The Elmore brothers and the flotation process for separating minerals

J K Almond

ABSTRACT: *To extract copper from ore broken near Dolgellau, North Wales, c 1898 Frank Elmore developed a technique of selectively transferring minerals from water into oil. Frank and Stanley Elmore began to exploit bulk-oil flotation internationally, but soon alternative schemes emerged in Australia and Europe and the brothers became involved in damaging litigation with rivals. Frank Elmore invented an improved technique, using less oil and with vacuum-generated bubbles; vacuum flotation was installed in North Wales c 1907 and applied in Australia, Norway and Canada. From 1910 related systems of froth flotation beyond the Elmore's control were introduced in the Americas and elsewhere. As the 20th century progressed, both the scale and scope of flotation treatment increased, so that it became the preponderant mineral-separating method. The pioneering contributions of the brothers are set in context.*

Introduction

At Glasdir (national grid reference SE 738 225), 5km N of Dolgellau in NW Wales, occupying a series of terraces on the steep and wooded hillside, are the foundations of a mineral-processing plant which was active for part of the 1890s and during some of the years until *c*1913 (Fig1). The site, accessible to the public by footpaths, lies within the Snowdonia National Park. The ore for which the dressing plant was built came from a nearby low-grade deposit of finely-disseminated chalcopyrite $CuFeS_2$ with iron pyrite FeS_2, carrying some silver and gold. The chief vein mineral was quartz, set within phyllite. At this site there took place some of the pioneering work in the development of mineral flotation.

The purposes of this account are to indicate the significance of the site remains, to sketch the wider scene of which they are a component and, a century onward, to record a tribute to the two brothers, Francis (Frank) and Stanley Elmore.

Antecedents to the developments from 1897 at Glasdir

During the seventy-year period from 1830 to 1900 world production of the major nonferrous metals increased about tenfold. The demand for larger quantities of metals led to attempts to work mineral deposits in geographical areas which were increasingly remote, as well as deposits which contained smaller proportions of wanted metals, and those from which the wanted metallic components were difficult to extract.

The Glasdir deposit had been the subject of attention in the 1860s, when some copper and gold had been obtained, but in the following decade it was deemed to be uneconomic to work. Then in 1892 the Glasdir mine was bought by Samuel Crowder, who, through his manager George Robson, set out to exploit the deposit once more, but using established dressing methods based upon specific gravity differences between minerals, it proved difficult to extract more than a minor proportion of the copper present.

Robson desperately experimented with oil formed of kerosene, or an allied petroleum-distillation fraction of relatively low specific gravity, combined with a ‘thick fatty’ component. We can only speculate why Robson was inspired to evoke the aid of oil to solve his problem. According to Samuel Crowder's subsequent reminiscence (1917, 257) ‘By accident he picked up a can of oil, and as he said, almost absentmindedly tried to concentrate some of the ore’ with a result that was ‘extraordinary’. However by 1890 it was recognized that oils and waxes could greatly modify the behaviour of mineral grains immersed in water. Around 450 BC Herodotus had recorded how feathers daubed with pitch were dipped by young women into mud containing gold: the gold adhered to the pitch while the other substances present did not. Over a long period of time greasy fleeces were used to collect particles of gold from moving streams of water-borne sand. It had been recorded that, in the presence of grease or oil, grains of metal-sulphide minerals, even those of lead (*ie* galena) with the high specific gravity of 7.5, showed a tendency to float on the surface of water and thus, by this perverse behaviour, to escape out of the dressing plant with the waste pulp. Indeed, in some quarters this

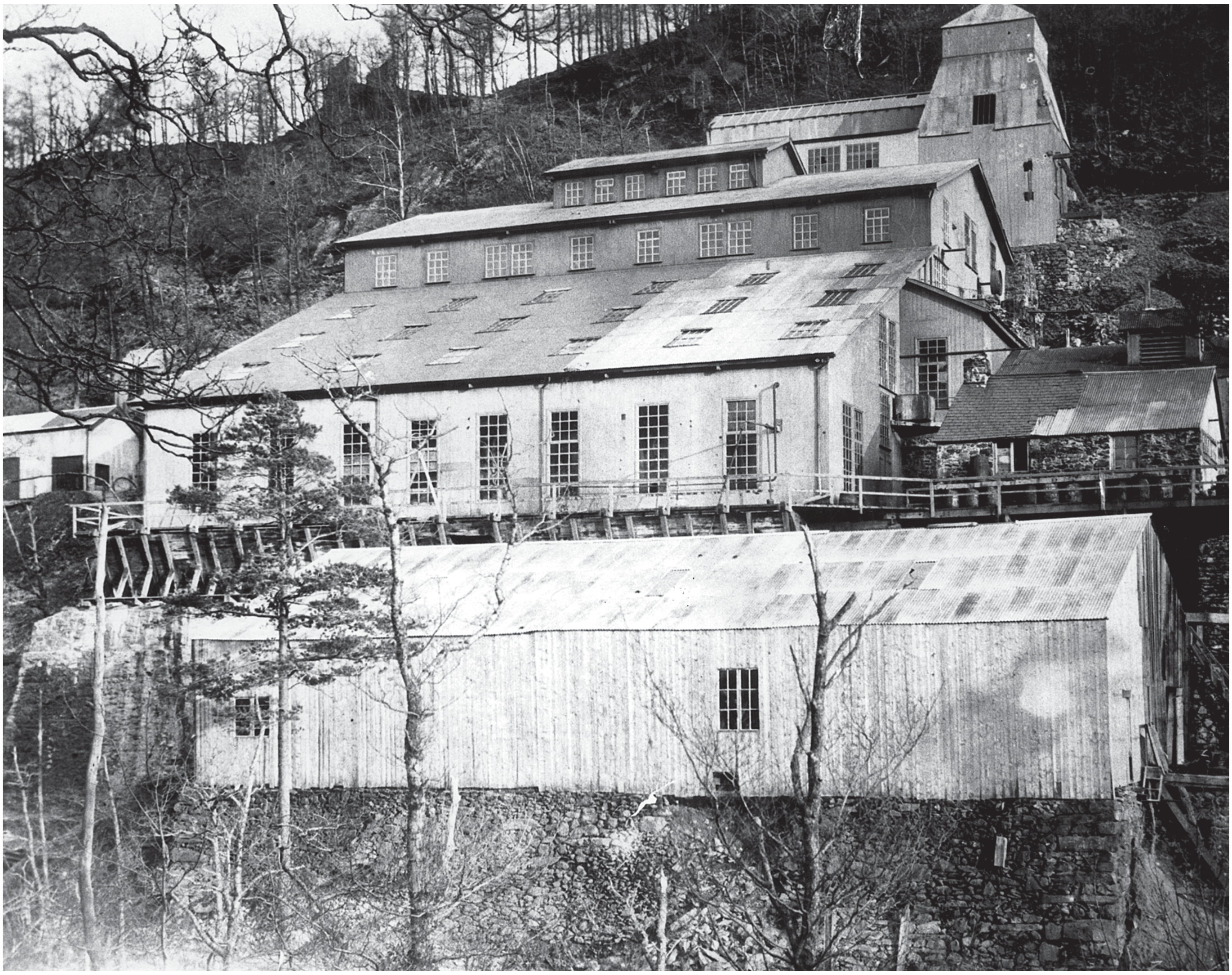

Figure 1: The mill at Glasdir, circa 1905. The flotation plant was located in the central building. The small stone-built structure on the right covered a tank for storing the re-cycled heavy oil. Several oil barrels are visible on the verandah in front of that building. (Gwynedd Archives Service)

tendency to float provided a convenient explanation for some 3 or 4% of unaccounted losses of gold as well as base-metal contents.

In 1860 a patent was filed by William Haynes of Holywell (BP 488) which described a scheme for separating metal sulphides from gangue minerals by mixing 10-20% of fat or oil with crushed ore, adding warm water, and subjecting the whole to rubbing or grinding when, it was claimed, the 'earthy matter' would sink to the bottom of the water, leaving the metal-sulphide grains united with the oil, although not 'floated' (Hoover 1916, 23).

In 1877 a German patent was granted to the Bessel brothers for a method of separating graphite from accompanying minerals by means of oil with boiling water to generate gas bubbles (Bessel 1877; Erhard 1977). (It happens that graphite is one of the easiest of minerals to float.) In 1885 a United States patent (No. 348,157 of 29 August) was obtained in the name of a married woman, Carrie Jane Everson (née Billings, 1842-1914). This proposed the separation of sulphides in ore from gangue by mixing the granular material with oil, adding water containing acid (which acid was stated to increase the selective adhesion of oil to sulphide particles), agitating the mixture, and collecting the oiled sulphides from the surface of the water (Hoover 1916, 21). Unfortunately for Mrs Everson, no operators of sufficient substance could be found to work out the practical details required for success; left a widow, she earned a living by nursing.

So we come back to Glasdir in 1894. Robson and Crowder were granted a British patent (No. 427 of 1894) for their proposal to separate metal-sulphide minerals from gangue by mixing moistened granular solids with a large volume of oil, when the sulphide particles would be selectively transferred into the oil. The relative quantities of oil and ore used were perhaps three tonnes of oil to one of ore (Rickard 1916, 24 and 35). Evidently the procedure was tried in batches of about one tonne, but practical results were disappointing, and the Glasdir property was offered for sale. It seems that the chief reason for Robson's defeat was the large proportion of oil lost during treatment; this occurred through 'oiling' of the gangue as a consequence of, among other factors, use of 'thin' oil (Rolker 1899-1900, discussion 385, 387, 389, 391). According to one chronicler, experimental apparatus and other evidence remained on the property (Rickard 1916, 47), but the extent to which these artefacts influenced subsequent developments was vehemently contested (Anon 1917).

The Elmores and bulk-oil concentration, 1897-1905

This was the point at which the Elmores appeared on the scene. William Elmore had been in business in London, making equipment for metal electrolysis. Two of William's sons, Francis Edward (1864-1932) and Alexander Stanley (1867-1944), had helped to instal new copper-refining apparatus near to Swansea (Jenkins 1987, 7), and, in the late 1880s, family members had opened a plant in Leeds to form copper tubes and other products by electrolysis. The Elmores were industrious patentees: between 1879 and 1885 William secured several patents to do with dynamos together with half a dozen related to the electrodeposition of metals or the extraction of metals by chemical means. From 1883 his sons followed the pattern so that by the late 1890s the family members between them had been granted more than 30 British specifications alone. In the 1880s William was an 'electrical engineer' with works at Blackfriars, in London. In 1885 his son Francis was enrolled as an associate in what was soon to become the Institution of Electrical Engineers, and throughout the 1890s he was resident in Leeds 'as technical advisor to several companies using electrolytic and electro-metallurgical plant' , while 'designing electrical and electro-metallurgical apparatus and superintending' its working (Elmore F E 1899). Alexander Stanley Elmore was elected a Fellow of the Chemical Society in 1893, and in 1895 was managing director of the Elmores' Patent Copper Depositing Company in Leeds.

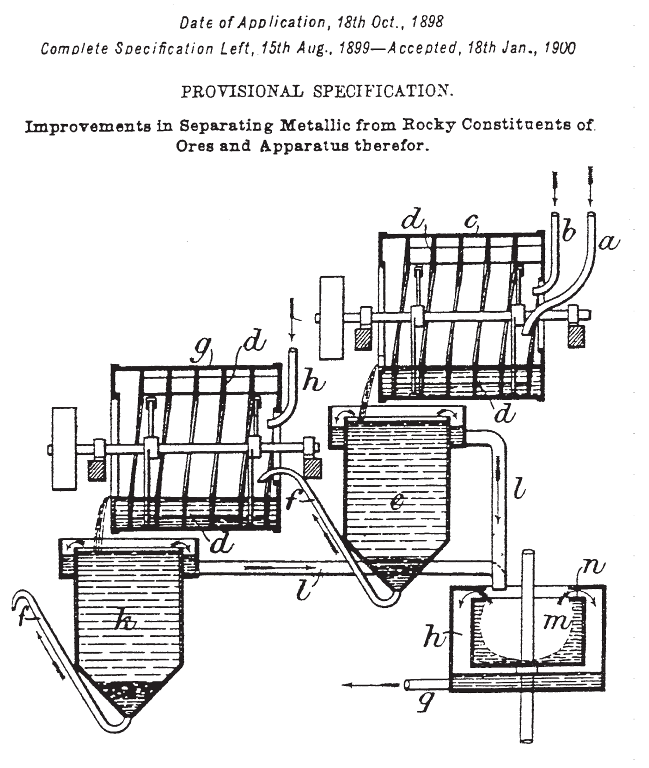

Figure 2: Proposed bulk-oil concentration plant as shown diagrammatically in F E Elmore's 1898 British patent 21,948.

William Elmore and business associates in 1896 bought the Glasdir mine from Samuel Crowder and put in some fresh dressing appliances to produce copper concentrates using conventional gravity methods, but only one third of the values were extracted (Elmore F E 1899-1900, 390).

It was in these circumstances that William's sons turned their attention to the problem. In 1897 Francis, or Frank as he preferred to be known and will be called throughout the subsequent text, was in his early thirties, and manager of Elmores' Leeds wire factory. According to a record written by his brother Stanley (Elmore A S 1916, 450), Frank may have been inspired by the sight, within the Glasdir mill, of metal-sulphide particles adhering to the surface of an iron pipe where a greasy hand had grasped it. At all events, deciding to make use of the observed attraction of some metal-sulphide grains to oil, Frank devised and built contrivances in which the desired separations could be achieved. The principle used in the Elmore bulk-oil concentration process was that, within an environment of both water and oil, minerals possessing metallic lustre (generally metal sulphides) would exhibit a preference for the oil while most other minerals, including the common gangue constituents quartz and slate, would remain wetted by the water. The feed to the separation process was in the form of a 'free-flowing pulp' of

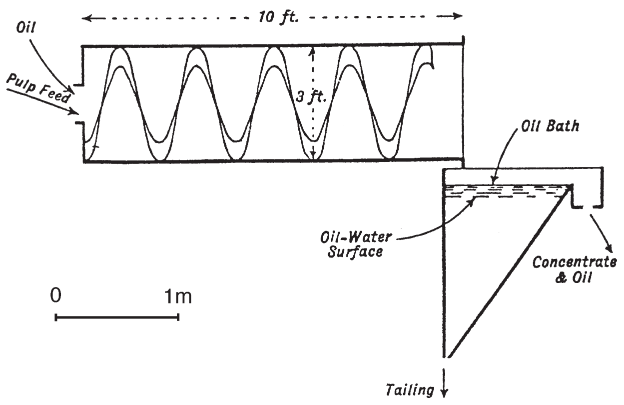

Figure 3: Elmore bulk-oil concentration process; two of the three treatment steps: (1) mixing aqueous pulp with oil in a rotating drum, and (2) separating the oil-sulphide fraction ('concentrate') from the water-gangue portion ('tailing'). (Truscott 1923, 391).

sand-sized grains in water.

Following work in an experimental plant 'erected in an odd corner of the mill' at Glasdir, an industrial prototype rated at 50 tonnes of ore a day was installed *c* 1899 (McDermott 1899-1900, 386). Frank applied for a British patent covering some features of his technique in 1898, from which Figure 2 is reproduced, and corresponding USA patents followed (Elmore F E 1898).

In bringing about a separation three steps were involved: mixing; separation of oil from water; and separation of mineral from oil. The first two of these steps are conveniently shown in Figure 3 taken from Truscott's book (1923). After comminution to, say, all minus 0.5mm, the mixture of ore and water (which at Glasdir was five of water to one of ore, by weight) was run into one end of a horizontal slowly-rotating drum fitted with helical flights to promote a kneading action. Oil was added to the contents of the drum in controlled quantities; with experience it came to be believed that the point of addition of the oil, and hence its time in contact with the components of the ore within the mixing drum, influenced the results obtained. At Glasdir, the weight of oil used was roughly the same as the weight of ore. Having been gradually carried along the length of the drum in the course of 50 to 100 seconds, the mixture of oil, water and pulverized ore discharged into a simple stationary settling tank or 'subsidence vessel' in which the separation of the two liquids took place so that a layer of oil floated upon the bulk of water. Those solid particles which remained wetted by water sank to the bottom of the settling vessel whereas grains which had acquired an oily surface coating reported in the oil layer, hence 'floating' on the water. The upper oil layer with its mineral load was continuously run over a weir from the tank. One of the critical operating details was to maintain sufficient difference in specific gravity between the water and oil for the latter to float when laden with 10 or even 20% of its weight of relatively dense mineral particles. If necessary to assist buoyancy, additional oil might be supplied to the settling tank. The specific gravity of the oil used was about 0.9, compared with water at 1.0; such an oil, a fairly high-boiling residue from primary fractional distillation of crude petroleum, possessed high viscosity at ambient temperature.

The third treatment step subjected the 'concentrate' fraction of oil plus entrained mineral particles to centrifugation in order to yield a granular mineral product containing some 4wt% of oil and a similar proportion of water, and an oily fraction for recycling (Rolker 1899-1900, 382). This third step was not easily performed to a consistently satisfactory level; rather than a single unit, the technique adopted involved two stages of centrifuges, and might be aided by heat. The success of this manipulation was one of the key factors in the technical viability of the whole process.

The Elmores' potential backers arranged for a reputable engineer to test and appraise the system at Glasdir, and favourable publicity was gained from the London meeting at which his report was presented and discussed (Rolker 1899-1900). He stated that from 'the very low-grade copper ore from the Glasdir mine, carrying about 1.12% copper ...[together with 24.5ppm silver and 1.5ppm gold] we obtained an average saving of 70% of the copper, 65% of the silver, and 69% of the gold, ...a good saving' (Rolker 1899-1900, 382-3). The engineer wrote that 'The mechanical contrivances brought into action by the inventor are excellently adapted to the work demanded... Seemingly insuperable mechanical difficulties have been very ingeniously overcome... ' (p 380). He cautiously concluded that with ores similar to the Glasdir material, the advantages of the process are a smaller consumption of water, and a higher yield than in wet concentration' (p 384). During the course of the discussion he remarked that 'when he made his tests not only was the inventor very much present, but also the gentleman who had conducted experiments during the previous years' (evidently alluding to George Robson) (p 390). Frank Elmore observed to the meeting that 'he did not claim that the use of oil was absolutely novel' (Elmore F E 1899-1900, 389).

Among the contributors to the London discussion was

Walter McDermott who, following 25 years experience in the mineral industry, had just been appointed manager/director of Fraser and Chalmers' equipment works at Erith, Kent. On this occasion he mentioned the affinity that diamonds had for grease and how this fact was being used in their extraction from mineral pulps. McDermott took a personal financial stake in the Elmores' work.

Developments from 1900

With the purpose of promoting the patented process internationally, beginning in 1900 the Elmores with their financial supporters set up a number of companies headed by the Ore Concentration Syndicate Limited. In 1901 a demonstration and testing works in the east end of London was opened, equipped with an oil plant rated at 25 tonnes of ore a day, that is one standard three-drum unit of the kind shown (in duplicate) in Figure 4. In the same year the syndicate began to issue literature describing the process and calling attention to its possibilities, so that eventually about 150,000 copies of pamphlets had been distributed (Elmore A S 1916, 452).

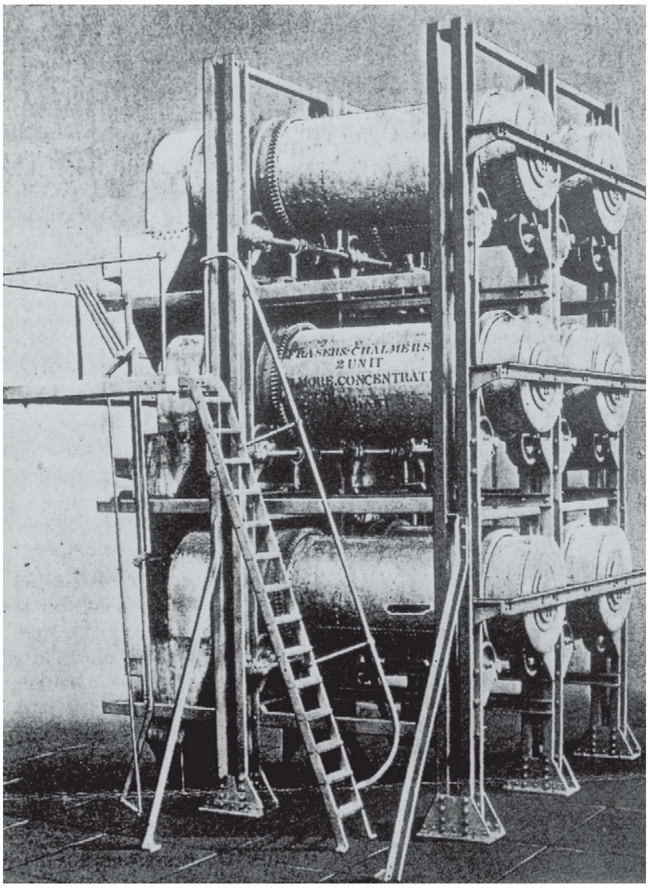

Figure 4: Two-unit three-stage commercial Elmore oil concentrator; nominal capacity 50t/day. Commonly the feed material was passed through three drums in series before final discard. (Compare the two treatment stages shown in Fig 2). (McDermott 1903, 294).

Samuel Whitworth, from Australia, was put in charge of the testing and experimental work (Whitworth 1923-24). Publicity was given to the ordering of an oil plant for the Independence mine in Colorado, and to an option which had been taken by the Elmore company's representative on the tailings dumps of the Mammoth Mining Co at Tintic in Utah, with the object of giving the process a thorough trial. At the same time, results were tabulated for 31 laboratory tests, the list including several copper 'ores', gold-bearing materials from the Transvaal and Western Australia, and mercury 'ore'. In nearly all the cases quoted, more than nine-tenths of the values were collected in the concentrates (Anon 1902, 760). Another significant event in 1901 was the granting to Stanley Elmore of patents which 'described a method of increasing the selective action of oil by adding acid to the pulp' (Hoover 1916, 24).

As far as Glasdir was concerned, writing early in 1903, Walter McDermott stated: 'The first working plant erected was the gradual growth of experiments at the Glasdir mine in North Wales and had a final capacity of 50 tons per day. Several thousand tons of ore were treated, but the mine has been closed for some time for financial reasons...' It was not commercially viable. He went on to report that 'The following plants have been ordered: 75 tons for Norway, 50 tons for Lake View Mine, Western Australia, 50 tons for Le Roi no.2, British Columbia.' In addition he claimed that within the previous few months three British oil plants had started regular work: at the Tywarnhaile mine in Cornwall a two-unit (50tons/day) outfit was processing old dumps of quartz and slate containing iron pyrite and chalcopyrite and assaying 0.6% copper; the concentrate assayed 8%, with an extraction of four-fifths of the total value. At the Sygun mine near Beddgelert in Wales, some 35km NNW of Dolgellau, the tailing from shaking tables, assaying 1% copper, was treated in four units (100tons/day) of oil plant. Nearer the west coast of Wales and 6km NW of Dolgellau, at the Clogau gold property (then being worked as St David's mine) six units were installed (McDermott 1903). Apparently the intention at Clogau was to recover metal values from the gold-battery tailings without regrinding, but the application seems to have been unsuccessful from the start. Sygun closed in 1904 (Bick 1985, 68).

It was later claimed that by 1904 about 30 units of oil plant had been supplied to ten different mining companies, representing an aggregate yearly capacity of about 300,000t (*ie* tonnes) of ore (Elmore A S 1916, 452). However, it is evident that only a minority of the units was used at anything like their capacity. In most, if not all of the situations in which the new process was tried it was handicapped in proving its performance: either the proportion of mineral to be selected from the feed was pathetically small for efficient operation (*eg* copper contents of only 1%) or the quantity of feed supplied was inadequate for continuous full-capacity working. For separating sulphide minerals, the running costs of the process were higher than those of gravity, or 'water' concentration. Understandably from the manner of its introduction, bulk-oil concentration was seen as a way of supplementing extraction in circumstances in which existing dressing methods proved unsatisfactory.

Frank Elmore (1899-1900, 392) commented that 'when the process was started it was with the idea that low-grade ore would be treated.' Moreover, even though the machinery and working techniques devised for bulk-oil flotation were effective, there can be little doubt that the method, involving large quantities of heavy mineral oils which, except by burning, could never be completely removed from material with which they came into contact, was inherently unpleasant. An informed commentator subsequently wrote that the process 'was in the hands of capable engineers ...[who] tried consistently to adapt... [it] to suitable ores... [It] was the first of the kind to approach commercial success' (Hoover 1916, 7). Whatever its unrealized potential, by 1905 bulk-oil concentration for sulphide minerals had been superseded by other developments in the field of flotation.

The Elmores and Minerals Separation Limited

In 1901 an option on the Australian rights to the Elmores' bulk-oil process was obtained by a group of London businessmen and their technical advisors, two partners, H Livingstone Sulman (*c* 1860-1940) and Hugh F K Picard (*c* 1870-1942). For nearly a year Sulman, Picard and businessman John Ballot were provided with working details of the Elmore system, but then the arrangement was dropped by the group which, instead, soon acquired patents from two other sources and organized a company called Minerals Separation Limited to profit from them. One of the patents purchased, BP 12,778 of 1902, was in the name of Alcide Froment, and it described the use, for separating minerals, of gas bubbles and agitation as well as oil. Froment was an engineer at Traversella in Italy where the bulk-oil process had been tried. Although Froment specified generation of the bubbles by the action of acid on calcium carbonate, later it was written of him that 'he furnished the link between bulk-oil and air-froth flotation' (Rickard 1916, 37, 38). The other patents upon which Minerals Separation Limited was founded were Arthur B Cattermole's 1902 BP 26,295 and 26,296 which sought to use the selective action of oil on metalliferous particles immersed in water (but in order to coagulate them to form sunken glomerules, not to float the individual grains).

By contrast with the Elmores, the attitude of Minerals Separation was extremely restrictive concerning the

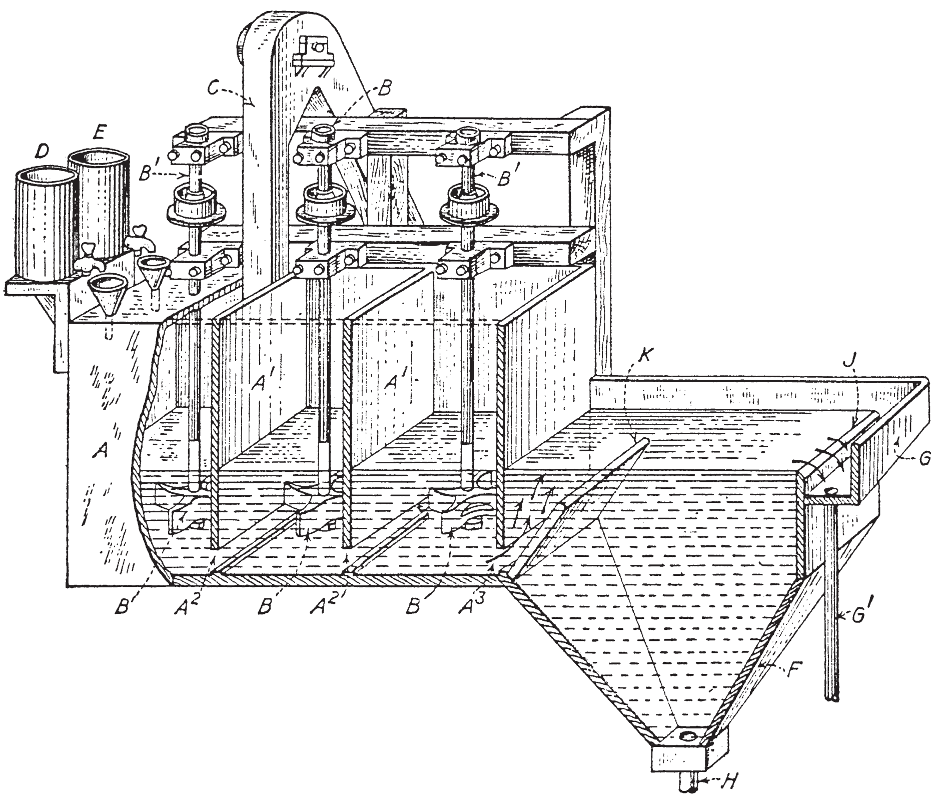

Figure 5: T J Hoover's mechanically-agitated froth-flotation machine of c.1910, promoted by Minerals Separation Limited. Pulp containing granular feed enters continuously down C; reagents are added at D and E; impellors B produce vigorous mixing and aeration of the pulp as it travels progressively through the three turbulent conditioning compartments. In the right-hand vessel mineral-laden froth flows over weir J into launder G while wetted sands and water discharge through H. (Hoover 1916, 135).

release of technical information. The latter company employed several people in research and development work, and from late 1906 until the end of 1910 the manager was Theodore J Hoover (brother of the mining engineer/businessman and later USA president Herbert Hoover). Both groups set out to charge licensees royalties for each tonne of ore treated using their methods; something like one shilling (5p) was obtained in some cases (Hoover 1916, 197, 200; Mitchell 1911, 997).

In the opening years of the 20th century the Elmores and Mineral Separation both saw the mineral deposits at Broken Hill in Australia as possessing great potential. Although Minerals Separation was the first of the two to be associated with a plant working on the field (begun in 1904-05 using the Cattermole system and, in its initial form, unsuccessful), following trials made at Broken Hill in 1906-07, the Elmores' second scheme, that of 'vacuum flotation' described in the next section, in 1908 displaced the Minerals Separation equipment at the Zinc Corporation's plant, treating accumulated zinc-rich residues from gravity concentration. However, in 1911 the Elmore plant was itself scrapped in favour of Minerals Separation's improved process of air-froth flotation carried out in mechanically-agitated machines developed by T J Hoover (Figure 5).

In 1907 the Elmores commenced legal action against Minerals Separation Limited for infringement of patents (BP 21,948 of 1898 and 6519 of 1901). This action proved to be both lengthy and costly; after losing the case initially, the judgment was reversed on appeal, only to be overturned again in 1909 when the defendants applied to the House of Lords.

In a well-documented account, Jeremy Mouat (1996, 21, 22) states how, in Germany in 1909, 'the Elmores successfully blocked the efforts of Minerals Separation to have the latter's patent registered', while in Australia Elmore companies started action against the Sulphide Corporation for patent infringement by its use of the Minerals Separation process. After nearly five years' entanglement with the courts, that case ended in 1914 when the Privy Council upheld an earlier ruling against the Elmores. While the arguments were still in progress, one comment made by a man close to the action (Mitchell 1911, 997) was 'to say the least, this patent litigation is absorbing enormous sums of money and proving a great blessing to the legal profession.' Mouat (1996, 22, 23) quotes from Theodore J Hoover's memoirs that 'The litigation cost ... millions of dollars and delayed the progress of the application of the invention many years. ... Compromise on almost any terms would have been more profitable.' By 1915 the Elmores were out of the legal arena; in any event, by then some of the formerly valuable patents had expired. Minerals Separation, on the other hand, was still pursuing infringement claims made against mineral producers in the USA.

The Elmores and the vacuum-flotation process, 1904-1916

Moving with discoveries made elsewhere, early in the century Frank Elmore became interested in the idea of lifting one species of mineral particles through a pulp

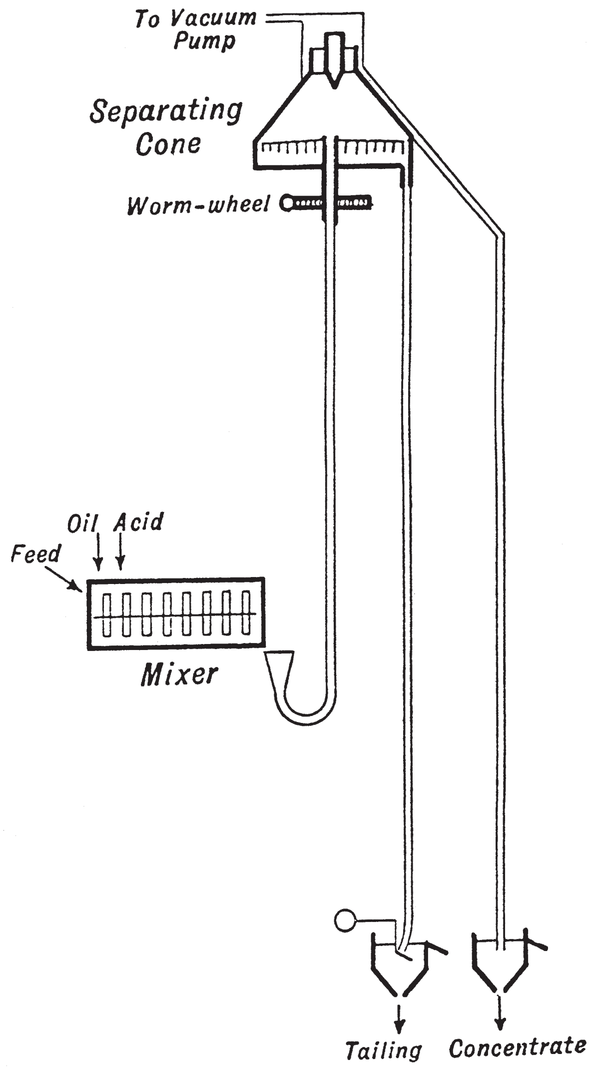

Figure 6: F E Elmore's vacuum-flotation system, patented in 1904. Conditioned feed pulp flows continuously from the mixer up into the vacuum chamber by siphon. In the chamber a froth of gas bubbles is generated, carrying sulphide particles up to the apex, from where a stream flows down to report as 'concentrate', while the water-wetted sands pass down to the 'tailings' sump. (Truscott 1923, 396).

by means of selective attachment to gas bubbles, and in 1904 he patented the use of bubbles generated by electrolysis (BS 13,578 of 15 June). More significantly, in BS 17,816 of 16 August 1904 he proposed to generate the necessary bubbles by carrying out the separating process under reduced pressure, and he described a way for putting it into effect, (Figure 6).

As in the bulk-oil process, the vacuum method required appropriate treatment of the feed (*ie* what became known as 'conditioning') before separation between mineral species was attempted. Here this conditioning was performed in simple paddle mixers into which the feed of comminuted ore in water was introduced together with small proportions of oil and acid.

The separation itself was made in a closed conical vessel connected to a vacuum pump. In order to overcome the effect of the vacuum and so to achieve the desired steady flow of aqueous pulp into the separating vessel and of two mineral-laden streams away from it by means of a siphon, long 'barometric legs' were needed, the lower ends of the discharge tubes being submerged in water to prevent air from being drawn into them. Buildings to house such plant tended to be 15m or more in height. The stationary separating bell was fitted with a slowly-rotating rake to move the non-floating hydrophilic sands fraction towards the 'tailing' exit pipe. The sulphide-mineral particles, made hydrophobic by the conditioning stage, attached themselves to the ascending swarm of freshly-generated gas bubbles, and so were carried upwards in the bell and thence found their way down the right-hand leg to the 'concentrate' container. Figure 7 shows a view of one of the commercial separating units, five feet (1.52m) in diameter; it was claimed that altogether around 150 of these were made in the years immediately following 1905, representing an aggregate capacity of something over two million tonnes of ore a year (Elmore A S 1916, 453). Each unit could handle between 25 and 40 tonnes in 24 hours. It was calculated that, in a pulp consisting of one tonne of ore to six of water, the quantity of air dissolved should suffice to lift 163.4kg of zinc-lead sulphides from an Australian Broken Hill feed (Rickard 1916, 26; quoting Hoover 1916, 102). However evidence from commercial operations showed that significantly greater weight could be lifted, thereby indicating that besides dissolved air other sources of gas were generally present, *eg* carbon dioxide generated by action of the acid.

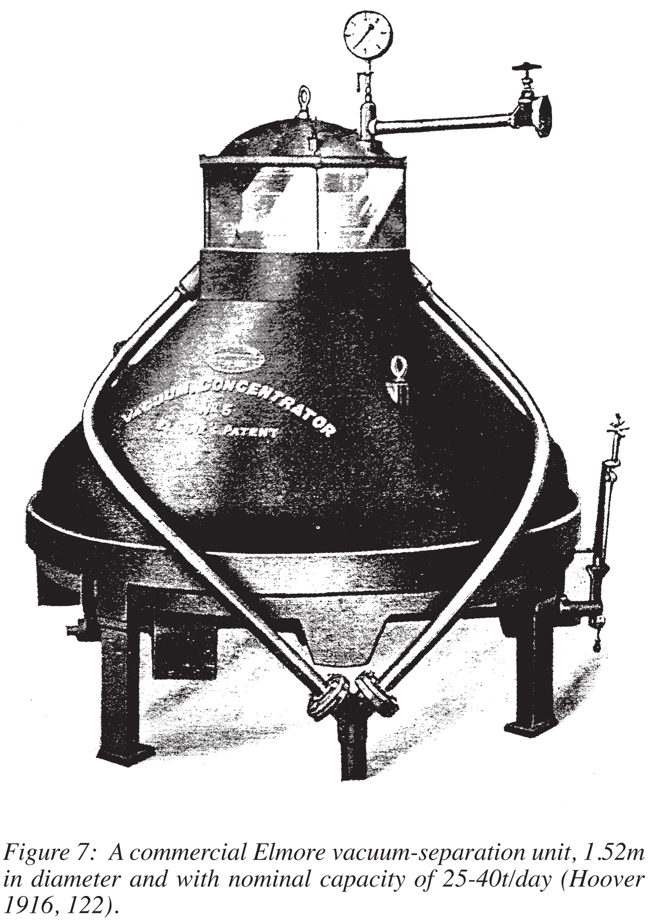

Figure 7: A commercial Elmore vacuum-separation unit, 1.52m in diameter and with nominal capacity of 25-40t/day (Hoover 1916, 122).

In this system the proportion of oil added to the pulp was reduced to 0.5% and even, in some instances, to as little as 0.015% (Rickard 1916, 26), although the important Broken Hill installation described below used close to 1%. According to Stanley Elmore, summarizing with hindsight (1916, 453), 'these vacuum plants have never been employed with a large proportion of oil. ... the flotation of ground mineral particles is secured by the attachment of bubbles ...the flotation of the concentrate results from the use of violent agitation, a minute proportion of oil, and the production of a froth.' The price of a vacuum unit, complete with pump, mixer and pipes, was £350 (Elmore A S 1907).

Applications of the vacuum process outside Australia

Units of plant were installed at several of the properties which had previously tried the bulk-oil process. In some instances this is not surprising as the Elmores themselves operated the properties: Stanley had financial interests in Glasdir and Sygun in Wales, and Tywarnhaile in Cornwall. Glasdir and Tywarnhaile were reopened in 1907 while in the same year the great Dolcoath, mainly a tin producer, was equipped to treat finely-divided chalcopyrite, the vacuum plant there running until the middle of 1909. However, it seems that the earliest installation in Cornwall was made at Falmouth Consols in 1905, the appliances being housed in the mill at old Wheal Jane; mining ceased there in

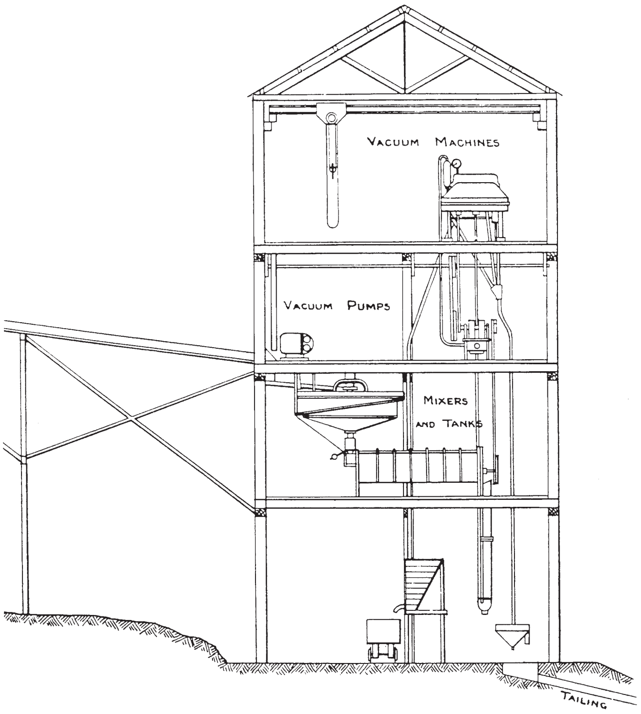

Figure 8: Diagram of Elmore vacuum-flotation plant at Åmdal in Telemarken, Norway, where in 1908 three units were installed to treat copper (chalcopyrite) ore. (Bennett 1909).

1914. By the end of 1906 the Clitters United mines near Gunnislake also had a vacuum plant (Cullimore, 1979). At Ramsley near South Zeal in Devon (NGR SX 650 930) an Elmore plant was erected in 1907 to treat copper ore, but the mine closed in 1909. Another British location from 1907 was at Hafna in North Wales (NGR SH 781 602), where the foundations of the flotation plant could still be seen in the 1990s, together with other remains of the mill on its terraced site (Short 1997, 92, 93). Somewhat later, *c* 1912 in the Cumbrian Lake District, an Elmore plant was put up at the Force Crag property where, in 1913, 32 tonnes of lead were produced; intermittent working took place here until *c* 1923 (Tyler 1990, 35-37, 46, 47).

Outside Britain, vacuum units were installed at six properties in Scandinavia and at a larger number in other parts of the world. As was the case in Britain however, several of the Scandinavian projects had working lives of only a few years. Among the more persistent were two in Norway, at the Telemarken mines and the Sulitjelma mine. The Telemarken mines, known locally as Åmdals Verk, had a history from 1540; the Elmore process was introduced in 1908 following a fire which destroyed the previous dressing plant, Figure 8. The ore fed to milling contained 4-6% copper, the flotation concentrate about 26%, and the tailing 0.2%, with more than nine-tenths of the copper in the feed being recovered in the concentrate. The flotation plant comprised three vacuum units and mill capacity was stated to be 76t/day. Even as soon as 1909 the warning statement was made that the low-grade deposits of the Telemarken mines were situated in a mountainous region, difficult of access, involving high freight charges and subject to ‘extortionate rates and taxes imposed by the Government and the Commune’ (Bennett 1909). About 1913 the equipment was sold to some molybdenum mines nearby (Nesvold Finn 1999, pers comm). In 1914 two producers north of Flekkefjord, Kvina mines and Knaben mine, used the Elmore vacuum process to concentrate molybdenite, MoS_2 (Claudet 1916, 127-8), for which there had come increased demand. In 1916 the system was also installed in Canada by one producer, Renfrew Molybdenum Mines Limited, near Mount St Patrick in Ontario (Claudet 1917, 124, 127). Several new or expanded Canadian molybdenite mills were then using flotation but favoured methods other than Elmores’ for achieving their aims.

At Sulitjelma in Norway, situated near the Arctic Circle, mining had started in 1891, the ore mineral being predominantly iron pyrite, with some chalcopyrite, contained in a gangue of micaceous schist. Early in 1909, after two years during which a single vacuum unit with a capacity of about 40t/day had been continuously treating part of the tailing from gravity separation, a 12-unit plant designed to process 500t/day began regular work, Figure 9. The copper content of the gravity tailings fed to this plant ranged between 0.8 and 1.4%; the concentrate of clean copper and iron sulphides contained 6% or rather more of copper, while the tailing from the Elmore plant assayed 0.15-0.30%. More than four-fifths of the copper was extracted into the concentrate. By 1910 the plant was stated to be recovering 800 to 1000 tonnes of copper a year from material which would otherwise have been discarded (Holmsen and Rees 1910). In each of the years 1912 and 1913 the copper contained in the concentrate exceeded 600 tonnes (Hoover 1916, 132).

In Mexico, at Santa Barbara in 1910, Elmore equipment was used to recover a sphalerite-pyrite fraction from the residues of gravity dressing (Crabtree and Vincent 1962, 40; citing Marcosson 1949).

Applications of the vacuum process in Australia

Far more substantial than any of the applications already mentioned was the performance of at least one plant at Broken Hill in Australia, where the vacuum-oil process was in use between 1906 and 1913. Working of the large high-grade lead-zinc-silver deposits at Broken Hill had begun before 1887, and by 1901 considerable tonnages

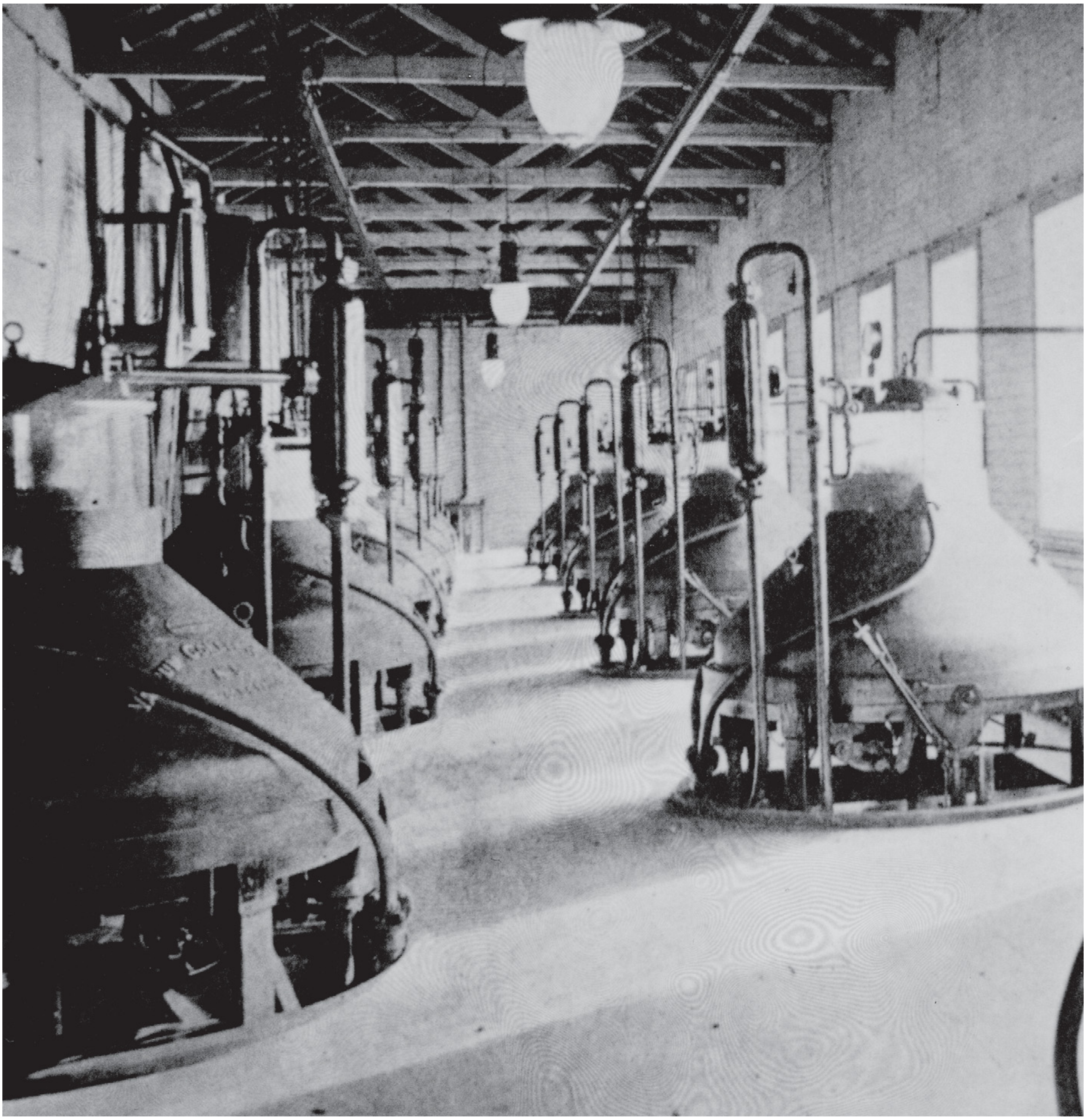

Figure 9: Elmore vacuum-flotation plant at Sulitjelma in Norway, showing the separator floor with 12 units. (Holmsen and Rees 1910, 380).

of metallic lead and silver had been obtained. Extraction of the zinc values, however, continued to pose a problem, partly because the zinc sulphide mineral, sphalerite, possessed a specific gravity of around 4.0 which was similar to that of some of the associated gangue minerals, *eg* rhodonite $MnSiO_3$ (SG 3.5) and garnet (SG 3.5-4.1). Large dumps of zinc-rich residues from gravity concentration had accumulated on the land surface. At the turn of the century gas-bubble flotation was proposed and developed by people in Australia (C V Potter and S D Delprat), with the first 50 tonnes of zinc concentrate marketed in 1903 (Truscott 1923, 392), followed by 58,000t in 1904 and more than 100,000t in 1905 (Wainwright 1930, 281). In l904-5 another operating company, the Sulphide Corporation was testing the process patented by Cattermole of England and promoted by Minerals Separation Limited; soon considerable changes had been incorporated so that it had become an air-froth flotation system. This used a fraction of 1% (by weight of feed) of oleic acid to condition the powdered feed suspended in 1% sulphuric acid solution at about 30°C. Strong agitation resulted in the generation of a froth which carried the hydrophobic sulphide particles and which was separable from the aqueous pulp. Sulman, Picard and Ballot's 1905 Australian patent 5032 was in accord with these conditions. At this time there was also introduced at Broken Hill A J F de Bavay's Australian-based method in which oil-conditioned hydrophobic metallic minerals were separated from hydrophilic gangue grains by being run gently onto a water-air surface, through which the latter sank while the former remained 'floating'.

It was into this climate of large-scale activity coupled with intense commercial rivalry that the Elmore vacuum process was brought in 1906, as a test plant sent in by the Ore Concentration Syndicate Limited (Mitchell 1911, 994). As the result of trials made with this unit, a total of 32 vacuum separators was supplied to four operating companies between 1907 and 1910, although only two of the installations, involving 26 units, were other than ephemeral.

For the Zinc Corporation, a company formed in 1905 to re-work the residues from the wet-concentrating mills, a 16-unit Elmore plant came into use in February 1908 as, compared with the available Minerals Separation process, it was judged to offer better economic return from treating 725,000t of dumped tailings containing zinc, lead and silver. Plant feed assayed 19.1% zinc while the final zinc concentrate assayed 46.0% and weighed 246,000t, indicating an extraction of just over four-fifths of the zinc into one-third of the weight. The discarded tailing from the operation assayed 4.9% zinc (Hoover 1916, 126-28). Reagents consumed for each tonne of feed were 9.37kg sulphuric acid, 3.97kg British imperial residuum oil, and 4.77kg limestone (Wainwright 1930, 297). The commercially-critical level of 45% zinc in the concentrate, coupled with a lead content of only 6.6% to avoid incurring smelter penalties, was achieved by subjecting the floated fraction of bulk sulphides, containing some 43% zinc and 10% lead, to gravity separation, *eg* on shaking tables; for this to be practicable the oil adhering to the grains had first to be burned off, a procedure which was considered 'objectionable' (Wainwright 1930, 296).

Treatment costs for this Elmore installation were 45-50p/t (Mitchell 1911, 996, 997). By 1910 the supply of favourable residues particularly suitable as feed for the plant was approaching exhaustion and it became evident that the Minerals Separation flotation system then developed could give more efficient performance than the Elmore, especially upon the material of finer size which awaited treatment. The Zinc Corporation apparently wanted to put up 'a Minerals-Separation plant for the treatment of slime, and run it conjointly with the existing Elmore plant [but] difficulty in agreeing with the patentees ... placed the Corporation in the position of having to use one process only' (Mitchell 1911, 996). Hence, after impressive service, the Elmore installation was abandoned in July 1911. Following the change of systems it was found possible to dispense with the offensive oil-burning step.

As for the other substantial Elmore plant at Broken Hill, comprising 10 vacuum units, few details can be given, save that it was built for the British Broken Hill Proprietary Company and worked between June 1910 and November 1913 (Wainwright 1930, 295). By 1909 more than 1.1Mt of zinc concentrates had been produced by flotation at Broken Hill; by 1911 the total had grown to 2.1Mt, and by 1917 to 4Mt (Wainwright 1930, 281). Elsewhere in Australia, 'Elmore machines and process were still in limited use in 1938' (Crabtree and Vincent 1962, 40; citing Sutherland and Wark 1955).

Aside from their technical capabilities, the kinds of flotation appliances which supplanted the Elmore vacuum apparatus nearly all gave the operator open access to the froth. To the mill man struggling to wrest the best economic product from a flowing mineral pulp, ready contact with the froth was valuable, even if only for

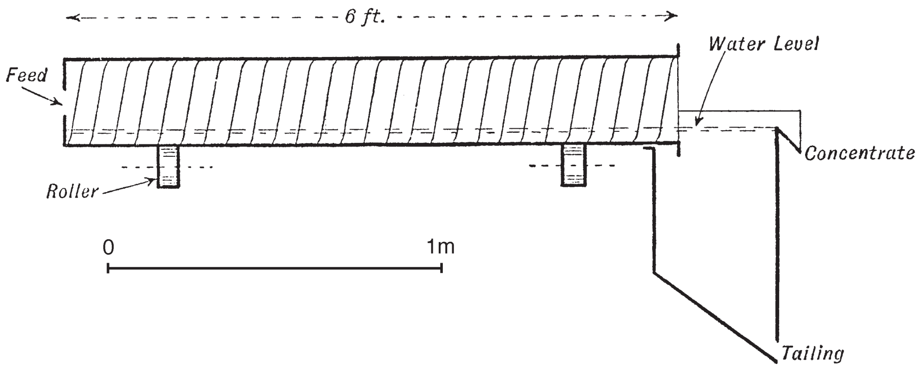

Figure 10: The MacQuiston tube concentrator, patented in 1904 and put to work at two places in the USA. Although not using more than a very small proportion of oil in the process, the form of apparatus has similarities with that of Elmore's 1898 scheme (compare Figs 2, 3). MacQuiston's process aimed to achieve a separation by repeatedly confronting mineral grains with an air-water interface at which metal sulphides would tend to remain. (Truscott 1923, 395).

reassurance. By its nature the vacuum apparatus precluded personal contact with the freshly-formed froth, and, although the bells had glass viewing windows built into the upper dome, must have caused considerable frustration. But who can tell how the Elmore flotation system might have progressed had the economic incentives for it been maintained ?

Two applications possessing features reminiscent of the Elmores' bulk-oil process

MacQuiston's tubes

In North America by 1910 there had been a number of trials made with flotation systems, including one semi-commercial arrangement, at Golconda in Nevada, of Arthur P S MacQuiston's 'skin-flotation' process. MacQuiston patented his method in Britain in 1904 and it seems possible that the Scot obtained some measure of inspiration from Frank Elmore's design of apparatus for the bulk-oil treatment of mineral pulps. The 'skin-flotation' technique, like that of de Bavay developed in Australia, achieved a separation between metal-sulphide grains and others on the basis of their responses at a water-air interface; but MacQuiston's preparation of the feed pulp was effected in a revolving cast iron tube with an internal helical corrugation (Figure 10). Each tube weighed 204kg, and was so arranged that the lowest segment of the periphery was immersed in water. Sand-sized deslimed feed entered at one end and hence, while the solids were moved forward along the length of the rotating tube, they were repeatedly subjected to immersion followed by rolling and sliding through the water surface, accompanied by contact with air. Any particles present which were hydrophobic would remain on the surface of the water to be carried over the discharge weir of the separating box. It was soon found that the efficiency of separation could be improved by conditioning with dilute aqueous sulphuric acid, and small proportions of soap and oil.

A hundred of MacQuiston's tubes were used at Golconda to concentrate chalcopyrite and other metal sulphides from a quartz gangue which also contained the dense minerals spinel and garnet, thereby frustrating satisfactory separation of the sulphide grains by gravity methods. Capacity was about 125t of ore in 24 hours (Ingalls 1907, 766). By 1912 a second more substantial installation had been made at Mullan in Idaho, where sulphides of lead and zinc were treated (Hofstrand 1912-13). The 248 tubes produced 13.5t/day of 45% zinc concentrate together with 1.8t/day of lead concentrate, the plant remaining in use until 1920 (Crabtree and Vincent 1962, 41; quoting Dalton 1932).

The Murex process

Around 1908 a process appeared which took the idea of the selective affinity of oil for certain minerals and, in order to accomplish a separation between different species, combined it with the properties of a magnetic field. What became known as the Murex process was suggested by A A Lockwood (Truscott 1923, 450-51). In practice there were three main steps to obtaining a separation: firstly, a 'magnetic paint' was prepared by blending powdered magnetite, Fe_30_4, with oil; secondly, the loaded oil was mixed with the aqueous pulp containing the crushed minerals; thirdly, the resultant slurry was passed through a magnetic field, (Figure 11). Influenced by the magnetic field, those mineral particles which had magnetite adhering to them would be lifted away from the rest of the population. There then remained the problem of disengaging the oil and magnetite from the two separated product streams. Arthur F Taggart (1945, 12-50, 239-40) cited three applications, one at the Wohlfahrt lead mine in Clausthal to separate galena from barite and siliceous gangue minerals, and another at Darwin in California in 1917 where partly-oxidized lead-silver ores were treated to extract, at a cost of \$1.96/t, four-fifths of the wanted mineral values for consumptions of 7.5kg/t of petroleum residuum, 0.4kg/t of oleic acid and 8.5kg/t of magnetite. Thirdly, at the Mawchi Mines in Burma the method was used to remove unwelcome sulphides from the coarse sand-sized gravity concentrates, to leave a product of cassiterite, wolframite and scheelite assaying 38% tin and 32.5% WO_3. Around 1913 an installation was made in Western Australia at the Whim Well copper mine. In 1914 the Murex process was installed at Broken Hill (now Kabwe) in

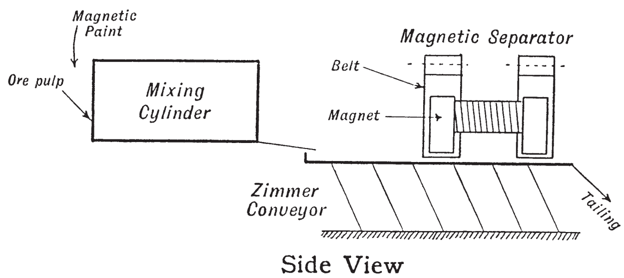

Figure 11: The Murex process c1910. Like F E Elmore's bulk-oil process, this exploited the selective coating of metal-sulphide grains with oil. Here, powdered magnetite was mixed with the oil to give a 'magnetic paint' so that, in a magnetic field, the sulphides could be lifted away from the non-oiled grains. (Truscott 1923,451).

Northern Rhodesia in an attempt to produce from the lead-zinc deposit a lead sulphide concentrate for smelting on the site, but only one year later the method was abandoned, apparently partly because of the high war-time price of oil (Speak 1919, 203).

At this time Theodore J Hoover was engaged as consulting engineer for the Murex Company, but, as with the MacQuiston process, the scheme proposed turned out to be of limited commercial application, largely because of the growth in alternative competitive treatment methods. By 1920, the chief business of the Murex Company Limited had become the manufacture of ferrotungsten, and in subsequent years, from its base on the northern bank of the Thames at Rainham in Essex, Murex produced a wide range of ferroalloys, metals and salts.

Wider adoption of flotation processing

As far as froth flotation was concerned, the first commercial plant in the USA to use the system began work in October 1911, at Basin in Montana for the Butte and Superior Copper Company. It was designed to treat gravity tailings containing 5-8% zinc (Fuerstenau D W 1962, frontis.), and its builders ignored the Minerals Separation patents, thereby provoking prompt legal action for infringement. In South America a flotation installation under Minerals Separation licence was made in Chile in 1912 at the Braden Copper mine where, by

Table 1: Materials treated by froth flotation in the USA in 1960

Raw resource	Flotation plants	Feed treated (millions of metric tons)	feed wt/total wt (%)	product/feed wt (%)	flotation product/national product (%)
metallic					
copper, molybdenum, zinc, lead, sulphur	92	141.0	78.3	3.8*	copper 99.5 zinc+lead >75
iron oxide	4	1.390	0.77	39.1	-
manganese and tungsten	4	0.407	0.23	14.5	-
gold and silver	4	0.120	0.07	2.5	-
fuels					
bituminous coal	26	3.0	1.67	71.6	-
anthracite	5	0.726	0.40	53.1	-
industrial minerals					
phosphate	15	19.0	10.55	33.4	33
potash	7	10.9	6.10	26.0	60
clay, feldspar, mica, quartz, spondumene ($LiAlSi_2O_6$)	10	0.935	0.52	42.0	-
glass sand	5	0.725	0.40	92.1	10
ilmenite and magnesite	4	0.560	0.31	44.6	-
fluorite	6	0.440	0.24	37.1	-
bastnaesite ($[La,Ce]FCO_3$), calcite, garnet, kyanite, talc	7	0.423	0.24	24.2	-
barite	5	0.403	0.22	64.3	40
other					
waste paper	3	0.023	0.01	85.0	-
Total:	197	180.0	100.0		
chicle, naphthalene, oil	5	no quantitative information			

Notes: Data adapted from Merrill and Pennington 1962. Some entries in the original source deliberately contain combinations of materials to avoid disclosing confidential information. * overall average.

1915, it had been successfully enlarged to treat 3000t/day (Rickard 1916, 29-30).

T J Hoover's book: *Concentrating ores by flotation*, in its text published in 1914 listed a total of 14 Minerals Separation plants in use, with a combined daily capacity of 4900t; only three were outside Australia, including the largest (then of ll00t) at the Braden plant in Chile. Just two years later Hoover gave a list of more than 40 additional 'new users' of flotation processes, all but a few of them within either the USA or British Columbia, and all concerned to extract minerals containing one or more of the metals zinc, lead, silver and copper. He commented that the new technique was then adding to 'the world's wealth' at the yearly rates of 180,000t of spelter, 18,000t of lead, 155t of silver and 900t of copper. (Hoover 1916, 164, 271-73, 200).

To give some idea of the extent to which flotation was being applied some 45 years later in 1960, Table 1 lists the range and quantities of materials treated in that year in the USA. Of the total feed quantity of 180Mt, more than three-quarters (l41Mt) was treated in order to extract the major nonferrous metals copper, zinc and lead, together with molybdenum and sulphur. From these operations the weight of the wanted products was 3.8% of the feed weight, 96% being discarded as waste. The flotation concentrates provided 99% of the nation's copper and more than 75% of its zinc and lead. By contrast, at l.39Mt, the quantity of iron resources processed amounted to 0.77% of the whole quantity subjected to flotation as well as comprising only a small fraction of the ore supplied to blast furnaces, while the proportion of feed treated primarily to concentrate gold and silver, at 0.l2Mt, was 0.07% of the total.

In the USA's fuel industry, coals were subjected to flotation treatment to a limited extent, and principally to prevent stream pollution, although some fine-sized coal, low in mineral-matter content, was recovered. In the processing of industrial minerals, flotation was important for more than a dozen commodities: the l9Mt of rock phosphate treated by the method yielded one-third of the national product; and the l0.9Mt of potash-bearing material contributed six-tenths of the total. In the cases of the industrial minerals, the weight ratio of wanted product/feed ranged between 26% and 92%, in marked contrast with the corresponding ratios for copper etc (3.8%) and gold and silver (2.5%). In the beneficiation of glass sands flotation was used to extract from the feed a minor proportion of iron-bearing grains and other heavy-mineral impurities, being an instance of 'reverse flotation' in which the unwanted components are removed in the froth.

Waste paper features on the list, although at this date the scale of activity was minor; this is another case where it is the impurities, ink, pigments or coatings, which are removed to leave reusable cellulose fibres. Also in the non-mineral domain, flotation was used on one site to remove foreign matter from chicle (evidently the natural resource from which chewing gum is made), at three plants to concentrate naphthalene in the effluent waters from cooling towers handling coke-oven gas, and at one place to separate spent rolling-mill oils from water. (Merrill and Pennington 1962, 81, 87-89)

The quantity of reagents consumed in the 1960 USA flotation treatment of l80Mt of solid feed totalled 386kt, valued at 21.8 million US$. Nearly 100 different substances were listed by the US Bureau of Mines, categorized as modifiers, activators, depressants, collectors, frothers and flocculants. Processing of the l4lMt of sulphides took 247kt, an average of 1.75kg/t, while the remaining 39Mt of feed consumed on average double this amount. Of the 386kt of reagents, actual 'collectors', added in order to establish water-repellent surfaces on the mineral grains to be floated, accounted for 100kt, fuel oil being 56kt and kerosene 7kt. (Merrill and Pennington 1962, 58-61, 69)

The Elmore brothers: later biographical notes

In 1901, Frank and Stanley were elected members of the Institution of Mining and Metallurgy, but ten years later, when Henry Livingstone Sulman became president, both resigned. Sulman had been among the group which, at the beginning of the century, had had open access to the workings of the Ore Concentration Syndicate and went on to establish the rival company Minerals Separation Limited. After the final defeat of the brothers' legal attempts to gain wide financial benefits from the patents they held, one sympathetic commentator summarized their situation concisely: 'Fortune and the lawyers have treated the Elmores hardly.' (Anon. 1916).

During the period 1917-1930 Frank became sole or joint assignee of several more British patents concerned with the extraction and refining of nonferrous metals. The Chemical and Metallurgical Corporation Limited, with Stanley as managing director, was set up to handle commercial development. Frank died on 26 July 1932 at Boxmoor in Hertfordshire; by his will he bequeathed the major portion of his estate to provide scholarships for medical research in the University of Cambridge. Stanley, in 1941, regarded himself as being actively engaged in developing two processes in extractive metallurgy through the Stanley Elmore Company which was based in his deceased brother's former property at Boxmoor. There Stanley died on 4 March 1944, leaving the bulk of his estate in trust to be channelled in two directions: one was to provide scholarships in the University of Cambridge for the furtherance of medical research; the other was to advance 'education in relation to metals and the science of metallurgy by the establishment of lectureships scholarships or ... academic prizes in furtherance of metallurgical research in collaboration with the ... Institute [*sic*] of Mining and Metallurgy' (Elmore AS 1941).

As a result of this bequest, throughout the last 40 years the Stanley Elmore Fellowship fund of the Institution of Mining and Metallurgy has been an important source of money for post-graduate, sometimes post-doctorate work. Tenable at a UK university, for research into all branches of extractive metallurgy and mineral processing, the current value of the award is £12,000 to £16,000 (Institution of Mining and Metallurgy 1999, 3). Until the mid 1970s, although the IMM selected the beneficiaries, the fund was managed by solicitors and knowledge of some of its details was restricted (Wilson 1992, 311).

Conclusion

In the Royal School of Mines at South Kensington, for two-thirds of the 20th century there resided a tangible artefact from the Elmore vacuum flotation system, a separating unit (as shown in Figure 7) which carried the number '3'. It seems likely that this relic was removed from Tywarnhaile in Cornwall after the property was taken over by Imperial College in 1907: Walter McDermott was a member of the college's governing body. The vacuum unit was displayed on the occasion of the Tenth International Mineral Processing Congress, held at the college in April 1973 but, alas, since then it has been lost.

On the broader front, during the century since Frank Elmore took active steps to improve the yield of copper with its associated gold and silver from the low-grade mineral deposit at Glasdir, the flotation process has come a long way. We now know that flotation has proved to be the most important mineral-processing technique of the 20th century. Besides its use in the production of marketable concentrates of industrial minerals and coal, flotation has made possible the satisfaction of demand for the major nonferrous metals other than aluminium. Near the beginning of this text it is stated that the world output of such metals increased tenfold between 1830 and 1900. Between 1901 and the last quarter of the 20th century the combined world outputs of copper, zinc and lead again showed a tenfold increase, from 2Mt a year to about 20Mt. Flotation made that possible. A recent estimate suggests that, taking into account all of its applications, every 24 hours flotation deals with something over 4Mt of feed (Fuerstenau D W 1999, 3).

One young observer of the vacuum process in 1910 later recalled two features in particular: the reek of oil which pervaded the whole valley; and the great enthusiasm shown by the inventor, Frank Elmore (Pryor 1961, 219). It is certainly highly appropriate, at this centenary distance, to acknowledge the significant pioneering part played by Frank and Stanley Elmore who, stimulated to thought and action by their exposure to the broken rock from a mineral deposit in Northwest Wales, encouraged particles of copper-iron sulphides to transfer selectively from water into oil, and provided practical means for harvesting the particles so transferred. By their efforts with flotation in the first few years of the 20th century, the two brothers 'focused the attention of metallurgists upon the great possibilities of these methods', (Sulman 1910-11, xlv), and 'dispelled an attitude of incredulity' (Truscott 1923, 391), thereby greatly stimulating the involvement of others.

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The author

Following graduation in metallurgy, Jake Almond worked in the field of mineral engineering during the 1950s and '60s. After training in teaching, in 1970 he joined the metallurgy department of Teesside Polytechnic in Middlesbrough from where, through the 1980s and early '90s, he observed some of the activities and effects of the 'winds of change'. He is a former chairman and past president of the Historical Metallurgy Society, and currently a director of the North Pennines Heritage Trust.