in knowledge itself, but rather in the knowledge needed to design artifacts and for the efficient operation of hydraulic works. He was recognized as the foremost hydraulic engineer of his day, and was called upon as an outside consultant in numerous projects around the country. He became an exemplary figure for American engineers at the time when they were emerging as a separate profession. His condemnation of theory was shared by many American engineers; only in comparatively recent times have American engineers overcome their skepticism of mathematical theory. But in his devotion to the needs of engineering and his use of the best scientific methods he could muster he anticipated the direction of engineering advance in the coming century.

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[3] Winter, ""The 115,000-H.P. Turbines at Boulder Dam," pp. 549-550.

[4] See the velocity graph for the Hoover Dam turbines in ibid., p. 550, figure 419.

PROBLEMS

1. Assuming a mean low-water flow of 3,595 cubic feet per second, and the fall 33 feet, **(a)** how many foot pounds of work were in the falling water as potential energy? **(b)** How many horsepower of potential energy does this fall contain? **(c)** Assuming a constant head, how much would the flow have to increase to produce 15,000 horsepower? **(d)** If the head were 40 feet and other things remained the same, how many horsepower would be produced?

2. Given a flow at a mean low water of 3,595 cubic feet per second, the weight of a cubic foot of water at 62.33 and a fall of 33 feet, **(a)** how much power would be produced by water wheels with an average efficiency of 60 percent? **(b)** How much power would be produced by increasing the average efficiency of the water motors to 80 percent? **(c)** How much power at 86 percent?

3. If the mean low water flow of a hydropower system is 2,000 cubic feet per second, but the average for the entire year is 3,500 cubic feet per second, **(a)** how much (minimum) horsepower could be guaranteed throughout the year without water storage? **(b)** Assuming the water can be stored upstream and released at a uniform rate throughout the year, **(c)** how many horsepower can be guaranteed to users throughout the year?

4. If a flow of 3,595 cubic feet per second of water is to be carried in a canal with a cross sectional area of 500 square feet, **(a)** what would be the approximate velocity of the water (ignoring fiction)? **(b)** What would be the velocity of the water if the canal's cross section were widened to 2,000 square feet? **(c)** Assuming that the friction is proportional to the square of the velocity of flow, by what fraction would the friction be reduced by the shift from the canal with a cross sectional area of 500 square feet to one with a cross sectional area of 2,000 square feet?

5. Assuming a large breast wheel, such as those used at Lowell, with a fall of 33 feet and an intake of 50 cubic feet of water per second, (a) what would be the potential power of the fall of water used by the wheel? (b) At an efficiency of 60 percent how many horsepower would the water wheel produce?(c) Assuming that there is no shock at entrance and no friction, what should the discharge velocity be for 100 percent efficiency?

6. For a weir 3 feet wide with 2 sides and a depth of water on the weir of 3 feet (a) what would be the volume of water flowing over the weir? (b) What would the volume be if there were four sides (for two openings), a total width of the weir of 5 feet and a depth of water on the weir of 2 feet?

7. If a force of 1,443 pounds is applied to the shaft of a turbine by means of a Prony dynamometer whose brake is attached to a wheel 10 feet in diameter attached to the turbine shaft, and this slows the shaft velocity to 0.894 revolutions per second, (a) what is the power output of the turbine in foot-pounds? (b) in horsepower? (c) What is the corresponding power outputs (using the same turbine and dynamometer) where the force applied is 500 pounds and the speed of the shaft is 1.5 revolutions per second?

8. If the turbine being tested in 7, above, consumed 131 cubic feet per second, with a fall (head) of 15 feet, (a) what would the efficiency be in the two cases noted?

9. If one of the Francis turbines at Hoover Dam took in 3,600 cubic feet per second at 480 feet head, (a) what horsepower would be produced, assuming an efficiency of 90 percent?

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GLOSSARY

Abbreviations

E	energy
e	efficiency
ft-lb	foot-pound
Hp	horsepower
T	friction force
P	power
V	velocity

Boyden turbine: a Fourneyron turbine with Boyden's improvements, including a scroll case (in the form of a cup-shaped penstock), a diffuser, and overhead suspension by means of a low-friction bearing.

breast water wheel: a version of the overshot waterwheel, a vertical wheel in which the water is applied from the side. The breast wheels used at Lowell were "high breast wheels" or "pinchback wheels" in which the water is applied to the upper half of the wheel, often near the top.

bucket: the water holding devices on the outer periphery of a vertical, overshot, or breast water wheel. Sometimes (confusingly) applied to turbine vanes in Francis's time.

diffuser: a diverging tube used to slow down the water leaving a turbine, in order to increase efficiency, invented by Uriah A. Boyden.

draft tube: a tube into which a turbine discharges its water invented by Austin and Zebulon Parker. For Francis turbines the diffuser also functions as a draft tube, and the combination is sometimes called a draft tube-diffuser.

efficiency: the ratio of the output to the input of a turbine (or any engineering artifact or system). In the Francis era the term"coefficient of effect" was used, but the modern word is preferred today.

Fourneyron turbine: a water motor invented by Benoît Fourneyron in France. The water entered at the top through a pipe-like penstock. It then flowed through the fixed guides at the bottom of the turbine. The direction of the flow of water was turned 90 degrees, and it flowed out through a horizontal rotor in the radial direction. The water did not impact the vanes, hence it was a reaction or pressure turbine. Because the water entered under pressure which declined as the water moved through it, this and all other reaction turbines must be enclosed in an air-tight, usually metal casing. As improved by Uriah A. Boyden the Fourneyron turbine was widely used in the United States between 1845 and 1868.

gross power: the amount of power in falling water, as distinct from the net power realized by a water wheel or turbine. Synonymous with "potential energy," in most cases.

guides or guide vanes: curved devices which give a predetermined direction to the flow of water. Fixed guides were incorporated into the inlets of turbines by Benoît Fourneyron, and were used in early Francis turbines. Pivoted guides are now in universal use (first employed by James Leffel and later by John B. McCormick in their variations on the Francis turbine). Pivoted vanes can eliminate shock at the entrance to the vanes, and thus produce more uniform efficiency under varying heads or volumes of flow.

head: the height through which the water falls in a water wheel or turbine.

kinetic energy: energy of motion, equal to $1/2\,MV^2$, where M is the mass of water and V is the velocity. In English units energy is measured in foot-pounds, mass is measured in pounds, and velocity in feet per second.

mill power: a unit of water power used first at Waltham and later (in slightly modified form) at Lowell. It was originally the amount of water power needed to drive the larger of the two mills constructed by Francis C. Lowell at Waltham. This unit was ambiguous, and has been given different values by different authors; it was used by Francis only in reference to legally leased power; he gave it the value 96.49 gross horsepower.

mixed flow: a flow regime that is both inward and downward. This is the kind of flow characteristic of the Francis turbine.

net power: the amount of power in falling water actually converted by a water motor into useful work.

penstock: a conduit which carries water to a water wheel or turbine.

runner: the circular rotor of a turbine which carries the vanes. I have usually used the more descriptive term "rotor."

scroll or scroll casing: a spiral-shaped chamber invented by the Parkér brothers and employed in modified form by Boyden to give a spiral motion to the water to prevent shock as the water passed into the guide vanes. Today these devices, now sometimes called "volute chambers," surround Francis turbines and feed them water for the same ends as the original scroll cases.

shock: a sudden change in velocity which caused a loss of power. In modern engineering writings "shock" has been replaced with the phrase "angle of incidence losses." In the ideal water motor (or "turbine") as described by Charles de Borda and Lazare Carnot, "entrance without shock" was one of the three conditions necessary to approach 100 percent efficiency.

tangent entry: when water enters a turbine parallel (or tangent) to the moving rotor vanes, thus avoiding losses from shock.

turbine: originally (and in this work) an "ideal" water wheel, that is one designed according to the conditions laid down by Charles de Borda and Lazare Carnot, and hence capable of a theoretical 100 percent efficiency. In modern usage any power source operating by continuous rotary motion.

undershot water wheel: a vertical water wheel where the water acts upon the bottom of the wheel by impacting the vanes ("floats").

vane: the curved surface (usually metal) which channels the water in the rotor or "runner" of a turbine. Turbines operate by pressure on these vanes.

weir: normally an overflow dam; in the context of turbine testing (and this work), one or more rectangular openings through which water is admitted to a turbine or water wheel and by which the flow of water is measured.