The Falkirk Wheel

The Millennium Link's Key Attraction

by Lee Freeland

The Falkirk Wheel is the principal attraction and engineering triumph of the GBP84.5-million (US$172-million) Millennium Link project, initiated in 1994 to restore navigability across Scotland by connecting its historic Forth & Clyde Canal, and the Edinburgh and Glasgow Union Canal (Union Canal). The world's first rotating boat lift, the wheel has not only revitalized and reconnected neglected parts of central Scotland along its path, but also become an international tourist attraction for many reasons.

While the waterway has been part of the landscape for hundreds of years, all 39 locks on the former canal required some degree of restoration. The lift replaces 11 decayed locks to vertically transport vessels 115 feet (35 meters) between the two canals. When officially completed on May 24, 2002, the project became the U.K.'s first new ship lift in more than 125 years. It is considered very economical for its scope, with a final cost of less than US$35 million.

The Millennium Link was part of the larger Canals Restoration Project, which also included 4,593 feet (1,400 meters) of new channel, six new (two deep) locks, 32 refurbished locks, 146,000 tons of dredging, a 160-meter-long tunnel, a 361-foot- (110-meter-) long aqueduct and various road projects for the Forth & Clyde Canal. The entire project crosses 68 miles (110 kilometers) of Scotland. On May 26, 2001, after three years of construction, this inland waterway was opened for the first time in nearly 40 years. The Union Canal proved a similar undertaking, consisting of 12,467 feet (3,800 meters) of new channel, two aqueducts, one tunnel, three locks, 147,000 tons of dredging and numerous bridges.

Linking these vital canals, the Falkirk Wheel has facilitated steady annual increases in both numbers of boats and towpath users, while stimulating both long- and short-term development across the waterways' length. Visitors experience the wheel's movement in one smooth motion after their vessel has glided into one of its 55-ton caissons, or gondolas. These structures serve as the lift's

"cars," which are filled with meticulously balanced volumes of water and sealed tightly by lock gates.

The Wheel's Design

Multiple designs for the lift near the city of Falkirk were drafted and promoted between 1994 and 1999. The final plan was reminiscent of a massive Ferris wheel supporting four caissons. While potentially functional, the design was deemed unappealing and overly conventional. Millennium Link overseer British Waterways Scotland, a government body that manages and upkeeps canals, rivers, docks, buildings, structures and landscapes in Scotland, thus decided to begin the process anew. The conceptual design for the current wheel was completed in three weeks by a 20-person team of civil, mechanical and structural engineers, and architects. The international group included Morrison-Bachy-Soletanche, with leading specialists from Ove Arup Consultants, steel producer Butterley Engineering along with its consultant Tony Gee, and Scotland-based RMJM architects.

"It is elegant, dramatic, 21st-Century technology, but a structure still based on proven engineering principles," remarked Hugh England, divisional director of Morrison Construction, part of the Morrison-Bachy-Soletanche joint venture, contracting company for the project. According to information from the Falkirk Wheel's visitor center, its design was inspired by various regional sources, including a Celtic double-headed

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A rotating caisson in operation

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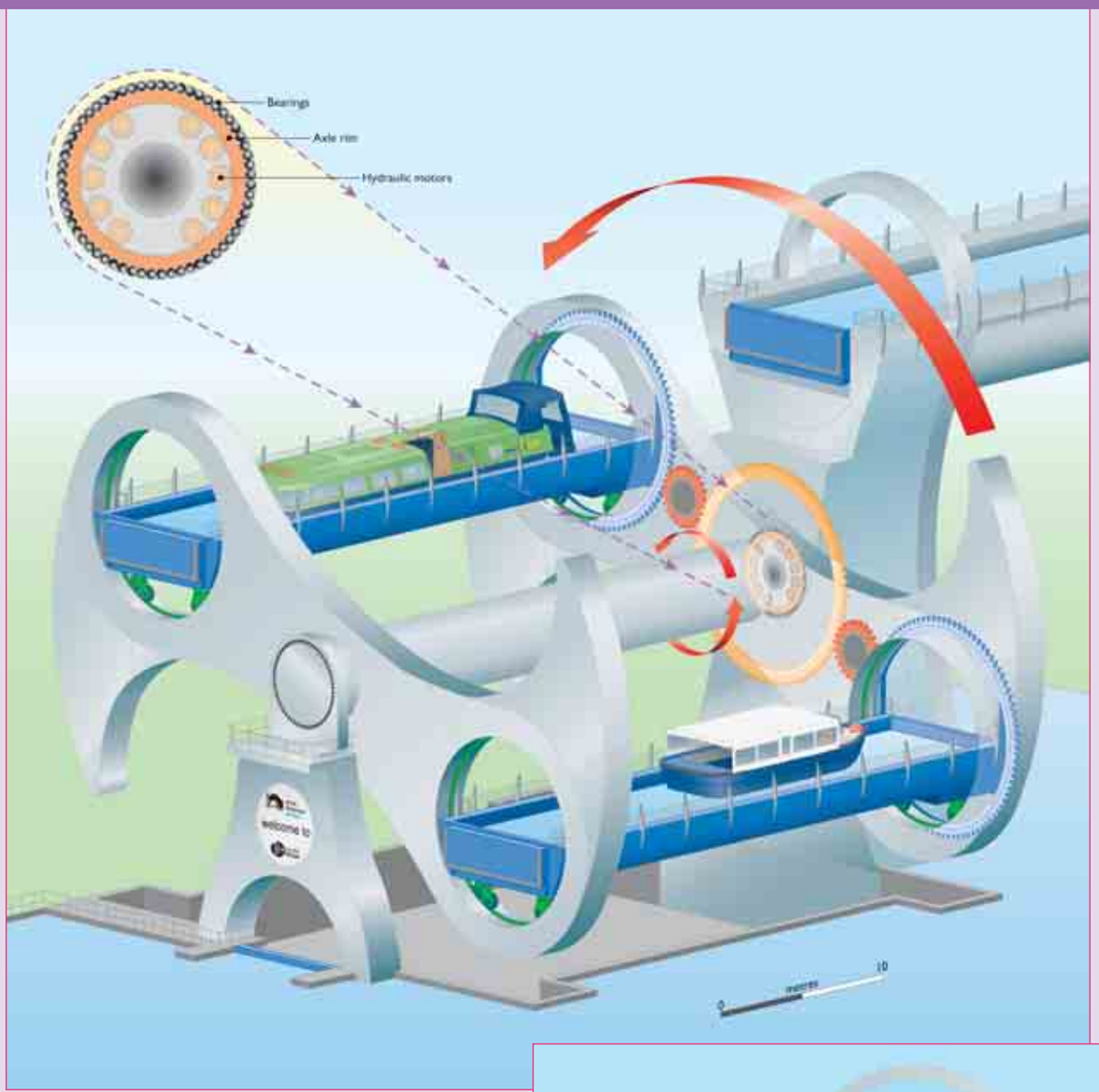
axe, a propeller of a Clydebank-built ship and the ribcage of a whale.

Challenges

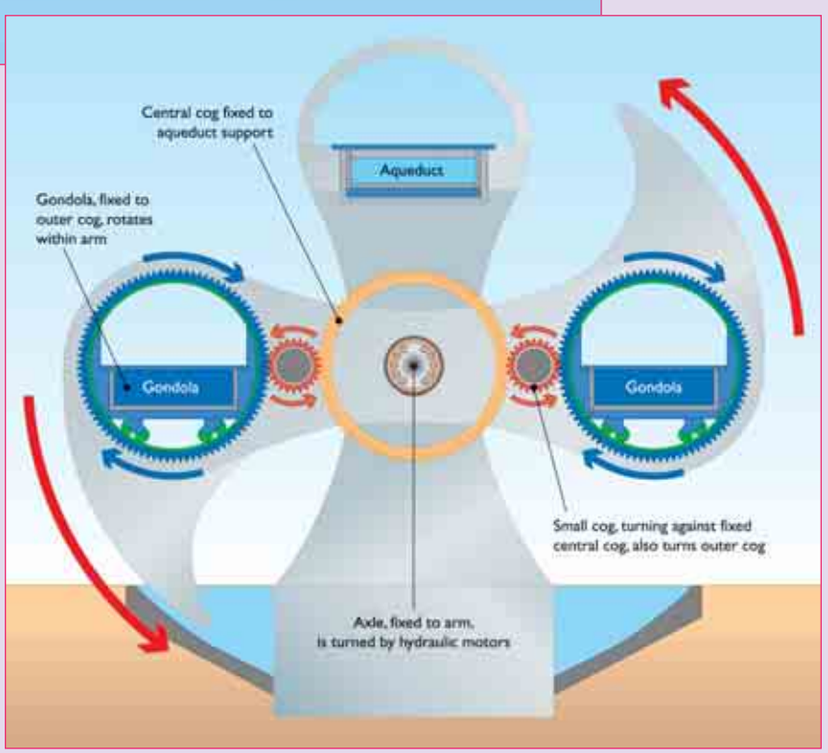
Various engineering challenges were met in the wheel's design, the primary of which was to ensure that each set of gondolas remained horizontal while in operation. Each caisson runs on small wheels that fit into a single curved rail fixed on the inner edge of each arm's opening. As a safeguard, a series of linked cogs was installed between the gondolas and arms, keeping the caissons at the same speed and maintaining their horizontal position. This eliminated the chance that the gondolas could have stuck to the rims of the large holes that they pass through due to friction and the force from the disturbed water. Had this happened, a slight further rotation could have tilted the caissons and caused them to fall over.

Since the arms rotate one way and then the other, the alteration of these forces also had to be addressed. Some sections even experience total stress reversals – from total tension to total compression. The danger was that fatigue could occur after repeated stress reversals, causing cracks through the superstructure. While design and detailing went far to avoid such an effect, bolted connections were favored over typical welded



Left: An isometric image of how the wheel works

Below: The cog system's operation



ones to add robustness to the lift, which weighs nearly 2,000 tons when loaded.

Constructing the Wheel

Parts of the 1,200-ton Falkirk Wheel were constructed and assembled at Butterley Engineering's steelworks in Derbyshire. It was necessary to fit the pieces together (each of which weighed 270 tons) to an accuracy of 0.4 inches (10 millimeters) to ensure a perfect final fit. In mid 2001, the structure was then dismantled and transported to Falkirk via 35 truckloads, then bolted back together on the ground and lifted by a 1,000-ton crane into position. This process occurred over a week.

The lift is required to constantly support and move its caissons, which are often filled with 600 tons of water and boats. Over 15,000 bolts were matched with 45,000 bolt

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Varied lighting schemes are employed to make the wheel a different experience after night falls.

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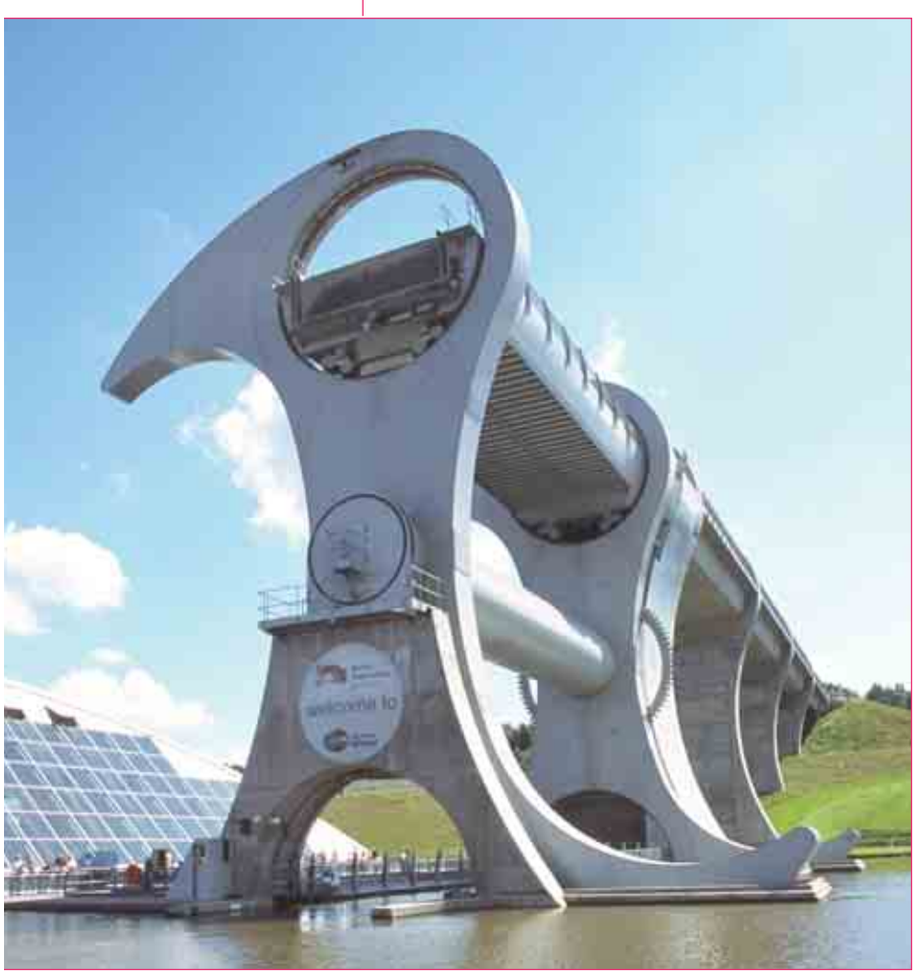
holes, and each bolt was hand tightened. Once this was complete, the entire wheel had to be suspended on a temporary, adjustable rig so that it could be aligned with the aqueduct. This procedure, required a tolerance of only 0.04 inches (1 millimeters).



A "front" view of the wheel from a boat in the lower canal

Much on-site dredging was required even before the structure could be brought to the canals. The former locks still carried 63 million liters of runoff surface water each day, which constantly had to be pumped around the construction work to avoid a flooding of the site that could occur within minutes. Furthermore, because the jobsite was formerly used for opencast mining and as a tar works, iron-oxide contamination of the shallow groundwater and ground required the canal to be fully lined throughout its length with water-retaining structures. Thus, a 107,639-square-foot (10,000-square-meter) basin/marina was constructed in the 82 feet (25 meters) of backfill. The aqueduct and wheel were built on top of this and supported on large-diameter-bored piles socketed into bedrock.

As the wheel is intended to last another 120 years, the most durable of materials were utilized in large quantities, including:

- 247,202 cubic feet (7,000 cubic meters) of concrete
- 1,000 tons of reinforced steel
- 1,200 tons of prefabricated steel
- 376,737 square feet (35,000 square meters) of canal lining

Wheel Operation

The reinforced-concrete boat lift uses the Roughcastle tunnel and a double staircase lock to connect the Forth & Clyde and Union

Canals. Water levels are monitored for precision by a computer system. Boats entering the wheel's upper gondola are lowered, along with the water in which they float, to the basin below. Using Archimedes' Principle of Displacement, an equal weight is lifted in the lower gondola. In addition to the aforementioned series of cogs, two 0.3-inch- (8-millimeter-) diameter cogs were installed behind the arm (hidden from view) nearest the aqueduct to which one end of each caisson is attached. A third cog of the same size is in the center, attached to the main fixed upright. Two smaller cogs were fit in the spaces between, with each cog having teeth that fit into the next, pushing against each other. These turn around the fixed central cogs, and the two gondolas, attached to the outer cogs, thus turn at the same speed as – but in the opposite direction to – the wheel.

Due to the simple mechanics this system of cogs provides and the precise balancing of the caissons, a group of only 10 hydraulic motors located within the central spine provide the 1.5 kilowatt-hours of electricity necessary to turn the wheel. This amounts to lifting 330 tons (over 80,000 gallons) of water and its cargo in one 7-minute movement for no more electricity than that required to boil eight kettles of water.

The arms connecting the main structure and the gondolas are attached about 25 meters apart to an 11.5-foot- (3.5-meter-) diameter axle. The wheel rotates along with the axle, which is supported by slewing bearings (13.1 feet [4 meters] in diameter) that are fitted to the ends of the axle with their outer

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A tour boat sailing through an aqueduct at the top of the lift

Facts and Figures

- The Falkirk wheel is 115 feet (35 meters) tall, 115 feet (35 meters) wide and 100 feet (30 meters) long.
- The wheel stands in a 330-feet- (100-meter-) wide, circular basin with moorings for over 20 boats.
- The Forth & Clyde and Union Canals are approximately 1.2 miles (2 kilometers) (horizontally) and 111.5 feet (34 meters) (vertically) apart.
- The hydraulic pump in the machine room of the wheel drives the system at one-eighth of a revolution per minute.
- The wheel can transport up to four 65.6-foot- (20-meter-) long boats at a time.
- The lift at Falkirk is one of only two boat lifts in the U.K.: the other is Cheshire's Anderton Boat Lift (ELEVATOR WORLD, May 1997).
- A consortium of partners are responsible for funding of the Millennium Link project, including the Millennium Commission, European Regional Development Fund, Scottish Enterprise Network, the Waterways Trust Scotland and seven local authorities.
- The engineering work on the wheel itself has received the following awards: the Brunel Medal 2002 from the Institution of Civil Engineers, the Structural Steel Design Award 2002 and the VIVA Award 2002 from Innovative Solutions for the Advancement of Transport in Great Britain and Northern Ireland.

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Left: Boat shows such as this one often take place at the wheel.

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rings mounted on the plinths, which sit atop piled foundations. The slewing bearing at the machine-room end of the axle has an inner ring gear, which rotates. This rotating annulus is driven by 10 hydraulic motors assembled on a stationary bearing and motor assembly, which is itself mounted onto a plinth similar to the one at the other end of the axle. The motors' driveshafts have pinion gears that act as stationary planetary gears in this train of gears and engage the rotating annulus ring gear. An electric motor drives a hydraulic pump, which is connected to the hydraulic motors by means of hoses.

The Docking Pit

The docking pit is an essential component to the efficient operation of the boat lift. It exists as a port similar to a dry dock that is isolated from the lower canal basin by locks and kept dry via water pumps. This is so that when the wheel stops and its arms are vertical, boats can pass through the open gates of the lower caisson without flooding the docking pit. Without this dry dock, the wheel would be mired in water at the lower canal basin, causing problems such as the bottom gondola becoming buoyant and requiring more power to move.

History

The Forth & Clyde and Union Canals, collectively called the Lowland Canals, were once connected by locks at Falkirk to provide a direct link between Glasgow and Edinburgh. These 11 locks stepped down across 0.9 miles (1.5 kilometers) to connect the canals, taking barges a full day to traverse the passage. They were dismantled in 1933, and the canals themselves were closed in 1963 due to road-building projects that blocked the waterways in over 30 places. Until the reopening and reunification of the canals some 39 years later, the dilapidated route experienced great economic hardship, with unemployment reaching a peak of 30% above Scotland's average in 2000.

The Forth & Clyde

The original plan for the Forth & Clyde Canal was for the waterway to leave the Forth by the Carron River to the first lock at

the Grange Burn and move west through the valleys of the Bonny and Kelvin Rivers to Stockingfield (Maryhill). Work began on June 19, 1768, but after nine years, lack of funds necessitated a halt of the project at Hamilton Hill. Eight years later, money forfeited from the Jacobite Estates was made available to complete the canal, and it finally reached the Clyde in 1790. In the same year, the Glasgow Branch was extended to Port Dundas.

The main canal was (and remains) 35 miles (56 kilometers) long, stretching from coast to coast. The Glasgow branch extended another 3.5 miles (5.6 kilometers). The system was 60 feet (18.3 meters) wide and 9 feet (2.7 meters) deep, rising 156 feet (47.5 meters) above sea level through 20 locks on the eastern side and 19 on the western. The waterway was extended when the Monklands Canal was joined to the Port Dundas Basin in 1793, then when it was joined with the Union Canal at Camelon (a village near Falkirk) in 1822.

There are a number of Scheduled Ancient Monuments – protected by the U.K. government due to national importance – on the Forth & Clyde Canal, including the Bascule Bridge at Port Dundas, Possil Aqueduct & Old

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Many angles of the lift are available for visitors to observe.

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Basin, Maryhill Locks and Kelvin Aqueduct. The Bascule Bridge and Railway Swing Bridge at Port Dundas are listed buildings. The Kelvin Aqueduct especially stands out, for at 403 feet (123 meters) long and 69 feet (21 meters) high, it was the largest structure of its kind in Britain when it was completed in 1790.

The Union

The Union Canal went under construction in 1818 and opened four years later. The canal was originally constructed to transport coal into Edinburgh, with the intention to break the monopoly consisting of Edinburgh coalmasters and Midlothian mine owners. A 31.5-mile (50-kilometer) contour canal, it ran from Edinburgh to Falkirk, where it joined the Forth & Clyde. Popular features of the canal include the Avon, Almond and Slateford Aqueducts, and the Laughin' and Greetin' Bridge at Glen Village, famous for the carved faces on its keystones. The Union began with only one canal tunnel along its length, which had to be cut through solid rock. It was necessary because a powerful landowner objected to the prospect of being able to see the canal from his house. Later, to protect the Antonine Wall, another tunnel was dug underneath the historical structure. This is one of the first passages through which most visitors pass on their tour of the Falkirk Wheel.

John Scott Russell discovered the physical phenomenon he called the "wave of translation" on the canal in 1834. While once popular as a means of recreation and transportation, a rapid decline in its use began when the railway between Glasgow and Edinburgh opened in 1842. This culminated in 1921, when ports at Hamilton and Hopetoun were sold to the Edinburgh Council and filled in.

The Wheel Today

As designed, the wheel has provided both its own area and the length of the canals it unites with increased tourism and leisure opportunities. Specially commissioned boats and a large tourism staff guide visitors through "The Falkirk Wheel Experience," which includes a trip on the lift. Helping to draw over 12 million visitors to the Millennium Link per year, the Falkirk Wheel is widely accepted as an impressive feat of modern engineering. British Waterways Chief Engineer George Ballinger's 2000 prediction has rung true: "As Scotland's Eiffel Tower, the public will flock to it."