Inclusions in 19th-century American wrought iron structural cable wires

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ABSTRACT: A sizeable number of inclusions in three wrought iron cable wires used in the Wheeling Suspension Bridge (circa 1849) were investigated by energy dispersive spectrometry X-ray analysis so as to profile their frequency and distribution as well as composition. Significant differences in the inclusion chemistry for the wires were obtained that indicate the ore may have come from different sources and/or was processed differently and possibly at more than one venue. The findings are consistent with the manufacturer's handwritten agreement found in the Wheeling and Belmont Bridge Company manuscript archives.

Introduction

The 1849 Wheeling Suspension Bridge (WSB) is the earliest long-span suspension bridge[1] in the world. The cables are made of wrought iron drawn into wire, which was laid parallel and periodically wrapped with smaller diameter wire.[2] Figure 1 shows the Bridge with its dimensions located over the Ohio River at Wheeling, Virginia (now West Virginia) (Cuddy 1999, 35). The Bridge is still in service[3] and for the 150th anniversary of its completion was overhauled (Cuddy 1999), providing access to wire for sampling,[4] which was performed by Emory L Kemp, West Virginia University. Three wires were made available to us for characterization.

The wires were first sectioned and prepared metallographically. Light microscopy of a radial section

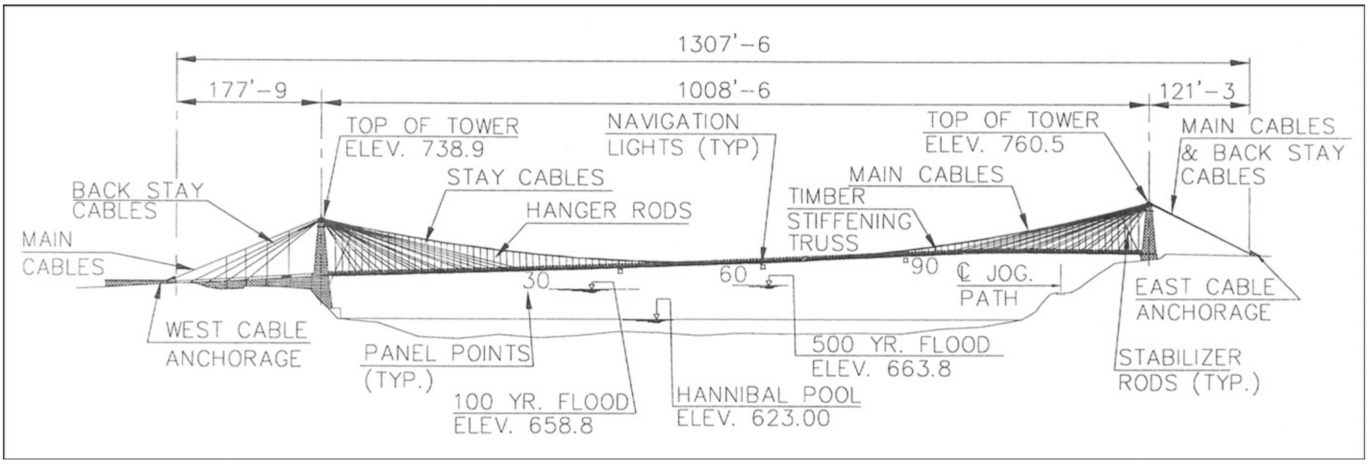

Figure 1: Schematic drawing of Wheeling Suspension Bridge (from Cuddy 1999, 35; credit: Lichtenstein Consulting Engineers, Inc.).

(Fig 2, with indication of general energy dispersive spectrometry (EDS) X-ray analysis locations) of the first wire sample (denoted WSB-1) revealed an asymmetric flow pattern and evidence of piling (Elban and Goodway 2002). It was decided to investigate the inclusions in radial and longitudinal sections of the three wires in sufficient numbers to assess the variety of elements present, how frequently they occur, the dependence of their occurrence on inclusion size, and the overall composition of the inclusions. The reason behind this activity is expressed by Gordon (1983, 95):

> 'The composition of the ore used to make the pig would be reflected in the composition of the slag included in the metal only to the extent that elements in the ore were retained in the pig and not lost in the blast furnace slag. The composition of the slag inclusions in the iron samples would, however, accurately represent the slag that was used in the puddling furnace or finery; this could be expected to be characteristic of both the pig used and the details of the refining process employed at the works in question.'

Historical background of the bridge cables, their wire and its manufacture

The Wheeling Suspension Bridge was designed by Charles Ellet, Jr. (Kemp 1972; Kemp 1979; Kemp 1999; Kemp and Fluty 1999). The details of his design appear in a report (Ellet 1847) prepared for the City Council of Wheeling, Virginia. This design/report was not his first effort as it was preceded by similar reports for other suspension bridges proposed to be built in St Louis (Ellet 1840) and Fairmount, Pennsylvania (Ellet 1843).

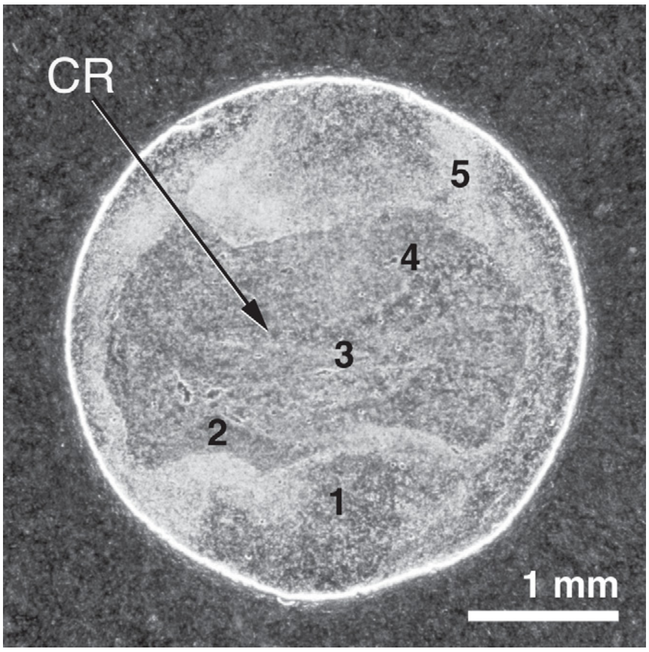

Figure 2: Radial section of Wheeling Suspension Bridge wrought iron wire (WSB-1) showing EDS X-ray analysis locations; CR denotes core region.

Information about the wire and cables and relevant simplifying assumptions in Ellet's analysis are contained in his plan for the Wheeling Bridge which states:

> 'The flooring is supported by 12 cables of iron wire, each of which will be about four inches in diameter, and 1380 feet long.' (Ellet 1847, 9).
>
> 'Each cable will be composed of 550 strands of No. 10 wire. There will be 6600 strands in the 12 cables. The strands of wire intended for the same commercial number are not always of the same size; but for the sake of convenience, and to have a fixed standard, and the calculations which will be found in this report assume for No. 10, a wire which weighs one pound avoirdupois for each 20 feet in length.' [5] (Ellet 1847, 11–12).
>
> 'Each strand of this wire will sustain, according to different experimenters, from 1300 to 1800 pounds. Wire varies much in strength; but 1500 pounds is a moderate average for good wire of the size prescribed, and may be safely assumed in our calculations. (See Note B.)' (Ellet 1847, 16).
>
> 'NOTE B. I have not yet tested the strength of the wire to be used in the construction of the Wheeling Bridge, but have little doubt that it will exceed the moderate average assumed in the report. The wire used in the construction of the Freibourg bridge, according to the report of M. Chaley, the engineer of that work, supported, on average, 1760 pounds per strand, reduced to the standard of one pound avoirdupois for each twenty feet in length. I have obtained results almost as great in testing some American wire. M. Seguin, the engineer of numerous suspension bridges on the Rhone, found a mean strength of 1500 pounds per strand reduced to the same standard.' (Ellet 1847, 42).

Information about how the main cables were to be fabricated is not provided in Ellet's Wheeling Bridge report. However, in his considerably more detailed St Louis Bridge report, Ellet (1843, 17) writes:

> 'The separate strands of wire of which these great cables are composed are laid parallel to each other, and bound together by ligatures of annealed wire placed at every two to three feet; by means of which

> they are drawn into a cylindrical shape, and present the appearance of a solid bar of iron, which they greatly exceed in tenacity. The cables thus formed are stretched between the summits of the towers, and between the towers and the abutments…'

Presumably, the ligature wire was annealed to achieve a tight wrap on the cables. Since the maximum strain capacity would be available with annealed wire, it minimized the chance that the wire of the ligatures would break in wrapping or in service as the cables were stressed.

John A Roebling (1847) also submitted a proposal to the Wheeling and Belmont Bridge Company (Wingerter 1912, 169; Fetherling 1983, 35). In his handwritten specification, Roebling (1847, 12–13) proposed to use only two main cables, each $9^{1}/_{2}$ inches in diameter. They would also consist of parallel wires but would be fabricated differently. Unlike the European (French) cable manufacturing practice (eg, Freibourg Bridge), he proposed to:

> 'protect it [cable] by a continuous and perfectly compact and solid wrapping, laid on by my patent wrapping machine. As this wrapping is put on with great force, and perfectly tight…'

The compressing and wrapping of the wires in these 'selvagee' cables (Shelley 1862, Fig 26, Plate 57) would make them less flexible as desired. Further, their design configuration minimizing surface-to-volume ratio together with liberal application of paint would give them improved corrosion resistance. However, additional constraint was to be provided at the piers by numerous significantly smaller diameter stays made of wire rope. Prior to the construction of the Wheeling Suspension Bridge, Roebling had successfully produced the first twisted iron ropes used in American engineering applications: Allegheny Portage in 1842 (Sayenga 1980, 295–7) and Allegheny Aqueduct in 1844 (Ferguson 1981, 96).

Adhering to Ellet's design, the original construction of the Wheeling Suspension Bridge used twelve cables, having a total weight of 455,400 pounds of No. 10 wire. The total length of the wire in these cables would be 9,108,000 ft. Such a huge amount of iron may well have dictated the need for multiple sources.

Although Ellet's report is dated 26 October 1847, the Wheeling and Belmont Bridge Company issued an earlier solicitation for the cable wire in their Advertisement Specification No. 1: handwritten manuscript document 'Notice to Contractors (by Order of the Board, Thomas Sweeney, Pres.)' stating:

> 'On the seventh of September [1847] proposals will also be received for furnishing 500,000 pounds of No. 10 iron wire. Parties proposing for any part of this contract must specify the quality of the iron from which the iron will be made; the greatest lengths in which they will agree to deliver it, and the greatest monthly quantities they can supply after the first of April next.
>
> This material will be subjected to close inspection; it must be as free from flaws as it can be produced, and capable of resisting not less than 50 tons per square inch of section.
>
> Of this wire 50,000 pounds will be required on or before the first of November, 50,000 pounds more on or before the first day of March, and the balance at the rate of 60,000 pounds per month thereafter until the whole is delivered.
>
> Proposals will be received for the whole or any portion of the quantity herein specified.'

The Bridge Company received an immediate response. A handwritten contract was submitted dated 8 September 1847 by D Richards and Co (Wheeling) to provide wire, possibly to involve two sources. According to a manuscript document, D Richards & Co agreed to supply wire:

> 'made of Iron Furnished by Msrs Stephens Shoenberger & Co. of Dubled refined Charcoal Iron made of Mafsuria [Missouri] Iron Mountain or Juniata Bloome made at the Juniata Works Exprefsly for the purpose Dubled Rolled and Piled and Selected so as to have the Iron Clear of Flaws or crofs [cross] Crcks [Cracks]....'

The Bridge Company response was almost as prompt. From Minutes Book of the Wheeling and Belmont Bridge Company, Vol 1, entry dated 10 September 1847:

> 'The President [Thomas Sweeney] in behalf of the Committee appointed to confer with Messrs. D. Richards Co. in relation to contracting for wire for the contemplated Bridge, reported verbally that the Committee recommended, that the Board contract with those gentlemen namely David Richards and Joshua Bodley, who compose said firm of D. Richards Co. for making and furnishing said wire at the price of 8 and a half (8 $^{1}/_{2}$) [cents] per pound for the large or no ten iron wire…'

The identity of D Richards and nearly everything about his company remains a mystery; a bit more information about Joshua Bodley is available. (See Appendix). While nothing has been found about the wire-making equipment and facilities of D Richards & Co (or Joshua Bodley and Co), some idea of its monthly wire capacity can be obtained from the payment figures received as recorded in the Minutes Book of the Wheeling and Belmont Bridge Company, Vol 1. Forty-five hundred dollars was paid the Company for 20 July to 21 August 1848, and subsequently for 21 August to 18 September 1848, corresponding to remuneration for providing about 1,060,000 ft of wire in each of these time periods.

Other studies of inclusions in iron

Interest in the composition of wrought iron has been a topic of active scientific inquiry beginning at least from the mid 1800s. For example in a pioneering study, Calvert and Johnson (1857) investigated the chemical changes that occur in pig iron during its conversion to wrought iron. Their approach, based on wet chemistry, provided only a bulk sample analysis.

As analytical techniques evolved and became more sophisticated, spatial analysis of sectioned iron and steel samples became possible. A number of studies have focused on the chemistry of the inclusions. Barraclough and Kerr (1973) used an electron probe microanalyser (EPMA) to investigate slag streaks in blister steel. The Ethiopian bloomery process, which was still being used at the time of the article, was investigated in great detail by Todd and Charles (1978); they reported analytical results for numerous slag inclusions in iron implements (knife and digging stick) and iron ore using an EPMA and a scanning electron microscope (SEM) with energy dispersive X-ray spectroscopy (EDS). Hedges and Salter (1979) performed a careful EPMA analysis, involving numerous mineral, metal, and alloy standards, of iron currency bars in an effort to establish their source.

Gordon (1983) used EPMA analysis of inclusions in two rifle barrels of different manufacture to show that they were made of Marshall British iron. Extensive results from the examination of iron implements from South Africa were obtained by Gordon and van der Merwe (1984) that included numerous EPMA analyses of corrosion products and inclusions. Limited EDS analysis results for inclusions are included in the microstructural characterization study of carburizing iron to make blister steel described by Rostoker and Dvorak (1988). More EDS results for inclusions are reported in a later study by Rostoker and Dvorak (1990) that attempts to differentiate bloomery, finery, and puddling irons. Gordon and Killick (1992) performed EPMA analysis to determine the phosphorus content in ferrite from a number of forges in the Lake Champlain region.

In an extremely comprehensive study, Buchwald and Wivel (1998) used metallographic and EDS analytical methods to characterize approximately 900 slags and iron items from several Scandinavian countries produced from 700 BC to 1850 AD. About 10,000 analyses were obtained either of individual slag phases or as averages. One important outcome was finding a definite correlation between the metal phase and its slag inclusions; they were also able to distinguish between irons made by the direct and indirect processes. In another ambitious study, Starley (1999) used EDS analysis of inclusions in an attempt to identify the technology of production of iron items from late Medieval times through the late 1800s. A very interesting metallurgical study on artefacts from Thomas Jefferson's nailery at Monticello, Virginia, was recently reported by Abdu, Gordon, and Knopf (2003) in which elemental analyses of slag inclusions were used to identify domestic, rather than English, sources for hoop and nail rod iron.

None of the studies above were done on structural iron. Most of the studies did not involve American iron from the 1840s–1850s. Also, the number of iron inclusions investigated tend to be somewhat limited; other than the work by Buchwald and Wivel (1998), the maximum number for which analysis results have been reported is 43 (Todd and Charles 1978). In comparison, in the current work about 250 inclusions total in the three wires were analyzed, and particularly noteworthy is the large number of inclusions characterized for each wire sample.

Preliminary characterization

The diameter of each wire was measured in several locations, avoiding obviously corroded areas, using a dial caliper. The average diameter of WSB-1 and -2 is essentially the same: 3.48mm (0.137in.) with variations of 0.65 and 0.29%, respectively. WSB-3 has a smaller diameter of 3.37mm (0.133in.) with a variation of 0.74%.

Using a Clark model DRM12 tester, Rockwell (B scale) hardness was determined for separate radial sections that underwent final polishing with a 1.0μm alumina/water slurry. Single indentations were placed in the approximate centre of a total of six samples for each wire. Microscopic examination of the impressions revealed they were radially symmetrical. The average hardness values are:

	HRB
WSB-1	85.4 (F = 2.3)
WSB-2	89.1 (F = 0.3)
WSB-3	82.9 (F = 0.6)

These relatively high hardness values are attributed to work hardening that is consistent with the extension of grains visible in Figure 2 from Elban and Goodway (2002, 514).

Method

Metallographic sample preparation

Since wrought iron is often anisotropic, radial and longitudinal (ie, along cylindrical axis) sections of wire were mounted in phenolic, fine ground (240-320-400-600 grit SiC papers), rough polished (5.0 and 1.0μm alumina/water slurries), and final polished (0.5μm alumina/water slurry) using standard manual techniques (Elban, Borst, Roubachewsky, Kemp, and Tice 1997). For WSB-1, chemical etching was accomplished by cotton-swabbing polished surfaces with 3% nital (HNO_3 in ethanol) for 10s. For WSB-2 and -3, a weaker concentration of nital (1 or 2%) was used for longer exposure times, typically 15 or 30s. The resultant contrast in subsequent photomacrographs of the wire sections comes from numerous inclusions and grain boundaries. The microstructure of the Bridge wire (WSB-1, in particular) has been discussed previously by Elban and Goodway (2002).

Energy-dispersive spectrometry (EDS) X-ray analysis

Standardless, semi-quantitative chemical analyses of numerous inclusions and ferrite grains present across each radial and longitudinal section prepared metallographically were obtained. This was accomplished using a ThermoNORAN EDS Low Atomic Number X-ray Detector in a JEOL model JXA-840A SEM at 110,000x magnification and 60s counting times.[6] The embedded samples were prepared for SEM by being surrounded by silver paint, so that no carbon needed to be deposited on the surface. Scanning electron micrographs were taken of five to seven areas containing prominent inclusions across the section and inclusions chosen for analysis were labelled, so they could be identified for future reference and re-analysis if necessary. Spectra were obtained for the inclusions, where an effort was made to select inclusions of varying size and appearance. For the most part, separate inclusions had been very much broken up during processing and did not appear to have individual variation in internal structure.

Results

The radial sections of WSB-2 and -3 (Figs 3 and 4, respectively, showing general EDS X-ray analysis

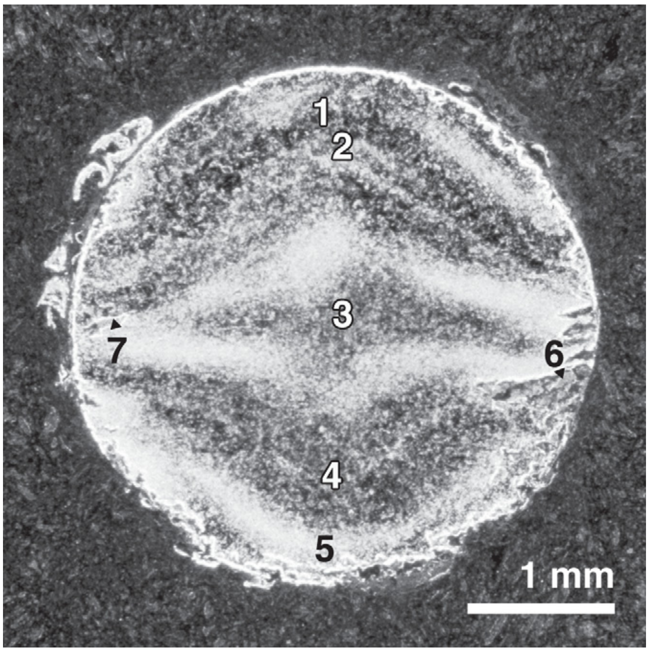

Figure 3: Radial section of Wheeling Suspension Bridge wrought iron wire (WSB-2) showing EDS X-ray analysis locations.

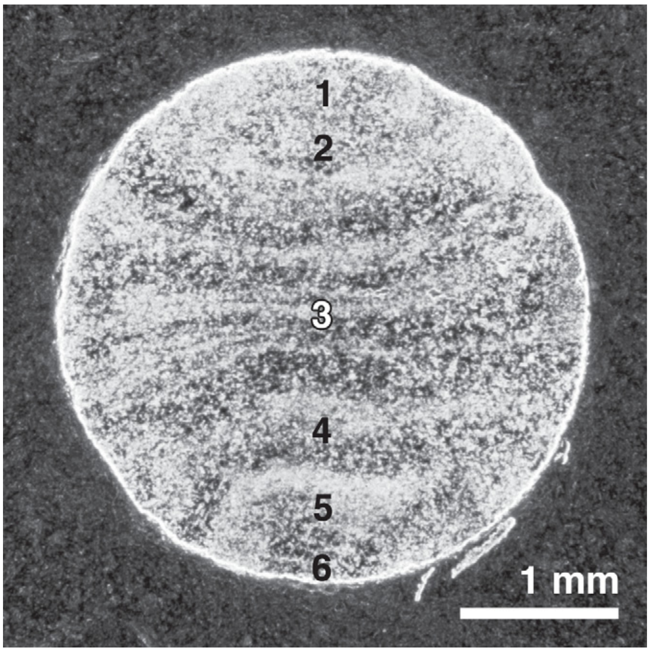

Figure 4: Radial section of Wheeling Suspension Bridge wrought iron wire (WSB-3) showing EDS X-ray analysis locations.

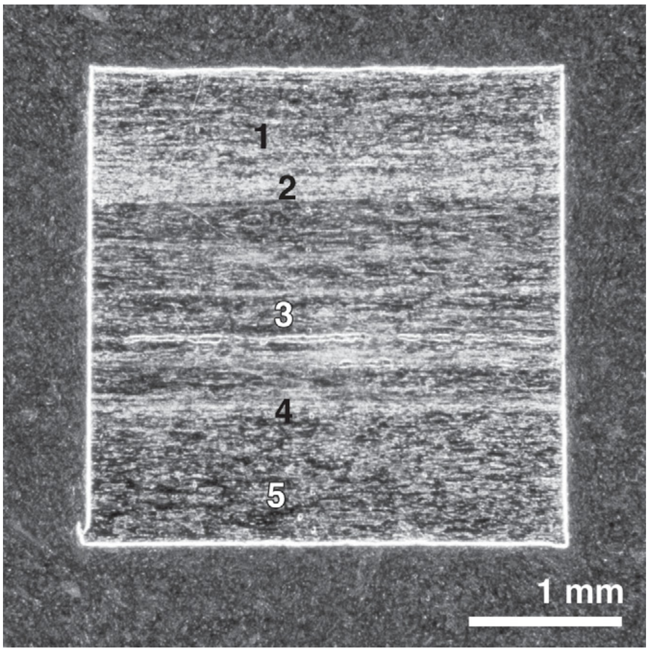

Figure 5: Longitudinal section of Wheeling Suspension Bridge wrought iron wire (WSB-1) showing EDS X-ray analysis locations.

locations) have distinct bulk deformation flow patterns that are different from WSB-1 (Fig 2). Despite not having a 'core' region, the sections of WSB-2 and -3 also reveal piling[7] that appears to be on a finer scale. The longitudinal section for WSB-1 appears in Figure 5, also with indication of EDS analysis locations. Since this is representative of the longitudinal sections for WSB-2 and -3, they are not included.

EDS analyses of ferrite in WSB-1 revealed iron with small amounts of carbon and no phosphorus or sulphur detected. Trace amounts of chromium, gallium, and nickel showed up in separate single probes. A larger amount (3wt%) of strontium occurred in one additional probe. Analyses of ferrite in WSB-2 also revealed high-purity iron with small amounts of carbon without phosphorus or sulphur. Trace amounts of arsenic, gadolinium, osmium, and thorium were detected in separate single probes. The fewest elements were found in WSB-3 ferrite. Small amounts of carbon were detected without the presence of sulphur. However, two probes recorded trace phosphorus. Trace sodium also accompanied phosphorus in one of the probes.

Referring to Table 1, fourteen elements were found in inclusions in all three wires. In addition to Fe (the primary ingredient), C and O were almost always detected as expected. Al and Mg were also present along with two transition elements, Mo and V. The presence of the remaining common elements (Ca, K, Mn, Na, P, S, and Si) has been used in particular by Rostoker and Dvorak (1990) to provide insights into iron processing methods and conditions. Quantitative information for these seven elements appears in Tables 2 and 3–5. The variation in inclusion chemistry can be viewed by noting the elements not common for all three wires in Table 1. In particular, WSB-1 wire has only two distinct elements, while WSB-2 and -3 wires have five and nine elements, respectively, missing in at least one wire. In fact, only two elements are duplicated in WSB-2 and -3: Pb, and Ti.

Table 1: Summary of EDS X-ray analysis results for elements found in inclusions in wrought iron wires from the Wheeling Suspension Bridge (WSB)

Wire number	Sample, section	No. inclusions	Elements detected in all three wires	Elements missing in at least one wire	No. elements detected
WSB-1	A (Radial)	26	Al, C, Ca, Fe, K, Mg, Mn, Mo, Na, O, P, S, Si, V	Te, U	16
	B (Longitudinal)	33			
WSB-2	S-1 (Radial)	55*	Same	Os, Pb**, Sm, Ti, Zr	19
	II-2a (Longitudinal)	48***			
WSB-3	L-1 (Radial)	50****	Same	Cl, Cr, Cu, Pb, Ru, Ta, Tc, Ti, W	23
	III-2a (Longitudinal)	40			

Notes: * Includes three apparent corrosion products, two 'mosaic' regions, and one crack region. ** Detected twice: (1) in crack region and believed associated with exterior paint that had penetrated crack; (2) in prominent stringer with large amount of Al. *** Includes 21 prominent stringers of undetermined size. **** Includes six apparent corrosion products.

Table 2: Frequency of various common elements from EDS X-ray analysis of inclusions in wrought iron wires from the Wheeling Suspension Bridge

Wire number	WSB-1			WSB-2			WSB-3		
Section	Radial	Longitudinal		Radial*	Longitudinal		Radial**	Longitudinal	
Total inclusions analyzed	26	33		51	48		44	40	
Constituent	Times detected		Frequency	Times detected		Frequency	Times detected		Frequency
Ca	5	7	0.20	20	12	0.32	25	15	0.48
K	1	5	0.10	13	nd	0.13	17	3	0.24
Mn	2	12	0.24	12	5	0.17	19	1	0.24
Na	4	nd	0.07	2	nd	0.02	2	nd	0.02
P	17	10	0.46	25	10	0.35	28	17	0.54
S	14	4	0.31	13	10	0.23	14	9	0.27
Si	19	17	0.61	41	32	0.74	36	32	0.81

Notes: *Does not include analyses for three apparent corrosion products and one crack region. ** Does not include analyses for six apparent corrosion products.

The frequency of the seven common 'processing' elements detected in inclusions in the three wires appears in Table 2. Some interesting differences are obtained in examining this means of assessing inclusion homogeneity. Ca, K, and Si were found least often (gauged against the total number of probes) in WSB-1, while Na and S were detected there most often. Here, it is important to recognize that many of the inclusions in WSB-1 contain only Fe and O and are wüstite (Elban and Goodway 2002, 514), which is not the case for WSB-2 and -3. Ca, K, Mn (same as WSB-1), P, Si were most frequently detected in WSB-3, indicating that inclusion chemistry is most nearly uniform in this wire, although even here significant variation exists.

A summary of the EDS results (reported as average quantities) for the seven common elements by general analysis location in each metallographic section of the three wires is given in Tables 3–5. WSB-1 wire does not appear to be nearly as well fluxed as WSB-2 and -3 wires. WSB-1 inclusions have relatively low Si content except for one probe performed outside the central or 'core' region, labelled CR (Fig 2). Ca content is low except outside this region and in the transition region going to inside the 'core'. K and Na contents are low (denoted *tr* for trace) or not detected (*nd*) except in these

Table 3: Summary of EDS X-ray analysis results by region for various common elements found in inclusions in (a) radial and (b) longitudinal sections of Wheeling Suspension Bridge wrought iron wire WSB-1 (See Figs 2 and 5 respectively.)

Region no./location	Inclusions analyzed	Average wt% element (detected in number of inclusions)						
		Ca	K	Mn	Na	P	S	Si
(a) Radial section								
1/ outside core	4	2(1)	tr(1)	1(2)	tr(3)	1(3)	tr(3)	2(4)
2/ just inside core	5	1(1)	nd	nd	nd	tr(4)	tr(3)	tr(4)
3/ inside core:centre	5	1(1)	nd	nd	nd	tr(4)	tr(3)	tr(3)
4/ just inside core	6	nd	nd	nd	tr(1)	tr(2)	1(2)	1(3)
5/ outside core	6	1(2)	nd	nd	nd	1(4)	tr(3)	1(5)
(b) Longitudinal section								
1/ outside core	6	7(1)	1(1)	1(5)	nd	9(1)	nd	12(1)
2/ just inside core	8	3(4)	1(4)	1(7)	nd	2(4)	tr(3)	5(6)
3/ inside core:centre	7	tr(1)	nd	nd	nd	1(4)	nd	1(4)
4/ just inside core	7	tr(1)	nd	nd	nd	nd	1(1)	1(3)
5/ outside core: roughly symmetric with region 1	5	nd	nd	nd	nd	tr(1)	nd	tr(3)

Table 4: Summary of EDS X-ray analysis results by region for various common elements found in inclusions in (a) radial and (b) longitudinal sections of Wheeling Suspension Bridge wrought iron wire WSB-2 (See Fig 3.)

Region no./location	Inclusions analyzed	Average wt% element (detected in number of inclusions)						
		Ca	K	Mn	Na	P	S	Si
(a) Radial section								
1/ near top circumference	7	2(3)	1(3)	1(1)	nd	1(4)	1(2)	4(6)
2/ major inclusion boundary approx 15% of the way inside top circumference	8	2(3)	1(2)	1(3)	nd	1(2)	tr(1)	3(4)
3/ centre	8	1(3)	tr(1)	nd	tr(1)	1(4)	1(4)	1(7)
4/ major inclusion boundary approx 80% of the way inside top circumference: roughly symmetric with region 2	8	1(4)	1(2)	1(2)	nd	1(5)	tr(1)	3(7)
5/ near bottom circumference: roughly symmetric with region 1	8	2(3)	1(1)	1(2)	nd	1(4)	1(2)	3(7)
6/ apparent substantial corrosion zone at circumference	8	nd	nd	nd	nd	tr(2)	nd	1(3)
7/ enormous inclusion/radial crack at circumference	7	2(4)	tr(4)	1(4)	2(1)	1(4)	1(3)	5(7)
(b) Longitudinal section								
1/ major inclusion boundary near top circumference	8	tr(3)	nd	nd	nd	tr(4)	nd	tr(3)
2/ major inclusion boundary approx 25% of the way inside top circumference	8	1(1)	nd	nd	nd	nd	tr(3)	1(4)
3/ major inclusion boundary approx 40% of the way inside top circumference	8	2(1)	nd	2(2)	nd	tr(2)	nd	tr(6)
4/ minor inclusion boundary approx 65% of the way inside top circumference: roughly symmetric with region 3	8	1(5)	nd	1(1)	nd	tr(2)	tr(6)	1(8)
5/ minor inclusion boundary approx 80% of the way inside top circumference: roughly symmetric with region 2	8	nd	nd	nd	nd	nd	tr(1)	tr(6)
6/ major inclusion boundary near bottom circumference: roughly symmetric with region 1	8	tr(2)	nd	1(2)	nd	1(2)	nd	2(5)

Note: Analytical results for radial section do not include analyses for three apparent corrosion products and one crack region, all at the circumference.

regions. In WSB-2 and -3, Si and Ca contents are generally higher than in WSB-1. K levels are also higher while the presence of wüstite is infrequent.

Table 6 demonstates the size dependence for the occurrence of large amounts of three key inclusion constituents (Fe, Si, and Al). Not surprisingly, more than half of the inclusions analyzed in all three wires have very high (≥95 wt%) Fe content with WSB-3 wire having the highest frequency (0.69). Inclusions containing a high content (≥5 wt%) of Si in WSB-1 and -2 wires are infrequent (0.07 and 0.06, respectively) but somewhat more frequent (0.17) in WSB-3. Inclusions in WSB-1 with high amounts (≥15 wt%) of Al are rather prevalent (0.31) in contrast with WSB-2 and -3 where they are very rare (0.04 and 0.02, respectively).

Discussion and Conclusions

The ferrite is very high purity with only a few probes detecting anything other than C. When P was detected in ferrite, its very low concentration compares favourably with measurements obtained by Gordon and Killick (1992, 157) for Champlain iron. Although not specifically investigated, it appears that any diffusion of elements from inclusions into ferrite, during processing, occurred only over limited distances and in very small amounts.

In examining Table 1, finding Ti in WSB-2 and -3 wires is interesting because it is reported to be present in magnetic iron ore (magnetite) from Lake Champlain, New York, Wisconsin, and Missouri (Overman 1850, 235).[8] The latter region relates to the contractual agreement by D Richards & Co to supply ‘iron made

Table 5: Summary of EDS X-ray analysis results by region for various common elements found in inclusions in (a) radial and (b) longitudinal sections of Wheeling Suspension Bridge wrought iron wire WSB-3 (See Fig 4.)

Region no./location	Inclusions analyzed	Average wt% element (detected in number of inclusions)						
		Ca	K	Mn	Na	P	S	Si
(a) Radial section								
1/ near top circumference	8	2(5)	tr(4)	1(5)	nd	4(5)	tr(2)	4(8)
2/ about 20% of the way inside top circumference	8	2(7)	1(3)	1(7)	nd	6(8)	tr(2)	8(8)
3/ major inclusion boundary at centre	8	tr(2)	1(1)	1(1)	1(1)	tr(3)	tr(1)	tr(4)
4/ major inclusion boundary approx 70% of the way inside top circumference: roughly symmetric with region 2	8	1(2)	tr(1)	1(1)	nd	1(1)	tr(1)	1(6)
5/ near bottom circumference: roughly symmetric with region 1	8	4(6)	1(7)	2(4)	nd	2(7)	1(5)	10(7)
6/ apparent substantial corrosion zone at circumference	8	1(3)	tr(1)	1(1)	tr(1)	3(4)	1(3)	3(3)
(b) Longitudinal section								
1/ near top circumference	8	2(4)	1(2)	1(1)	nd	2(3)	tr(3)	2(8)
2/ major inclusion boundary approx 25% of the way inside top circumference	8	1(2)	tr(1)	nd	nd	1(1)	tr(2)	1(7)
3/ centre	8	1(3)	nd	nd	nd	1(5)	tr(2)	1(4)
4/ approx 65% of the way inside top circumference: roughly symmetric with region 2	8	1(4)	nd	nd	nd	1(4)	1(1)	1(8)
6/ near bottom circumference: roughly symmetric with region 1	8	1(2)	nd	nd	nd	1(4)	tr(1)	1(5)

Note: Analytical results for radial section do not include analyses for six apparent corrosion products at the circumference.

Table 6: Chemical composition–size(∂) dependence from EDS X-ray analysis of selected elements found in inclusions in Wheeling Suspension Bridge wrought-iron wires

Wire	Constituent (high level)	Small $(\partial \leq 5\mu m)$	Medium $5<\partial \leq 10\mu m$	Large $10<\partial \leq 40\mu m$	Very large $\partial > 40\mu m$	Total	Frequency
WSB-1							
	≥ 95 wt% Fe	18[1]	5	12	0	35	0.59
	≥ 5 wt% Si	1	0	3[2]	0	4	0.07
	≥ 15 wt% Al	9	8	1	0	18	0.31
WSB-2							
	≥ 95 wt% Fe	28[3]	10	13	4	55	0.56
	≥ 5 wt% Si	2	2	2	0	6	0.06
	≥ 15 wt% Al	0	0	3	1[4]	4	0.04
WSB-3							
	≥ 95 wt% Fe	25[3]	22[1]	10[5]	1	58	0.69
	≥ 5 wt% Si	8	5	1	0	14	0.17
	≥ 15 wt% Al	1	1	0	0	2	0.02

Notes: The numbers of inclusions analysed were 59, 99 and 84 respectively for WSB-1, WSB-2 and WSB-3. Superscripts: [1] two inclusions have no oxygen, indicating they are metallic iron; [2] two inclusions are slag matrix, probably primary fayalite (Fe_2SiO_4); [3] three inclusions have no oxygen, indicating they are metallic iron (one case) or iron alloys (two cases); [4] detected in a prominent stringer with a large amount of lead; [5] one inclusion has no oxygen, indicating it is metallic iron.

of Missouri Iron Mountain or Juniata Bloom'. It is reported that in 1846 blast furnaces commenced smelting Missouri ore from Iron Mountain and Pilot Knob, making these deposits the first to have national prominence; further, pig iron from Missouri was being delivered to Wheeling mills in the same time period (Scott 1929, 15). Bulk-deformation processed products made of Missouri iron were also appearing in Wheeling at least as early as 1850; for example, Scott (1929, 64) reprints a business card for Johnston, Sweeney & Co, Manufacturers, Wheeling, Virginia, with the heading 'Missouri Iron Works' and listing a diverse line of sixteen products including tire iron, buggy iron, horse shoe, round and square, nail rod and sheet iron. Considering the combined results in Table 1 and this information, it appears likely that the ore used to make the three iron wires came from at least two sources.

According to Overman (1850, 235–6), smelting ores containing Ti was quite challenging at the time of the bridge wire manufacture. Ti does not combine easily with much of anything and normally had to be removed with the cinder. To work around this undesirable approach, it was necessary to resort to different furnaces often with no hearth, or hearths of granite and gneiss rather than sandstone. Hence, it is possible that the iron for WSB-2 and -3 wires was smelted differently from WSB-1.

Referring to Table 3 (a) and Figure 2, showing the radial section of WSB-1, it is evident that the iron differs according to its location in the wire section. The large spatial variation in the amounts of various common elements in this wire (outside versus inside the 'core' region) provides quantitative indication that piling occurred. This was practised to obtained a more homogeneous product with improved mechanical properties. It is unknown whether scrap iron was also used, thus contributing to (and explaining) the chemical inhomogeneity (Eylon and Suzuki 2002). It is interesting to note that if scrap iron was used in WSB-1, this could explain its lack of K.

It is worthwhile pointing out that piling[7] is much more readily apparent when the wires are examined in radial section. However, it is not so easily identifiable in longitudinal sections (eg Fig 5) which are frequently considered in other microstructural characterization studies of wires and rod stock. Presumably, emphasis is given to longitudinal sections to gain important information on deformation textures and whether recrystallization and grain growth has occurred.

Particularly interesting is the relatively large number of inclusions with high (≥15wt%) Al in WSB-1 wire compared to WSB-2 and -3 (ie a frequency of 0.31 versus 0.04 and 0.02, respectively). We proposed (2002, 517) that furnace lining bits high in alumina (Al_2O_3) became incorporated in the WSB-1 iron during smelting or refining as the more likely explanation rather than Al coming from the ore. This reasoning was based on the higher concentration of Al in the inclusions than what has been considered to come from ore. The absence of Al-containing inclusions in WSB-2 and -3 suggests that either the furnace lining had been replaced before processing the iron for these wires or the iron was processed at a different venue having furnaces with newer or superior (ie more spall resistant) brick. A lower operational temperature, giving rise to lower thermal stresses would also explain the difference.

The low or mostly non-existent K values in WSB-1 wire are surprising given the expectation that charcoal rather than coke was used as the fuel in the smelting operation. 'The potash comes from wood (charcoal) ash, which is to be expected from either a bloom iron or fining operation' (Rostoker and Dvorak 1988, 185). On the other hand, use of charcoal is indicated on the basis of the low S and Mn concentrations in inclusions present in WSB-1. The relatively low amounts of S in WSB-2 and -3 together with the more frequent presence of K indicate that charcoal was certainly used as the fuel in smelting this iron.

Perhaps the wrought iron in WSB-1 wire was made by the puddling process using charcoal,[9] thus explaining the relative absence of K. If so, this would explain the large amount of wüstite present in WSB-1 because mill scale (waste iron oxide coming from very hot iron as it undergoes bulk-deformation processing) was added into the sand hearth to react with C in the pig in a process known as pig boiling (Chard 1995, 8–9). Perhaps the mill scale also reacts with K, thus explaining the relative absence of K.

Although the wires from the Wheeling Suspension Bridge do not give up their secrets[10] easily, important insights have been obtained from the EDS X-ray analysis of numerous inclusions contained in the wires. In summary, the quantitative compositional differences for the inclusions indicate that the iron ore used to make WSB-2 and -3, compared to WSB-1, was different and/or processed under different conditions and hence possibly at different venues. This is consistent with the agreement provided to the Bridge Company by D Richards & Co.

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Appendix: Tracking down frontier wire makers

While scant primary source material on David Richards and Joshua Bodley and their business concerns has been located, census records and various Wheeling city directories provide valuable information about these wire makers who made a substantial contribution to the infrastructure of the western frontier in antebellum America. Even so, it is unclear how men with seemingly modest resources were able to manufacture such a large amount of high quality iron wire in what was a somewhat remote part of the country at the time.

An entry for David Richards, age 43, with occupation of farmer and real estate valued at $8400, appears in the (28 August) 1850 Ohio County, Virginia, Census (Schunk 1990, Vol I, 66). A single entry (dated 1839) lists David Richards as the plaintiff in a lawsuit with Samuel Brown, defendant (Craft 2000, 1330). There is also a separate entry dated 1839 for D Richards & Co, again involving Samuel Brown (Craft 2000, 1363). An additional entry (dated 1854) appears for David Richards, deceased, with the remark ‘Resolution of respect passed by Court’. This was possibly motivated, at least in part, because David Richards was elected a Justice of the Peace in 1852 and apparently had been serving as a Commissioner for a poor house in Ohio County at the time of his death (Craft 1997, 80 and 167). In addition, David Richards & Co, blacksmiths and machinists, 12 Clay Street, corner of 4th Street, is listed in the 1839 Wheeling City Directory (Bowen 1839, 87). Joshua Bodley, blacksmith, is also listed with residence on alley numbered 12, between 6th and 7th Streets (Bowen 1839, 43).

Neither David Richards nor D Richards & Co are listed in the 1851 Wheeling City Directory, but there is an advertisement (Fig 6: from Taylor 1851) for Joshua Bodley and Co, corner of Fourth and Clay Streets (Fig 7: map from White 1873, 39–40), the same location given earlier for D Richards & Co, claiming that they made the wire for the Wheeling Suspension Bridge. An explanation for the company name change has not been discovered.

Joshua Bodley (blacksmith) is also listed in the 1851 Wheeling City Directory (Taylor 1851, 36). An entry for Joshua Bodley, age 42, with occupation of blacksmith and real estate valued at $14,000, also appears in the (13 October) 1850 Ohio County, Virginia, Census (Schunk 1990, Vol II, 277).

Shortly after its involvement in the Wheeling Suspension Bridge, there is indication that Joshua Bodley and Co also supplied wire for the cables and assembled them (said to be over 600 feet in length) in Wheeling for a suspension bridge in Tennessee. A newspaper[11] gives a short account of supplying wire for the Nashville Bridge (1850). This bridge was designed by Adolphus Heiman to span the Cumberland River; it collapsed in 1855 but was rebuilt (Denenberg 2002, 9–10). At least one picture exists, a print by George B Kirchner, showing what it looked like before being destroyed by Confederate troops prior to Union occupation of Nashville (Kirchner Prints 2002).

Joshua Bodley and Co continued its wire-making enterprise at least for a while in the 1850s. Kemp (1997,4) reports that the Company helped with the major repairs to the Wheeling Bridge after 1854 by supplying additional wire. Listings in city directories provide somewhat mixed information. In the 1859–60


J. BODLEY & Co.,
Corner of Fourth & Clay Sts., East Wheeling,
MANUFACTURERS OF
WAGONS, CARTS, TIMBER WHEELS,
IRON AXLETREES, SCREWS, &c.,
ALSO, of Bridge, Telegraph, and Market Wire---Made of the best Missouri Iron.
☞The Wire for the Wheeling Suspension Bridge, was made at this establishment.

Figure 6: Wheeling City Directory advertisement for Joshua Bodley and Co. indicating its involvement in making the wire for the Wheeling Suspension Bridge (from Taylor 1851).

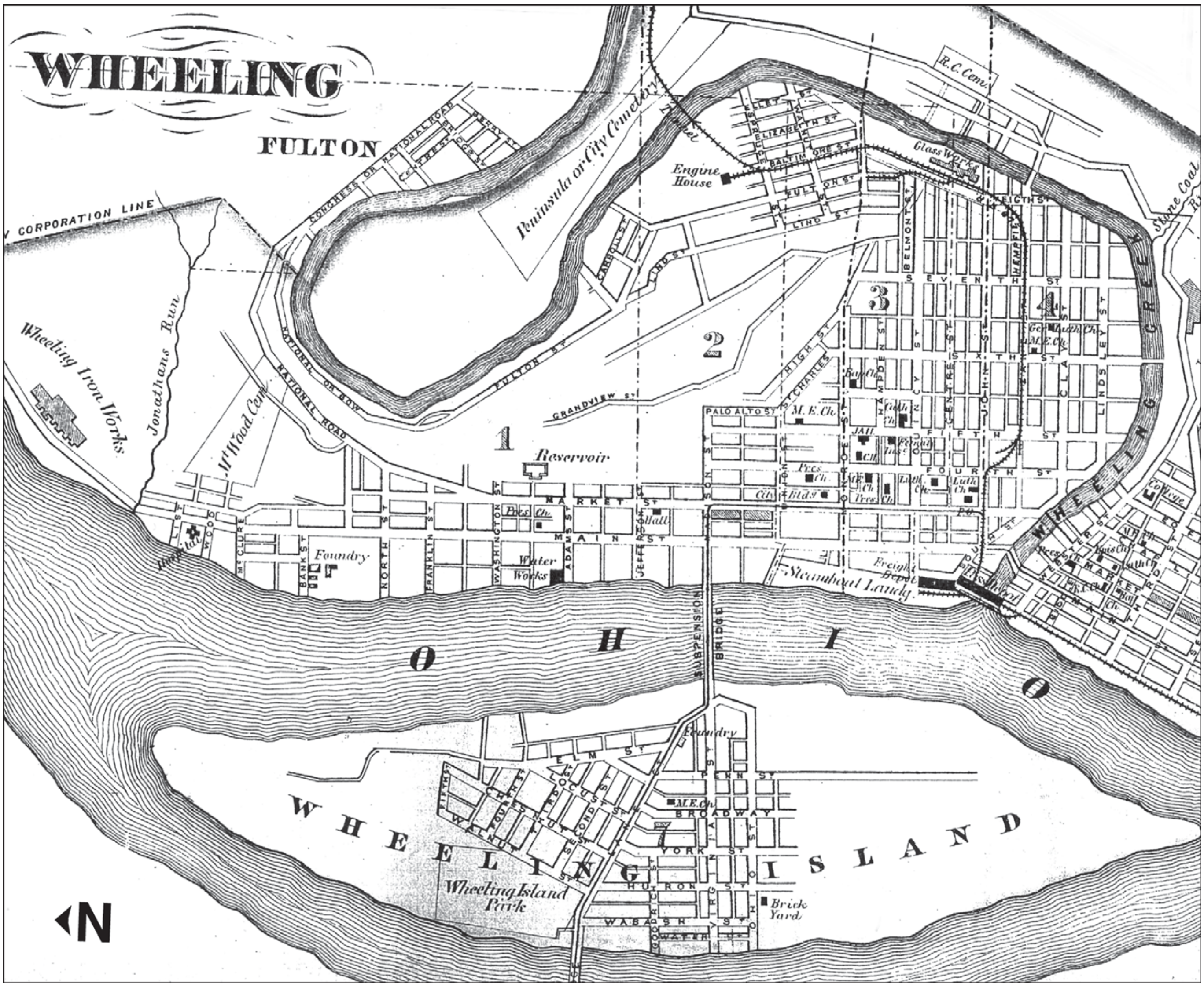

Figure 7: Map of downtown Wheeling after the Civil War showing the location of the Wheeling Suspension Bridge; Joshua Bodley and Co. is at the corner of Fourth and Clay Streets—centre right on plan (from White 1873, 39–40).

Wheeling City Directory, Joshua Bodley is listed as a manufacturer of wagons and wire, also machinist (Thurston, 1859, 11). Whereas, in the 1856-57 Wheeling City Directory, he is listed only as a wagon maker (Williams 1856, 29).

During the Civil War and afterwards, the manufacturing activities of Joshua Bodley and Co apparently never returned to making iron wire. Later developments documented for Joshua Bodley and Co focus on manufacturing wagons.[12] The reason(s) for ceasing the wire-making operation, despite an auspicious beginning, and the disposition of what would seem to be wire-making equipment of significant scale are also unknown. In particular, nothing about D Richards & Co or Joshua Bodley and Co appears in books on iron making in Wheeling by either Scott (1929) or May (1945), arguably the two most complete reference sources on this topic.

Returning to the wire-making activities of D Richards and Co for the Wheeling Bridge, there is documentation for a connection with the Virginia Mill. A brief description[13] of the mill of the Virginia Iron Works in Wheeling, capable of manufacturing about 1000 kegs of nails per week, revealed that the nails were made of Missouri and Tennessee iron. Relevant to the current work, it was further stated:

> 'this iron is probably as good, if the not the best, in the United States, for the manufacture of wire. From it, D Richards & Co are now [1848] preparing the wire for the new suspension bridge…'

The Virginia Mill had only a brief history.[14] The company that built the mill was organized in 1847 (Newton, Nichols, and Spankle 1879, 233), and the mill continued operation until 1851 when the mill was moved to a new location south of Wheeling to become the Benwood Iron Works (Newton, Nichols, and Spankle 1879, 233; Maddex 2001, 84). In 1852, the original site was sold to the Baltimore and Ohio Railroad for development as its terminus, and the mill was demolished (Scott 1929, 16). The details about the original mill's construction and equipment are sparse, but apparently tilt hammers were used in making the nail plate (Loveday 1983, 49–50). It was claimed to be 'the first mill erected in the West solely for the manufacture of nails, and was equipped with 40 machines' (Scott 1929, 15). The mill was located at the confluence of Wheeling Creek and the Ohio River (Maddex 2001, 84) near to Joshua Bodley and Co.

Notes

1. A 'long-span' bridge is currently defined as having a clear span of a thousand feet (305m) or more.
2. Wire rope fabricated in this manner (Shelley 1862, Fig 24, Plate 57) was used previously for the Freibourg Suspension Bridge built in 1835 (Shelley 1862, 188).
3. A great storm in 1854 destroyed the deck and flung the cables (still intact) into the river. (From eyewitness accounts the effect was in some ways similar to the famous Tacoma Narrows Bridge collapse in 1940.) The Wheeling Bridge was rebuilt by Charles Ellet, Jr and William K McComas. It was overhauled in 1860 by McComas, but not until 1872 does a Roebling enter the picture, when wire rope stay cables were added according to a design by Washington Roebling, John Roebling's son. (Kemp 1999, 23–26; Kemp and Fluty 1999, 22–24).
4. A photograph of a portion of broken original wire removed from the north-east anchorage of the Wheeling Suspension Bridge in 1998–9 during renovations is shown at *wheeling.weirton.lib.wv.us/landmark/bridges/susp/wire01.htm*. An excellent detailed history of the Bridge and numerous other photographs are also provided at this Web site (*wheeling.weirton.lib.wv.us/landmark/bridges/susp*).
5. According to 'an extract from a letter addressed to William H. Starr, Esq., of New York,' published in 'Iron Works at Wheeling, Virginia', *The Merchants' Magazine and Commercial Review conducted by Freeman Hunt*, **19** (1848) 230, '20 feet of No. 10 wire should weigh 100 [1 lb.] avoirdupois.' We tested Ellet's specification by weighing a 9$^1/_2$-inch length of WSB-1 wire, which gives about 0.98 lb. for 20 feet.
6. Standardless analyses involve comparisons with internal theoretical elemental standards. In literature provided by ThermoNORAN, the minimum detection limit ranges between 0.1 and 1wt%. However, a number of factors, such as background and number of counts, can significantly influence this assessment. While spectra peaks are identified automatically, careful manual inspection, as prescribed by the manufacturer, was performed to sort out ambiguities in overlapping peaks.
7. Piling in iron can occur without the presence of white lines. These require sufficient As and/or P to be present. While we do detect P in inclusions, these are seldom wüstite. Due to the drawing process, any chemical gradients in the iron wire were very much thinned down. In this study, emphasis was given to analyzing inclusions because of their frequent prominence.
8. Overman is used as a closely contemporary authority on possible iron ore sources containing Ti. Later authorities do not encourage confidence that their sources were actually in production at the time of the Bridge construction.
9. Initially, pig iron made in charcoal-fired blast furnaces was used in American puddling operations; conversion to coal was well along in Eastern Pennsylvania during the 1830s–1840s (Gordon 1996, 135–36). However, it would not be surprising that western sites such as Wheeling lagged behind or at least that more proprietors there persisted in using charcoal iron. This would seem to be borne out by the virtual absence of FeS inclusions in the wires, whereas the prominence of FeS is characteristic of iron made in coal-fired puddling furnaces. The ratio of these inclusions to the total S-containing inclusions is 1/17, 0/28, and 1/22 in WSB-1, -2, and -3, respectively.
10. While the emphasis in the current study is on comparing the inclusion chemistry for the three wires in an effort to understand iron ore sources and processing conditions leading up to drawing, limited information was also obtained on what appears to be a manufacturing defect in the wire. In one instance in WSB-2 (Table 1), Pb was detected in a ≈ 0.1mm long radial crack at the exterior surface. While the source of the Pb is unknown, it seems reasonable to propose that lead paint, used to inhibit corrosion sometime after the cable was assembled, had penetrated the crack. This would mean that the crack was present in the wire after being drawn. This conclusion is substantiated by the presence of an unusually large inclusion nearby, and the absence of corrosion products that would rule out stress corrosion cracking. Exactly when the lead paint would have been applied is uncertain since Ellet (1840, 46–47) indicated that the bundles of wire that form the cables were to be coated with varnish in his Mississippi Bridge proposal.
11. *The Daily Wheeling Gazette*, 21 November 1849, p3.
12. Joshua Bodley and Co supplied wagons to the Union army during the Civil War ('First West Virginia Infantry: First Regiment Virginia Infantry,' Chapter 6, *www.lindapages.com/1wvi/1wvi-6.htm*, 2002). Reeves (1870, 26) discusses the Company's prominence as a wagon manufacturer (name changed to Bodley and Son) after the Civil War. A subsequent newspaper account (*The Wheeling Daily Intelligencer*, 14 September 1886, appearing at *wheeling.weirton.lib.wv.us/history/bus/weed86.htm*) describes the great wagon works of the Bodley Brothers, now located from Eoff to Chapline Streets and on the opposite side of Eighteenth Street. This prosperous firm with strong southern markets was operated by John and James W Bodley, sons of Joshua (Cranmer 1902, 658).
13. 'Iron Works at Wheeling, Virginia,' *The Merchant's Magazine*, Volume XIX, August 1848, p230.
14. A colourful description appears in 'Wheeling Industries: The Virginia Mill and its Successor, the Benwood Iron Works,' *The Wheeling Intelligencer*, 5 February 1874.

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