Francis and His Turbine

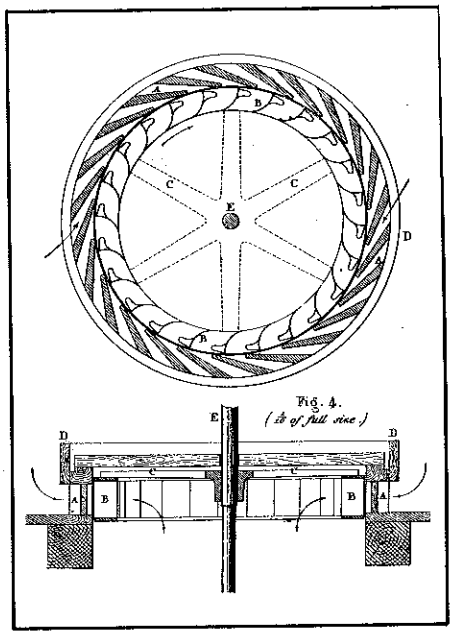
James Francis, a pioneer in early waterpower development, invented the popular turbine that bears his name. This article describes his work which resulted in this important contribution to the hydro industry.

By R.W. Shortridge

In 1849, James Bicheno Francis performed extensive studies on a turbine with inward radial flow. Although he did not invent this type of turbine, he made major improvements in its design and construction. His studies of its operating characteristics were far more comprehensive and precise than any that had preceded them. He published a detailed account of his experimental work on this turbine in an 1855 book, "Lowell Hydraulic Experiments", which became an early classic. The book was published again, with additional material, in 1868 and 1883. It is not surprising that this type of turbine, in which the path of water flow is (at least initially) radially inward from its periphery, has become universally known as the Francis turbine.

Francis was born in England in 1815. His father was superintendent of a railroad and harbor in Wales, and young Francis was employed at the age of 14 under the chief engineer of the works of that harbor. At 16, he worked under the chief engineer of the Grand Western Canal, In Devonshire and Somersetshire. He came to America in 1833, still a teenager.

He immediately was employed to help survey routes for the New York, Providence, & Boston Railroad. In 1834, his superior, George W. Whistler, left to take charge of the extensive hydraulic improvements under way at Lowell, Massachusetts, and young Francis accompanied him. Whistler left Lowell in 1837 to become chief engineer of a railroad, and the 22-year-old Francis succeeded him as chief engineer for the corporation known as the Proprietors of the Locks and Canals on Merrimack River. Francis was to remain in this position throughout the remainder of his career. Upon his retirement in 1884, he became consulting engineer for the same corporation until his death in 1892.



The Howd wheel, patented in 1838, preceded Francis' designs which improved efficiency.

Francis was one of a dozen charter members of the American Society of Civil Engineers, which was founded in 1852; he served as its president from November 1880 to January 1882.

Development of water power at Lowell, Massachusetts began in 1821, when the state chartered The Merrimack Development Company, which then bought a number of farms near Pawtucket Falls, in Lowell. The Proprietors of Locks and Canals on Merrimack River, originally formed for improving navigation on the river, in 1826 bought the property from Merrimack Development. This property now included, in addition to the real estate, a 950-foot-long dam just above Pawtucket Falls that Merrimack Development had built, The Pawtucket Canal, which it had enlarged, and several short canals branching from it to various mills in the vicinity. The Proprietors corporation now occupied itself primarily with the selling of mill sites and water-power privileges.

In 1839, the last available waterpower privilege was sold to Massachusetts Cotton Mills, and at this time all the establishments that owned privileges bought all the stock of the Proprietors corporation. These establishments owned a total of 91 mill powers, a mill power being defined as the right to draw 25 cubic feet of water per second on a fall of 30 feet for fifteen hours per day; a mill power equalled about 60 horsepower. In 1846, a new canal and a new dam allowed 139 mill powers, or about 9,000 horsepower, to become available.

Up to about 1844, most of the

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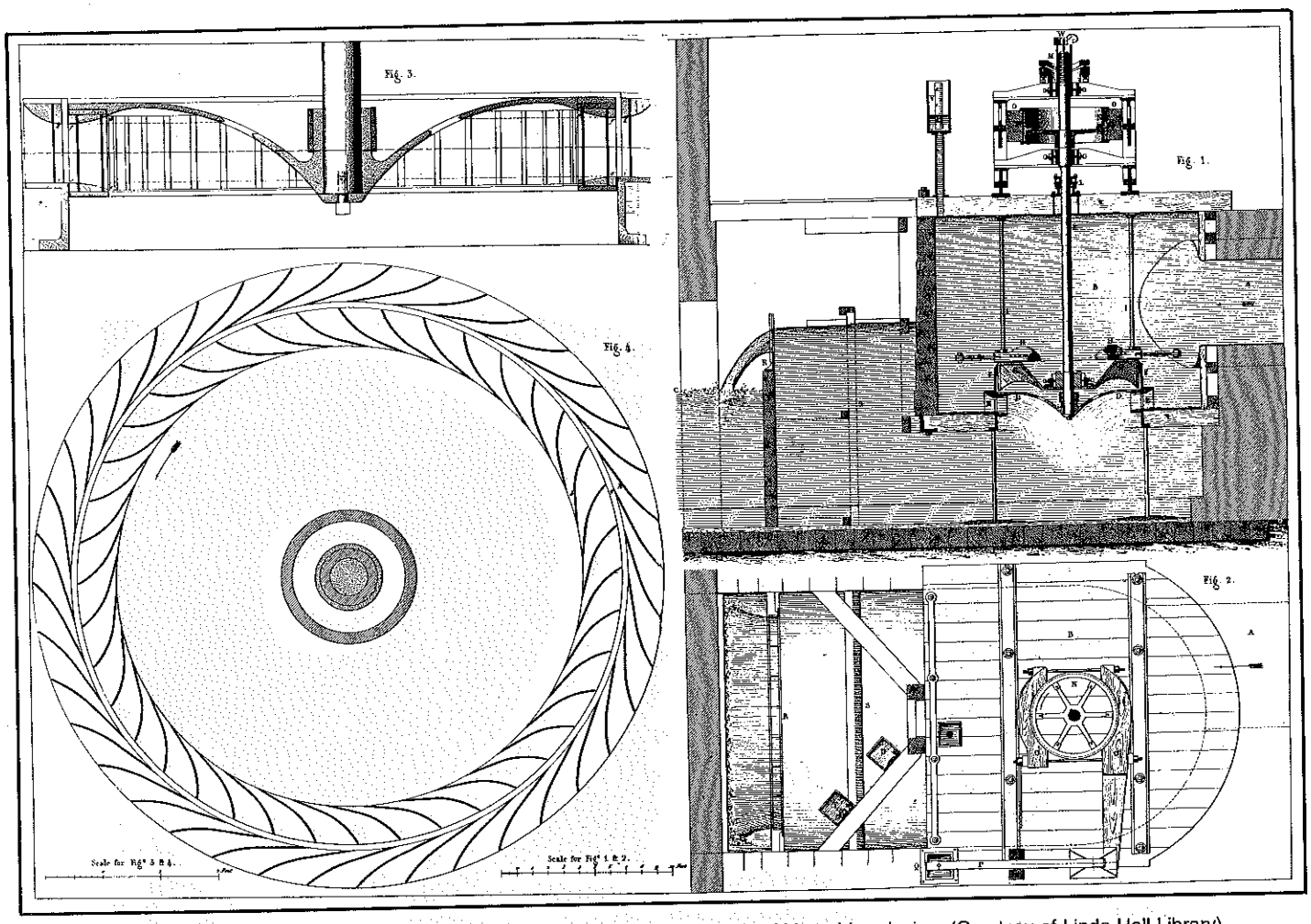

A Plate from Francis' 1855 book, "Lowell Hydraulic Experiments," shows features of his turbine design. (Courtesy of Linda Hall Library)

Lowell mills derived their power from breast wheels, which operated simply by the weight of the water in the buckets of the wheel. The best ones operated with an efficiency approaching 75 percent. Elsewhere in the country, reaction turbines of various types were coming into use. While quite inefficient by comparison with the large overshot and undershot wheels, they had the advantages of being less expensive to build and install, occupying relatively little space, being less impeded by backwater, and not requiring expensive masonry wheelpits.

In 1844, a hydraulic engineer named Uriah A. Boyden, inspired by European work on the Fourneyron turbine, for which efficiencies of 75 percent were claimed, built one for the Appleton Company cotton mill at Lowell. The Fourneyron turbine is one in which water flows radially from the inside to the periphery of the runner. Boyden's turbine reached an efficiency of 78 percent. He then entered into an incentive contract with the same company to design and build three more such turbines, each about 2 1/2 times as powerful as the first one. His price was $1,200 for his services, plus an extra $400 for every percent of efficiency gained above 78 percent. James B. Francis, as chief engineer for the corporation of which the Appleton Company was part-owner, was detailed to make the efficiency measurements, and found that these turbines operated, under optimum conditions, at 88 percent efficiency. Boyden's fee was thus increased from $1,200 to $5,200.

As a result of this project, in 1849 the companies of which Francis was chief engineer bought all rights to use Boyden's improvements relating to turbines, and it became Francis' responsibility to design and superintend the construction of similar Fourneyron-Boyden turbines for other mills at Lowell. These were completed in 1851.

In the meantime, Francis was proceeding on the design and construction of a pair of turbines with a flow regime the opposite of that of the Fourneyron turbine, namely, from the periphery radially inward. Apparently, the first turbines of this type had been designed and constructed by Samuel B. Howd, of Geneva, New York, who received a patent on them in 1838. (One reference indicates that the French mathematician, Jean Victor Poncelet, conceived of the idea of this type of turbine in 1826, but did not actually reduce the idea to practice; survey of the literature does now, however, bear out this statement). Many Howd turbines had been built before Francis began his studies on the type; they had been constructed simply and cheaply, but were quite inefficient.

In 1849, Francis undertook to improve the design of the Howd turbine and build two for the Boott Cotton Mill at Lowell. While giving credit to Boyden for a number of the minor features of the design, Francis

The Lowell Canal System and its associated structures is one of the most historically significant waterpower sites. The project is a key feature in tours given by both the National Park Service and Massachusetts Heritage State Park. The site is also used by the University of Lowell in connection with educational programs.

The facilities are owned by Boott Hydropower, Inc., a wholly-owned subsidiary of Consolidated Hydro, Inc., of Greenwich, Connecticut.

The newest hydropower plant, completed in 1985, is the Eldred L. Field Hydroelectric Plant, named for the Founder of Boott Hydropower, Inc.

Five hydroelectric plants have been developed at Boott Mills. They are:

Assets Power Station	795 kW
Bridge Street Power Station	3,440 kW
Hamilton Power Station	1,180 kW
John Street Power Station	2,500 kW
Eldred Field Power Station	15,000 kW

Altogether, the plants produce about 81 million kWh per year.

The 15 MW Eldred L. Field Hydroelectric Plant at Boott Mills, Lowell, Massachusetts. The plant houses two 120 rpm, 7.5 MW Kaplan turbines, which operate at 33.5 feet of head.

felt that he had "so modified the form and arrangement of the whole, as to produce a wheel essentially different from the Howd wheel, although it may, possibly, be technically covered by the patent for that wheel."

Francis carefully measured the efficiency of this prototype turbine, and found it to be as high as 80 percent under optimum conditions. He noted at least two obvious flaws in his original design. One was the lack of a draft tube (called by Francis a "diffuser"), and the other was an abrupt increase in the cross-section of the water stream as it left the vanes and entered the runner blades. He stated that when as much attention had been paid to its theoretical design and practical construction as had already attended the development of the Fourneyron turbine over the years, his "centre-vent water wheel ... will not be much behind that celebrated motor, in its economical use of water."

Francis conducted his experiments on this turbine, on the Fourneyron turbines, and on the flow of water over weirs and in short rectangular canals, with a degree of experimental control and precision unprecedented for hydraulic measurements of that period. Where various types of data were to be collected, for instance, multiple observers were used, and their watches were synchronized, so that all measurements in each set were obtained simultaneously. All imaginable sources of error were minimized; thus, for example, the gravitational constant was corrected for the latitude and altitude of Lowell. Overall errors in the various experiments were reduced from about ten percent to about two percent.

In the original Francis turbine, the inward flow through the runner was purely radial; only after the water left the runner did it begin to flow in an axial direction. In a logical development, the runner blades were gradually modified over the years so as to cause the water to turn in an axial direction before discharge from the runner. Even so, because the modern inward mixed-flow turbines did evolve from Francis' original inward radial-flow turbine, all are termed Francis turbines, in honor of the civil engineer whom some consider to be the father of modern hydraulic engineering. □

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Acknowledgment

The 1855 and the 1883 editions of Francis' book "Lowell Hydraulic Experiments" are in the collections of Linda Hall Library of Science and Technology, Kansas City, Missouri, and much of the material for this article has been drawn from these volumes. Grateful acknowledgment is given to Linda Hall Library for making them available.