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Engineering the Forth & Clyde and Union Canals (1768-1822), Scotland and their Regeneration via The Falkirk Wheel (2000-2001)

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Abstract

The 58 km. Forth & Clyde Ship Canal was created across Scotland between the North and Irish Seas from 1768 to 1790, then the world's deepest sea-to-sea canal. In 1822 it was joined near Falkirk by the smaller scale 50 km long Union Canal from Edinburgh by means of an impressive flight of 11 locks, now being replaced in use by the innovative "Falkirk Wheel" rotating boat lift, the key element in the £78m. Millenium Link canal regeneration project. This paper, essentially an enlargement of the historical comment in the Author's recent ICE Smeaton Lecture*(1)*, relates to contemporary civil engineering practice on these navigations and its significance. It concludes with a description of the basic operational principles of the Falkirk Wheel.

The Forth & Clyde Canal

Introduction. In 1764 John Smeaton (1724-92) was brought in by the Canal's proprietors to plan and, in 1768, to direct the massive and novel undertaking of the Forth & Clyde Canal, his largest project. He had successfully completed Eddystone Lighthouse and was Britain's leading "Civil Engineer", a title that he is believed to have been the first to use, probably in 1754. In 1767 Smeaton proposed a 2.1m. (7 ft.) deep canal from Grangemouth (as it became known) to Dalmuir locking up from both sides of Scotland to a long summit level (see Figure 1), capable of taking small sea-going ships, and estimated to cost £147,340. After the Act of Parliament was obtained for the project in 1768 Smeaton was appointed "Chief Engineer" and chose the experienced Robert Mackell (d.1779) as "Resident Engineer".

Cutting of the canal by contract began at Grangemouth on 10 June 1768 and the work proceeded westwards. In May 1771, acting on a suggestion of Mackell, approved by Smeaton, the line was altered to come closer to Glasgow thus accepting the necessity for a large aqueduct over the River Kelvin for the canal's completion (see Figure 1). By 1772, the canal had reached the east end of the summit level and in 1773 was navigable from Grangemouth to Kirkintilloch, only 7 miles from Glasgow, Stockingfield. Work on the substantial Luggie Aqueduct at Kirkintilloch had started and Smeaton, who for some time had been wanting to resign because of the pressure of other work, was released from his post with Mackell continuing in charge. By November 1777 the canal reached Hamilton-hill Basin, Glasgow, and work came to a 7-year standstill with the company £40,000 in debt, but at least it

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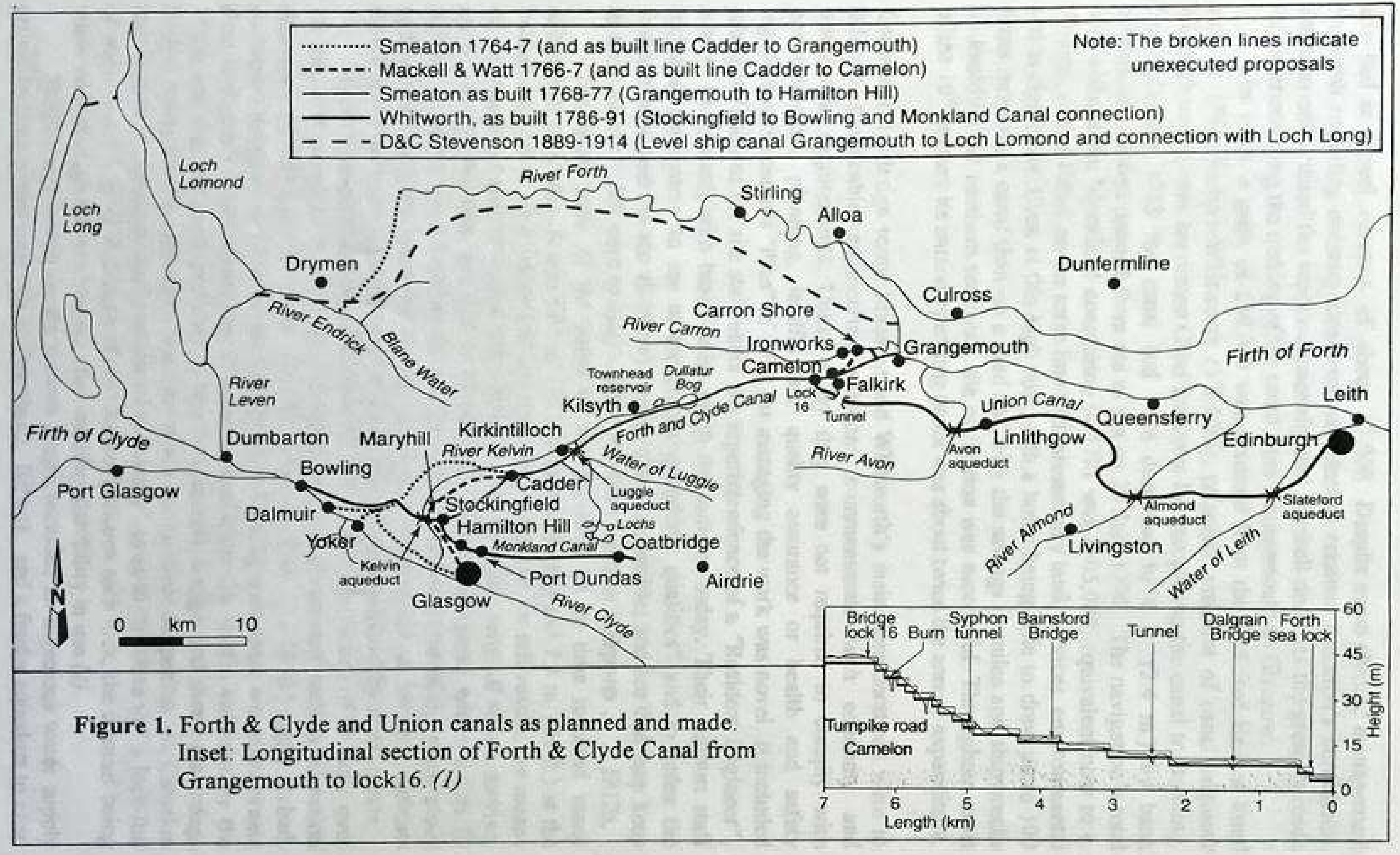

Figure 1. Forth & Clyde and Union canals as planned and made. Inset: Longitudinal section of Forth & Clyde Canal from Grangemouth to lock16. *(1)*

now had an annual revenue of about £5,000. Despite some chronic management problems regarding contract measurement, Mackell retained Smeaton's confidence. Smeaton only visited the work occasionally and Mackell deserves the greatest credit for superintending the making of the canal from Grangemouth to Glasgow.

In 1784, a grant of £50,000 was obtained from the Forfeited Estates Fund and, in 1785, Robert Whitworth (1734-99), principal assistant of canal engineer James Brindley, was appointed Chief Engineer for completing the canal to Bowling. By December 1788 the canal had been deepened to 8 ft. (2.4 m.) by bank heightening. It was opened from sea to sea on 28 July 1790. The navigation's total cost without the Monkland connection in 1791 was £305,000, equivalent now to c. £100m., or c. £400m. on the same line with present day land, services, environmental and bridge costs. Even at this high cost, with a horse being able to draw up to 100 times more on a canal than on a road and with the savings in miles and shipwrecks by avoiding the northern sea route, the navigation was successful. Throughout most of the 19th century its annual operating profit was about twice the annual expenditure.

Comment. In design terms Smeaton and Whitworth's main considerations were to achieve practicable engineering solutions commensurate with economy and operational requirements. Unlike today they were not required to comply with environmental, planning, landfill tax, quality assurance or health and safety legislation. Smeaton's "Plan" of 1768 for managing the work was novel. It included job specifications for site staff under the superintendence of a "Resident Engineer", a term he created, with basic duties much the same as today. Their support staff included surveyors "to see to the proper quantities, qualities" and to order the foremen who had "to see all (their) men as often as possible; and see that they keep to their labour". All were to keep written records (Smeaton's *Reports* . . ., 1812).

The large scale of the canal by the standards of its time required many substantial structures. It was 17.1 m. (56 ft.) wide at the top and 7.3 m. (24 ft.) at the bottom and 2.4 m. (8 ft.) deep and had unlimited headroom for tall vessels, by means of 43 aqueducts and 33 timber draw-bridges. The 39 locks, most of which survive, are 6.1 m. (20 ft.) wide and 22.5 m. (74 ft.) long between the gates, with a 2.4 m. (8 ft.) fall. In soft ground a timber floor and piling were used. Some of the many pipes and tunnels carrying water under the canal were constructed as inverted siphons including at least one large diameter wooden pipe of staves secured by metal bands.

From Grangemouth the canal rises 47.5 m. (156 ft.) by means of 20 locks over 16 km. (10 miles) to the 29 km. (18-mile) long, level, summit section. Camelon Aqueduct (1772) over a 4.9 m. (16 ft.) wide 3.3-4 m. (11-13 ft.) high, arched, underpass designed in 1770 for the Edinburgh to Stirling main road, was more ornate than Smeaton's other aqueducts. It became inadequate for traffic volumes by the 1820s and was replaced, probably at first by a bascule bridge, and then by a swing-bridge, being briefly seen again last year when cut by canal deepening. At Camelon (see Figure 1), Smeaton designed the locks "singly" so as to "treasure up" a lock-full of water in a 0.3 m. (1 ft.) depth of the channel between each lock, the channel being made wide enough for two vessels, thus enabling flexibility in use.*(1)*

Skilful engineering on the summit length included an ingenious water supply provision from a new reservoir at Townhead, Kilsyth, and a feeder aqueduct to near

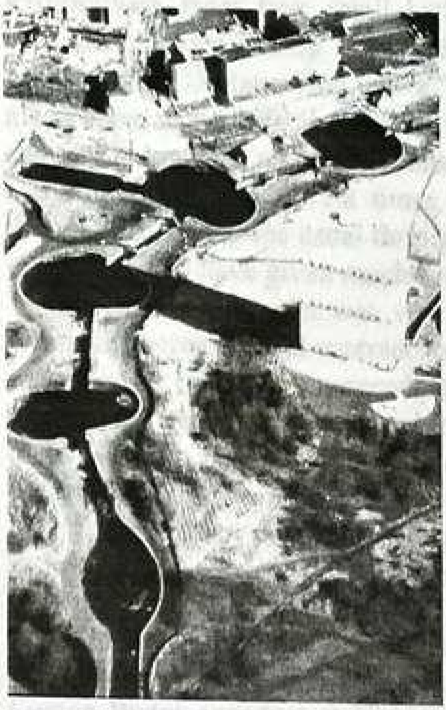

Figure 4. Kelvin Aqueduct east end, Maryhill Locks and dry dock. British Waterways.

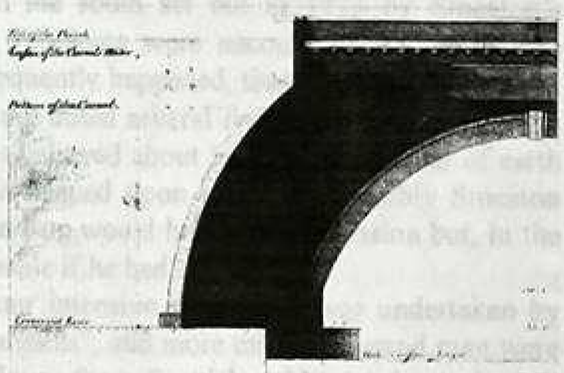

Figure 2. Luggie Aqueduct drawing, 1772. Royal Society Smeaton drawings, **V**, f. 26v.*(1)*

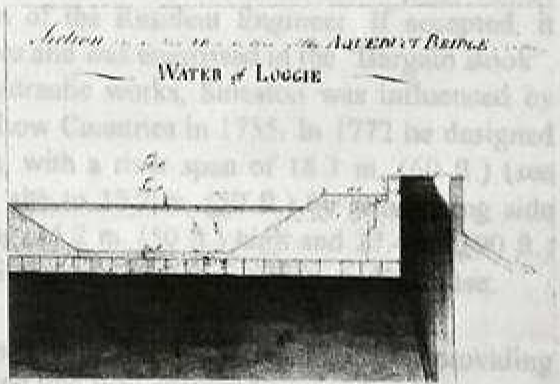

Figure 3. Luggie Aqueduct cross-section, 1772. Royal Society Smeaton drawings, **V**, f. 27.*(1)*

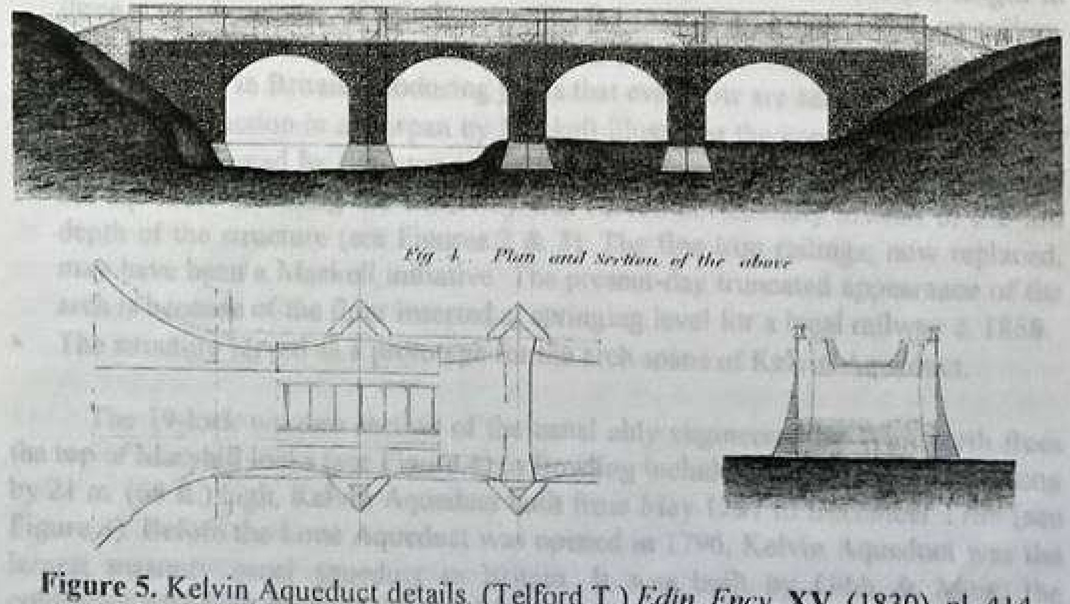

Figure 5. Kelvin Aqueduct details. (Telford T.) *Edin. Ency.* **XV**, (1830), pl. 414.

Kirkintilloch from four small lochs to the south set out in 1773 by Smeaton's assistant William Jessop (1745-1814). Problems were encountered by taking the canal through Dullatur Bog where "it frequently happened, that when the banks were made apparently perfectly, they have sunk down several feet in the course of a day and had to be again renewed, so that it is believed about 55 ft. perpendicular of earth and stones has, at different times, been heaped upon them".*(1)* Possibly Smeaton thought that taking the canal through the Bog would help water provision but, in the event, it would have given much less trouble if he had skirted it.

The whole project was very labour intensive. The work was undertaken by means of scores of local contracts or "bargains", and more than a thousand men were employed at times, an unprecedented figure for a Scottish public works project. It was largely because of the initial inexperience of the local work force that the canal took longer to build and cost more than planned. The work was let as follows. A potential contractor responded to a local printed advertisement, viewed the site of the lot offered and any drawings at a specified office, and then submitted a proposal for executing the work under the direction of the Resident Engineer. If accepted, it became immediately binding on all parties and was engrossed in the "Bargain Book".

In designing draw-bridges and hydraulic works, Smeaton was influenced by what he had learned from a visit to the Low Countries in 1755. In 1772 he designed Luggie Water aqueduct at Kirkintilloch, with a river span of 18.3 m. (60 ft.) (see Figure 2), but Mackell reduced this on site to 15.2 m. (50 ft.) by eliminating side paths. Overall it is 33.5 m. (110 ft.) long, 15.2 m. (50 ft.) high and 27.4 m. (90 ft.) wide, and of interest in design terms as Smeaton's largest aqueduct, and because:

- the canal passes over the Luggie Water at its full width (see Figure 3) providing the operational benefit of uninterrupted two-way passage for vessels.
- its waterway has horizontal masonry side arches for lateral stability – probably influenced by earlier continental practice (see Figure 3).
- the 15.2 m. (50 ft.) span river arch was built along its 27.4 m. (90 ft.) length in three stages by means of a timber centring 9.1 m. (30 ft.) long moving on rollers. This practice of Falkirk contractors William Gibb (1736-91) and John Muir, was probably new in Britain, producing joints that even now are scarcely discernible.
- The 3 m. reduction in arch span by Mackell illustrates the considerable degree of autonomy allowed by Smeaton to his Resident Engineer. Only the upper part of the aqueduct adjoining the waterway was curved horizontally instead of the full depth of the structure (see Figures 2 & 3). The fine iron railings, now replaced, may have been a Mackell initiative. The present-day truncated appearance of the arch is because of the floor inserted at springing level for a local railway c. 1858.
- The structure served as a prototype for the arch spans of Kelvin Aqueduct.

The 19-lock western section of the canal ably engineered by Whitworth from the top of Maryhill locks (see Figure 4) to Bowling included the 136 m. (445 ft.) long by 21 m. (68 ft.) high, Kelvin Aqueduct built from May 1787 to December 1789 (see Figure 5). Before the Lune Aqueduct was opened in 1796, Kelvin Aqueduct was the largest masonry canal aqueduct in Britain. It was built by Gibb & Muir, the contractor who built many of the canal structures, and cost £9,058.

Conclusions.

- The navigation significantly advanced the Industrial Revolution in Scotland.
- In structural and hydraulic engineering development terms the work although large scale, practicable, and long lasting, had little significance after c. 1805.
- Construction and maintenance of the canal proved a valuable training ground for developing skills which made a fundamental contribution to the nation's transportation infrastructure in succeeding decades. For example, the project provided experience to the firm of Gibb, whose name is still perpetuated today, and who became one of Telford's main contractors in the first three decades of the 19th century. Hugh Baird (1770-1827), the Forth & Clyde, and later, Union Canal Engineer gained experience during the canal's construction at an early age.
- The specification-contract procedure prevalent in use in engineering offices until the 1980s may have stemmed from Whitworth's practice at Kelvin Aqueduct.
- The project's most enduring contribution to the development of engineering practice was Smeaton's "Plan" of 1768 for managing the work and his use of standardised procedures in design - operations that are still relevant today.

The Union Canal

Comment. The next major associated development was the 50 km. (31½-mile) Edinburgh & Glasgow Union Canal, built from 1818-22, chiefly to provide Edinburgh with coal. It was 12.2 m. (40 ft.) wide at the top, 6.1 m. (20 ft.) at the bottom and 1.5 m. (5ft.) deep and joined the Forth & Clyde Canal at Lock 16 (see Figure 1). The Union Canal was skilfully engineered for operational economy by Baird, in consultation with Telford. It was made on one level, without locks from the top of the Falkirk flight, by means of a 636 m. (696 yd.) long tunnel, 70 bridges, 9 road aqueducts and the Slateford, Almond and Avon aqueducts, three "magnificent" iron-lined aqueducts of 8, 5, and 12 arch spans of 15.2 m. (50 ft.) respectively.*(1)* The longest is 247 m. long and 26 m. high. Each span was built to a standardised construction with hollow spandrels in the best Telford tradition, similar to Chirk aqueduct, but he did query the need for masonry spans in addition to iron troughs. However, on this project Baird was in charge and Telford's role was advisory.

The aqueducts had waterway troughs of unique cast iron construction, the same width as the locks in the Falkirk flight, 3.8 m. (12½ ft.), with curved sides.*(2)* At Almondell, the canal feeder crosses the River Almond by a 24 m. (80 ft.) novel cast iron trough span (see Figure 6). Its sides extend upwards as frames with joints radiating in direction to a common point below the riverbed and act partly as an arch.

Although this canal represents one of Britain's finest canal achievements in purely engineering terms, it was only gained at the considerable cost of £461,760. The venture was in financial difficulty from the outset and, as railways developed, the revenues expected to support this expenditure did not materialise. Despite a valiant effort to stem the railway tide, with "Swift" boats carrying nearly 200,000 passengers in 1836 and a c. 7 hour travel time between the cities, the canal was not able to compete and was taken over by the Edinburgh & Glasgow Railway in 1849.

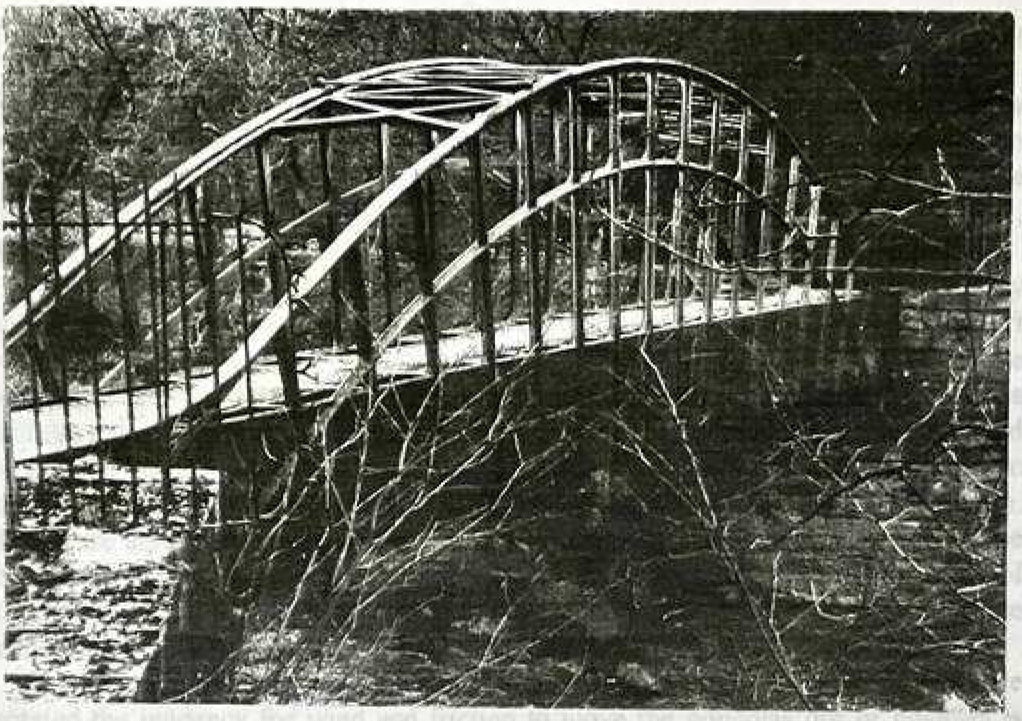

Figure 6.
Union Canal
Feeder aqueduct c. 1820,
River Almond.

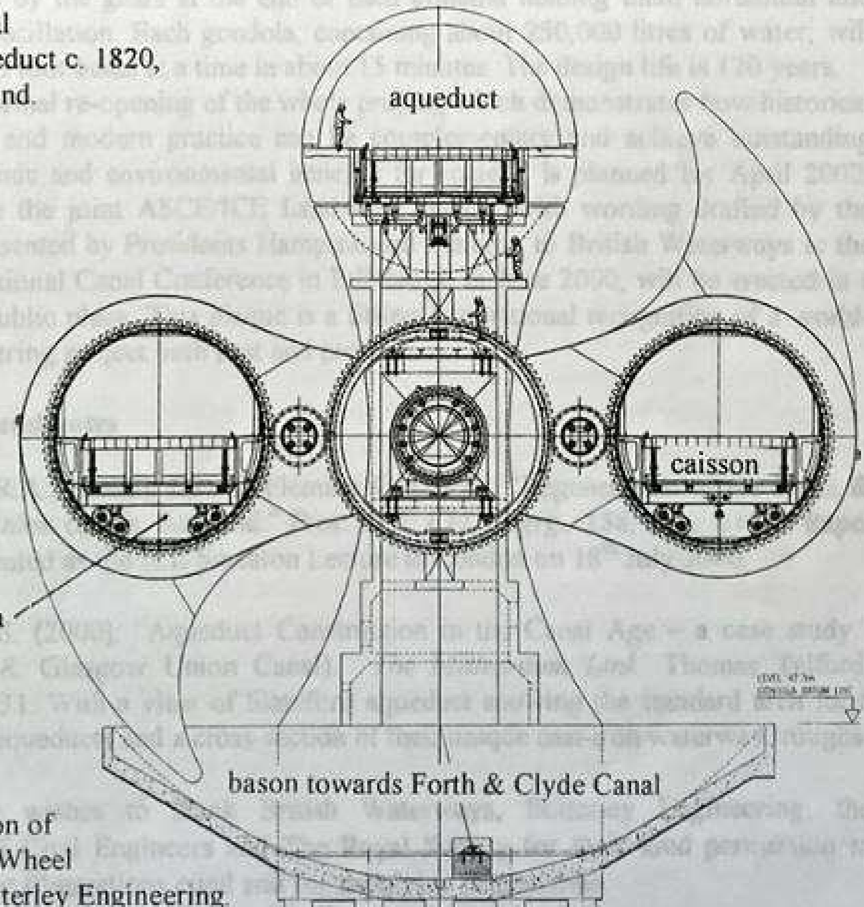

Figure 7.
Cross-section of
the Falkirk Wheel
turning. Butterley Engineering.

Decline and a new sustainable future – The Millennium Link and Falkirk Wheel

Both canals declined in use in the 20th century and were closed in the 1960s. They were severed or blocked in over thirty locations and the outlook for their preservation looked bleak until the £78m. "Millennium Link" project was conceived c. 1996. The centre-piece that made the whole project financially viable is the "Falkirk Wheel", which will replace in use the 11 x 3m. (10 ft.) rise Falkirk lock flight closed in 1933.

The "wheel" is a machine comprising two 35 m. long rotating arms rigidly connected to each end of a 3.8 m. diameter central axle 28 m. long. The arms support within semi-circular gondolas two water-filled boat carrying caissons with double watertight doors at each end. These allow transfer of the boats between the caissons and the aqueduct above and basin below (see Figure 7). The total weight to be moved is 1800 t., but the machine is essentially a balanced unit with the loads to be driven by the motors deriving from wind and friction being a small fraction of this figure. There are also loads caused by the unequal balance of water in the gondolas. The drive system has been designed to operate with the worst foreseeable combination of these loads. This is done by means of ten hydraulic motor gearbox units driving one end of the main axle, and for normal traffic they rotate the arms 180° in 4 minutes.

Each gondola of the wheel, sits in two circular rail tracks. When the arms are rotated the tendency for wind and friction to move the gondolas out of position is counteracted by the gears at the end of each gondola holding them horizontal and preventing oscillation. Each gondola, containing about 250,000 litres of water, will transfer up to four boats at a time in about 15 minutes. The design life is 120 years.

The formal re-opening of the whole project, which demonstrates how historical engineering and modern practice can be complementary and achieve outstanding socio-economic and environmental benefits for society, is planned for April 2002. By this time the joint ASCE/ICE Landmark plaque (with wording drafted by the Author), presented by Presidents Hampton and Fleming to British Waterways at the joint International Canal Conference in Edinburgh in June 2000, will be erected in a prominent public place. This plaque is a fitting international recognition of a world-class engineering project both past and present.

References and notes

(1) Paxton, R.A., Stirling J.M. & Fleming G. (2000). "Regeneration of the Forth & Clyde and Union canals, Scotland." *Proc. ICE, Civ. Engrg.*, **138**, May, 61-72. Paper 12216. Presented as the ICE Smeaton Lecture in London on 18th July 2000.

(2) Purves, S. (2000). "Aqueduct Construction in the Canal Age – a case study." (Edinburgh & Glasgow Union Canal). *The Millennium Link*. Thomas Telford, London, 23-31. With a view of Slateford aqueduct showing the standard arch form used on the aqueducts and a cross-section of their unique cast-iron waterway troughs.

The Author wishes to thank British Waterways, Butterley Engineering, the Institution of Civil Engineers and The Royal Society for their kind permission to reproduce the illustrations cited and for supplying information.