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Rushton, Michael J.D.; Lee, William E.

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Co-generation in the Early Days of Nuclear Power in the United Kingdom

Part 2: Metal Production

By MJD Rushton and WE Lee, Nuclear Futures Institute, Bangor University

SUMMARY

- The UK’s 2050 net zero target will require deep decarbonisation of all areas of the economy which provides tremendous opportunities for nuclear technology.
- The smelting and re-melting of metals accounts for a considerable portion of the world’s primary energy
- consumption and is responsible for almost 30% of industrial CO2 emissions. Nuclear power and hydrogen could play a key role in reducing this.
- Here the history of nuclear metal production in the UK is presented using case studies including the “atomic” smelters of the 1960s and the efforts of the European Nuclear Steelmaking Club. The precedent set by these programmes provides useful lessons that should guide the future application of nuclear technology to metal production.

INTRODUCTION

Expansion of nuclear power, together with renewables, would provide a proven route for decarbonising electricity supply. The UK has set an ambitious target to decarbonise the economy to net zero carbon emissions by 2050 and although many industries will achieve this through electrification this may not be possible in all instances. In such cases, nuclear technology could play a role by providing process heat and in certain cases radioisotopes. As a result, multi-role nuclear deployments could have an important position to play in securing our industrial future. There are important lessons that can be learnt from the past. In a previous article we described the cogeneration capability developed for the reactors at Calder Hall and Chapelcross [1]. Here we will consider historical examples of the co-generation of two important engineering materials: aluminium and steel. Aluminium smelting provides a good example of a large electricity consumer whilst steel making could additionally benefit from high-temperature process heat.

Experience at Britain’s atomic aluminium smelters has a lot to teach us about how the ownership, co-financing, and energy supply deals for nuclear and industrial projects should be structured. This has direct relevance to the small modular reactor programmes being developed today. In addition, we will discuss the research undertaken by the European Nuclear Steelmaking Club during the 1970s as it has relevance to the next generation of high-temperature reactors and a possible application for nuclear hydrogen.

NUCLEAR POWER AND ALUMINIUM SMELTING IN THE UNITED KINGDOM

The aluminium smelters established during the late 1960s on Anglesey and at Invergordon (Figure 1), provide a historical example of the use of nuclear energy to power an industrial process. The Hall-Héroult process used to extract aluminium from its ore, bauxite, via electrolysis of alumina dissolved in molten cryolite, is an energy-intensive process requiring 16 MWh of electricity (58 GJ) per tonne of aluminium. As a result, the cost of electricity drives the economic viability of smelting [2]. Not only must electricity be cheap, but it must also be uninterrupted: a power cut of as little as five hours can be catastrophic to the plant [3]. For these reasons, smelters had often been associated with large hydropower schemes as a source of reliable, cheap, and plentiful electricity. In the 1960s the UK had few suitable hydro schemes and lacked the required geography for any meaningful expansion, consequently, aluminium output was low. In Harold Wilson's "white heat of technology" and against the background of Magnox's operational success, the idea of the atomic smelters took hold eventually leading to the construction of Anglesey Aluminium and Invergordon. Both were linked to nuclear power station projects and experienced quite different fates.

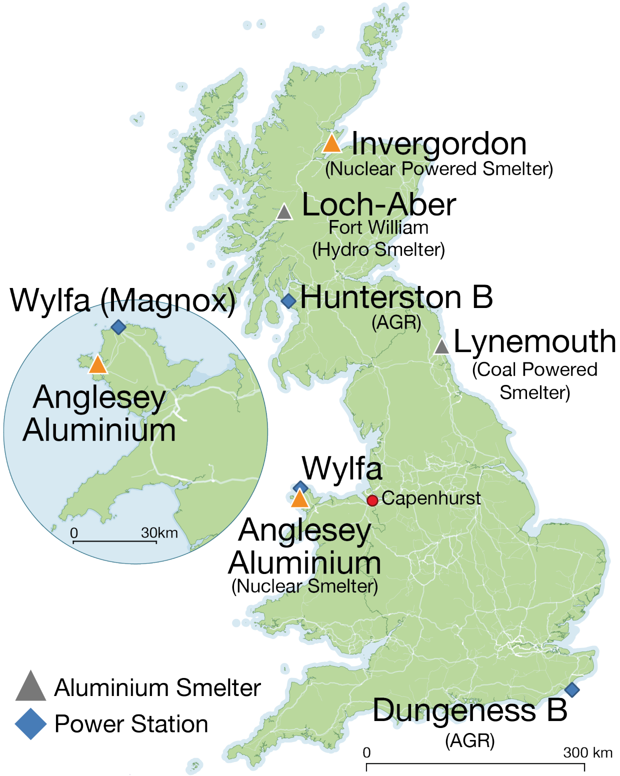

FIGURE 1: Map of the UK showing the locations of the Al smelters and relevant nuclear power stations. White lines show electricity transmission network

It was expected that the next-generation Advanced Gas Cooled Reactors (AGRs), which started construction in 1965, would build on the solid foundations established by Magnox. Reports started appearing in 1967 that a consortium led by Rio Tinto Zinc (RTZ) wanted to build an AGR to power an aluminium smelter [4], [5]. Originally, this was to be jointly owned by RTZ and the United Kingdom Atomic Energy Authority (UKAEA) who wanted electricity for their energy-intensive uranium enrichment operations at Capenhurst. Together, enrichment and aluminium smelting would provide significant and continuous electricity demand which it was felt would make the project economically viable, with any excess generation being sold back to the National Grid. It should be emphasised that this AGR would have been privately owned and would have been in addition to the Wylfa Magnox power-station that had already started construction in 1963 and ultimately did provide power to Anglesey Aluminium.

The state-owned Central Electricity Generating Board (CEGB) objected. This was due to RTZ and UKAEA planning to fund 40% of the project through Government grants. This would have set an awkward precedent that would encourage large industrial users to group together and produce electricity more cheaply than the CEGB, all facilitated by development grant funding [6], [7]. To avoid effectively undercutting themselves, the Government rejected the project in its original form but did agree support in the form of finance for construction and electricity supply deals. This led to two smelters being established: Anglesey Aluminium Metal Ltd in North Wales and the other at Invergordon in Ross & Cromarty in the Scottish Highlands. These locations were chosen as they provided deep water harbours for offloading bauxite ore, had access to the National Grid and were located in development areas. Each were expected to produce 100,000 tons of aluminium a year and would each employ around 900 people. Both smelters started operation in 1971 and were to experience quite different prospects. A third smelter was also established around this time at Lynemouth close to the coalfields of North East England– unlike Anglesey and Invergordon this was to be powered by a privately owned coal station receiving cheap fuel from the National Coal Board. Starting from 1974 this brought overall UK aluminium production to over 350,000 tons a year. This increase in capacity is impressive, as before these new smelters the UK produced only 38,000 tons of aluminium a year.

Anglesey Aluminium (Figure 2) and the Wylfa Magnox nuclear power station both opened in 1971 which started a 38-year partnership. Smelting consumed 255 MW of electricity making it the UK's largest single electricity consumer. Although within 15 miles of Wylfa the CEGB supply deal for Anglesey linked it with the first commercial AGR under construction in Kent: Dungeness B. Through the deal RTZ were provided with cheap electricity in return for contributing £33M towards building Dungeness B [8]. This contribution was funded by a 30-year Government loan.

FIGURE 2: Anglesey Aluminium Plant prior to closure (Crown Copyright: Royal Commission on the Ancient and Historical Monuments of Wales)

As a further sweetener, Rio Tinto had the rights to a share of the plutonium produced by Dungeness [9]. Having realised that private ownership of large amounts of plutonium was problematic, the Department of Energy agreed a series of quarterly payments running from 1971 to 2001 to compensate RTZ for the plutonium they never received [10]. These rather circular accounting arrangements were devised as a way for the Government to avoid accusations of providing undue subsidies– something which was causing friction with Norway who were partners in the European Free Trade Association. They had large hydro-powered smelters and Government subsidies to Britain's smelters would have been considered anti-competitive.

On paper, the Anglesey smelter was linked to Dungeness B, however, the construction of the first of a kind AGR proved to be a fiasco [11]. Construction started in 1965 with electricity generation expected to start in 1970 – this target was missed by 13 years as the first reactor of two started generating in 1983.

The second only came online in 1988 and it was only in 2004 that the station finally achieved something close to full load, 38 years after construction started and only five years before Anglesey Aluminium closed down [11]. The size of the CEGB meant there was capacity elsewhere to shield Anglesey Aluminium from these problems. The same cannot be said for the Invergordon project where problems with its associated AGR reactor, Hunterston B contributed to its downfall.

Anglesey Aluminium received its electricity primarily from Wylfa which was the last and by far the largest Magnox station providing 980 MW of electricity from its two reactors. In 2009 Anglesey Aluminium announced that they had been unable to re-negotiate their power contract with the Nuclear Decommissioning Authority (NDA) who then operated Wylfa [12]. Without cheap electricity, smelting operations closed in September 2009 with the loss of 400 jobs. Aluminium re-melting continued until its closure in 2013 and today only aluminium powder production remains. Wylfa power station originally due to close in 2010 managed to continue operation until December 2015.

The Invergordon smelter did not fare as well, closing after only ten years of operation in late 1981. This was due to several factors [7] but key amongst these was that its electricity price was too high. Invergordon's supply contract provided energy at 1.7 p/unit, by comparison, Anglesey paid only 1.3 p/unit [13].

Invergordon was linked to the construction of the Hunterston B AGR station. In return for cheaper electricity and a plutonium credit, the British Aluminium Company was to provide £30M towards Hunterston's capital cost (again forwarded to them in the form of a Government loan) [7]. Hunterston B would be operated by the South of Scotland Electricity Board (SSEB) rather than the CEGB. To further complicate matters the smelter itself was located in the area managed by the North of Scotland Hydro-Electric Board (NSHEB) meaning the power-supply negotiations involved three parties. Hunterston B was due to open in 1974, several years after the start of smelting in 1971 and ended up being another two years late, only opening in 1976. This gap in supply was filled by the NSHEB with expensive coal-fired electricity. The effects of this extended period on coal were made worse by escalating fuel prices in the 1970s. The construction delays also exposed a weakness in the original supply contract: the AGR's construction cost had increased beyond original estimates meaning British Aluminium's capital contribution increased above the £30M received from the Government. Further compounding matters, less than a year after it had opened, Hunterston B experienced an incident in which salt water entered the primary coolant circuit of one of the two reactors [14], [15]. Repairs cost £13M and prevented the unit re-entering service until February 1980 [16]. Without a supply agreement that insulated them from these teething problems Invergordon’s economic viability was gravely affected which caused its permanent closure in 1981.

Notwithstanding the financial problems experienced by Britain’s atomic smelters, nuclear power remains highly compatible with the process due to its ability to provide large amounts of reliable power and it is an idea that is worth

revisiting. With this in mind, a number of lessons can be learned from this historical example of co-generation:

- **Power-Station Ownership Model:** Both atomic smelters made capital contributions to the construction of two AGR stations. Crucially, however, this investment did not result in a physical asset which the aluminium producers could control. This loose coupling with their power providers meant their destiny was outside their control as they could not ensure cheap electricity which ultimately led to their closure. This is more evident when compared with the experience at Lynemouth where Alcan built their own 420 MW coal power station allowing it to outlast both Invergordon and Anglesey. Emissions from coal however proved to be its undoing as the power-station eventually closed due to the European Union’s Large Combustion Plant Directive. The experience at Lynemouth raises an interesting question: what would have happened if Rio Tinto and UKAEA had been allowed to build their own nuclear power station as originally planned? Tighter integration with electricity generation could have guaranteed lower prices in the long- term and would not have produced the carbon emissions that closed Lynemouth. It is interesting to note that some Small Modular Reactor (SMR) vendors are pursuing large industrial users as potential customers – given Anglesey’s power requirement of 255 MW, perhaps nuclear aluminium smelting is an idea whose time has come.
- **Industry requires established nuclear technologies to make informed investment decisions.** Electricity supply arrangements for the smelters were based on overly optimistic projections for the AGR which was then unproven. The technology risk associated with the reactors impacted on the aluminium smelter projects. Had the projects been linked to an established reactor system many of these issues could have been avoided.

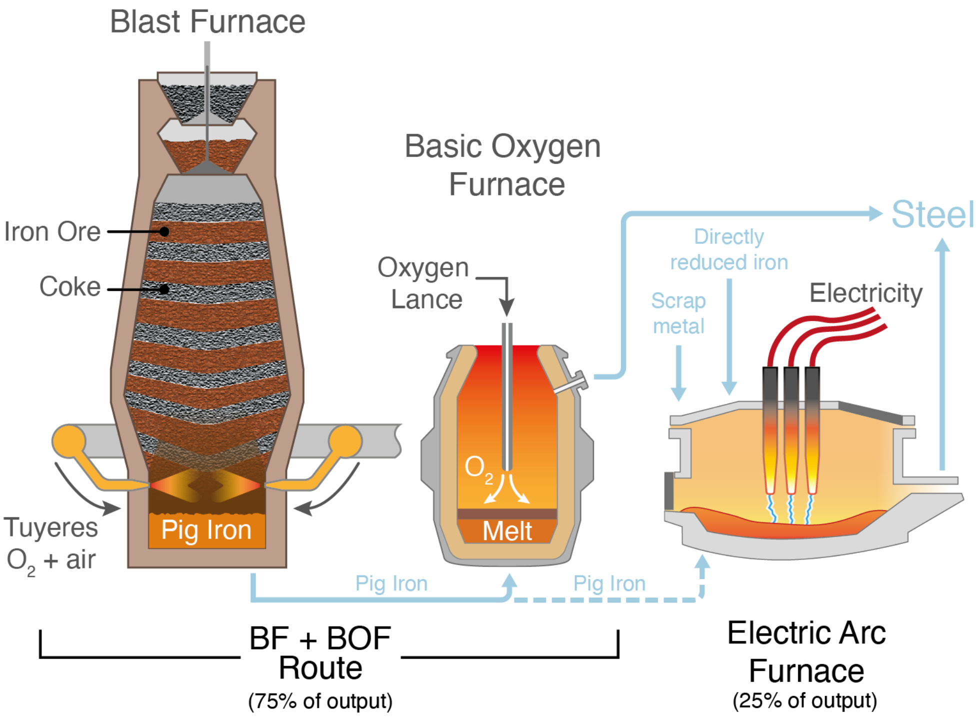

FIGURE 3: The major steelmaking routes. For reference, a blast furnace is around 60m high and 15m in diameter.

NUCLEAR STEELMAKING

Steel production requires massive amounts of energy meaning that nuclear heat and electricity have been considered to fulfil this need. Using conventional methods, the core process of producing liquid metal consumes between 1.6 GJ/tonne and 10.4 GJ/tonne [17]. Including additional contributions from transport, mining, transmission losses, and secondary forming operations, manufacturing one tonne of steel consumed 20.3 GJ in 2016 [18].

In 2017, 1689 million tonnes of crude steel were produced globally [18], accounting for 17% of industrial and 4.9% of total primary worldwide energy production [19]. Energy represents a significant portion of production costs ranging between 20% and 40% [20], [21]. Due to the scale of production, even marginal decreases in energy costs can yield considerable economic benefit.

Currently, 75% of steel production is via the Blast Furnace- Basic Oxygen Furnace (BF-BOF) route, with electric arc-furnaces (EAF) providing the rest, see Figure 3 [22]. In the BF-BOF route, coal is converted to coke in high-temperature ovens and finely ground iron ore is combined with powdered coke, limestone, and other additives before being pressed and sintered into pellets.

These are then added to the blast furnace with more coke which has two functions: it acts as a reducing agent, reacting with the oxygen in the pelletised iron oxide ore, and secondly, it is fuel providing the heat required by this reaction. Coke is a form of carbon and when it combusts and reacts with the iron oxide it emits large amounts of carbon dioxide. The product of the blast furnace is molten pig-iron which is rich in carbon. This is poured into a BOF where pure oxygen gas is injected, at supersonic speed, into the liquid metal. Carbon in the pig-iron reacts with the oxygen which leaves the melt as carbon dioxide, reducing carbon content sufficiently for it to be classed as steel.

The alternative EAF route is growing in popularity and is expected to account for 50% of output by 2050. Arc-furnaces are loaded with various combinations of scrap metal, blast furnace steel or directly reduced iron, which are then melted by application of a large electric current. Directly reduced iron which is a feedstock for this process has been the focus of recent nuclear steelmaking research. In this route, reducing gases (typically hydrogen and carbon monoxide) are passed through a bed of pelletised iron-ore at high temperature 800°C-1200°C, and the oxygen is removed from the ore to leave pig-iron, carbon dioxide, and water. Direct reduction does not produce liquid metal, instead, the pellets are converted into a porous metallic sponge, which has few engineering applications but becomes useful after melting in the EAF.

Currently, 89% of the energy input into the BF-BOF route comes from coal, 7% from electricity, 3% natural gas, and 1% from other gases [22]. Half of the energy for the arc furnace route is from electricity, 11% from coal, 38% natural gas, and 1% from other sources [22].

The electricity for EAF operation could be supplied by existing commercial nuclear reactor technology. A large EAF consumes up to 175 MW and there are often two furnaces on a single site [23]. The electricity demand of 350 MW for both furnaces is well within the capabilities of most existing reactor systems and could also suit some current SMR designs. However, electric arc melting is a batch process: furnaces typically operate for 45 minutes at a time and current nuclear power reactors tend to favour continuous operation at full power. However, careful scheduling of EAF deployment offers an excellent opportunity to utilise nuclear electricity during times when grid demand is low.

During the 1970s concerns regarding the rising cost and scarcity of coking coal and fossil fuels led to nuclear steelmaking being given serious consideration [24]. The European Nuclear Steelmaking Club was founded in September 1973 and included major European steelmakers from Belgium, France, Germany, Great Britain, Italy, Luxembourg, and the Netherlands [24]. Similar initiatives were established in the USA (Task Force on Nuclear Energy in Steelmaking – 1973), Japan (Research Association for Nuclear Steelmaking Engineering – 1974) and Germany [24]. This period also corresponds with a time of great development in high-temperature gas reactors. By 1973, the OECD's Dragon reactor (located at Winfrith in Dorset) had been successfully operating for eight years with an outlet temperature of 750°C [25], [26] and in Germany, the AVR pebble bed reactor first went critical in 1966 with outlet temperatures in the range 650-850°C which were increased to 950°C in early 1974 [27], [28]. With these experimental reactors, it was thought that by the mid-1990s high- temperature gas reactor technology would have been harnessed for use in steelmaking [24].

The primary thrust of the 1970s nuclear steelmaking research considered a direct reduction route producing sponge for EAF melting [24], [29] with the heat required being provided by a high-temperature reactor, reducing fossil fuel consumption [29]. The reactor would also provide heat to convert natural gas into the required reducing gases by steam reforming. In this application, natural gas is used as a chemical agent rather than as fuel, reducing fossil fuel consumption considerably (and avoiding the need for coke and coal). Consequently, in the proposed nuclear route gas would only account for 10% of the total cost of steel production and would help insulate steelmaking from the volatility of fossil fuel markets [29]. Using direct reduction with nuclear process heat, it was estimated that a reactor producing 3 GW heat would be required for a large steelwork producing 7 million tonnes a year [30]. On this basis, 92 such reactors would have been required to satisfy world steel demand in 1975 [22].

There are two reasons why nuclear steelmaking did not become reality. Firstly, fossil fuel prices have remained relatively low since the 1980s meaning nuclear steelmaking would have cost more than conventional methods. Secondly, despite early success with experimental reactors, progress in commercialising gas-cooled high-temperature reactors has been slow [27]. Without a well- proven reactor, it is unlikely that the steel industry would accept the technology risk associated with developing and integrating nuclear heat into the steel making process.

Steelmaking remains a carbon-intensive process due to its reliance on coal and natural gas as heat sources and carbon monoxide as a reducing agent. Despite the carbon savings, the nuclear steelmaking method proposed in the 1970s still relied on natural gas. However, current research has been ongoing to use hydrogen in steelmaking instead, which would help to further eliminate carbon dioxide emissions. Nuclear technology is suitable for producing hydrogen gas and if coupled with nuclear electricity and process heat, could provide a modern low carbon route to producing steel.

CONCLUSIONS

Making use of the unique capabilities of nuclear reactors above and beyond simply electricity production is not new as illustrated above. New nuclear reactors can be used to support a range of technologies, in particular, energy-intensive user industries such as steel and aluminium production. All of these can be done while producing low carbon outputs which could yield massive environmental benefits.

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