Co-Generation in the Early Days of Nuclear Power

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Nuclear Future

Published: 01/11/2020

Peer reviewed version

Co-generation in the Early Days of Nuclear Power in the United Kingdom Part 1: Calder Hall and Chapelcross

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Summary

- The first-generation Magnox plants at Calder Hall and Chapelcross
- did more than generate electricity.
- These plants were true multi-role facilities which in addition to supporting the UK's nuclear deterrent they produced radioisotopes for medical and industrial uses in addition to steam for reprocessing activities and providing space heating for buildings.
- These historic examples of co-generation may show the way forward for the next generation of nuclear power stations.

1. INTRODUCTION

Nuclear power has provided low carbon electricity for over 60 years. At its peak providing 29% of the UK's output and today contributes about 19% of the UK's output. The Government have made a legally binding commitment to achieve net zero carbon emissions by 2050 – on the basis of available technologies, new reactors proposed for deployment starting in the 2030s need to operate in a generating system dominated by renewables. On this timescale, nuclear is perhaps the most easily deployed low carbon electricity source that can provide baseload power whilst also plugging the gap between intermittent (renewable) generation and demand. As well as meeting this need, future nuclear reactors have the potential to generate more than just electricity by using heat for other purposes or for producing radioisotopes. A range of options for co-generation exists, using either low (60-400oC) or high (above 400oC) temperature heat [1]. Amongst other things, low temperature heat can be used for space heating and also for desalination of sea water. Higher temperatures open up a wider range of potential decarbonising strategies, for instance in the production of low carbon hydrogen which can be used in its own right or as a feedstock for other processes like synthetic fuel and ammonia production. In fact, any industrial process requiring high grade heat could benefit assuming it could be co-located with the power-plant.

The development of a co-generation capability that includes isotope production represents a commercial opportunity since there is a global shortage of key radioisotopes. In Part 2 we will examine historical examples of nuclear electricity generation being tightly coupled to industry. Namely the energy-intensive process of metal production, part 2 will also describe the early work to augment these electrical inputs with nuclear process heat from high temperature reactors [2]. Here we review key examples of historical UK co-generation, namely the first of the Magnox stations Calder Hall and Chapelcross. We came across these while helping write a report to the UK Government on nuclear cogeneration [1]. They highlight that from the earliest days of nuclear power the potential for reactors to provide additional benefit was recognised and to quote Winston Churchill in a speech to the House of Commons in 1948 "Those who fail to learn from history are condemned to repeat it". We also emphasise some of the lessons learnt from these case studies that are applicable today.

2. CALDER HALL

The earliest nuclear reactors were piles, dedicated to the generation of plutonium for military purposes.

These generated significant heat which was an unwanted by-product that had to be removed. The Manhattan Project made use of two such piles, the X10 pile at Oak Ridge, TN was graphite moderated and air cooled and produced 4MW of heat. The much larger water cooled piles in Hanford (Washington) were designed to operate at 250MW. It was not long before thoughts turned to harnessing this for useful work by generating electricity. In what is perhaps the first example of co-generation, engineers at Oak Ridge attached a toy steam engine to the X-10 pile. In 1948 this raised steam and generated the tiny amount of electricity required to light a 3V torch battery [3].

Unlike the earliest piles, the military and research reactors of the early 1950s included a steam cycle allowing them to generate increasingly significant electrical outputs. In 1951, EBR-1 (Experimental Breeder Reactor) in Arco (Idaho) produced 200 kWe which was enough for loads within its own building. In 1954 the AM-1 reactor at Obninsk in Russia became the first power station to export electricity to a grid. Despite this, the first nuclear power station that operated on a truly commercial scale was Calder Hall in Cumbria (Northern England) shown in Figure 1. When complete its electrical output was 196 MWe dwarfing anything that had come before (by comparison, Obninsk generated 5MWe). Notwithstanding its large capacity for electrical generation, Calder Hall's original purpose was to produce plutonium for Britain's atomic weapons programme. However, it also provided process heat for the Sellafield site and generated isotopes for industrial, medical and research purposes. This truly marks out Calder Hall and its associated facilities as a historical example of successful nuclear co-generation.

FIGURE 1: The four units of Calder Hall in operation

Once fully constructed, the Calder Works were comprised of four reactors, arranged in pairs (Calder Hall A and B, Figure 2), served by two turbine halls and at odds with later Magnox plants, used four cooling towers as heatsinks. The reactors were carbon dioxide cooled, graphite moderated and fuelled with non-enriched metallic uranium fuel. This was clad in an alloy of magnesium and aluminium, referred to as Magnesium Non Oxidising that identified Calder Hall as the first of what would become the Magnox series of reactors. This choice of reactor design was guided by Britain's circumstances following the 2nd World War: Clement Attlee saw the strategic importance of atomic weapons in positioning Britain for the Cold War to follow. With the McMahon Act passed by the USA in 1946, the UK's access to key nuclear technologies developed during the Manhattan Project was limited. As a result the decision was taken in January 1947 to develop our own nuclear weapons. This would be based on plutonium, due to the higher yields possible from a smaller quantity of fissile material and because it would avoid the need for a uranium enrichment plant. With this decision taken and without ready access to a supply of heavy water that would allow a water-cooled reactor to operate using natural uranium, a pair of air-cooled graphite piles were rapidly constructed at Windscale in Cumbria, just a few hundred metres from where Calder Hall would eventually be constructed. These opened in 1950 and allowed the Government's ambitious schedule to be met with a successful nuclear weapon test in 1952 on the Montebello islands off the coast of Australia.

Despite this, the Windscale Piles represented a bottleneck to the weapons programme which required large quantities of plutonium to provide Britain with an effective deterrent in the nascent cold war. A decision was therefore taken to construct Calder Hall in March 1953 with actual construction starting in the summer of the same year [4]. The first reactor at Calder Hall A went critical in June 1956 [5].

The offcial opening of Calder Hall by Queen Elizabeth II took place on 17th October 1956, which was when the first of Calder Hall's four reactors started providing power to the National Grid. At this point however, the reactor had already been settled in and generating 28MW of electricity for the month before the opening ceremony [6]. From February 1957 the second of the Calder Hall A reactors joined in by providing electricity to the grid [7,8]. Construction of Calder Hall B had started in 1955, two years after Calder A and its first reactor went critical in March 1958 with the second joining it on the night of 8-9 December 1958 [7]. Finally, the 1st April 1959 marked the point at which all four reactors were connected to the National Grid [9]. By any standards the design and construction of Calder Hall was incredibly rapid, made all the more impressive by the fact that much of the technology required in its construction was not fully developed when Goodlet and Moore started their design work on the plant at Harwell in 1951 [10].

The opening of Calder Hall could not have come soon enough as the Windscale Piles, built in haste, had key design faws which led to a catastrophic fire in 1957 caused by a failed attempt to anneal the Wigner energy from the graphite moderator of pile 1. As a result of this serious nuclear incident, both piles were ultimately closed.

The original design capacity of each Calder Hall reactor was 35 MWe, however this was soon up-rated to 46 MWe meaning that, in total the entire plant could generate on the order of 200 MWe electricity. The Harwell design on which Calder Hall was based was called PIPPA; this stands for Pressurised Pile Producing Industrial Power and Plutonium [11]. As will be discussed later it lived up to this name by not only producing electricity and plutonium but by providing process heat to the Sellafield site. Originally, PIPPA had been tuned for electricity generation with Pu considered as a useful by-product, in its original form it promised a thermal effciency of 25% [4]. However the primary role of Calder Hall was always to produce Pu, as a consequence the PIPPA design was altered so that electricity generation was seen as a happy by-product. This decreased the thermal effciency somewhat to 19.8% [4]. The CEGB Magnox plants that followed were primarily designed with electricity generation in mind and had better efficiencies. The early CEGB stations at Berkeley and Bradwell were 25% and 28% efficient whilst the final Magnox stations at Oldbury and Wylfa improved this to 33% [12].

The Calder Hall reactors were originally designed for a 20 year life, in the end they operated for 47 years, only closing in 2003. A significant portion of the station's 200 MWe output was reserved for the Sellafield site. This major industrial complex requires a considerable amount of reliable power. There are potentially grave consequences if Sellafield loses power completely - as an example reprocessing waste stored at the HALES (Highly Active Liquid Evaporation and Storage) and HAST (Highly Active Storage Tanks) facilities, generates considerable heat from radioactive decay and must be continuously cooled which requires electricity [13]. Calder Hall was able to provide power for such applications for over forty years. Following its closure this job has been carried out by the 168MWe gas fired Fellside Combined Heat and Power Plant built adjacent to Sellafield. This opened in 1990 and is itself due for replacement between now and 2025 [14].

Given the current interest in using nuclear power to provide district heating and process heat for industry, it is worth noting that Calder Hall acted in this capacity from the earliest days of the nuclear industry [15]. Not only did it provide electricity to Sellafield but it also provided steam to enable industrial processes. In particular steam was piped into the Magnox reprocessing plant where plutonium was extracted from material irradiated in Calder Hall's reactors. It performed this task for forty years until the Fellside CHP took over [16]. The workers at Calder Hall also benefitted from this heat as the site's stairwells, control room and administration block were heated with Calder Hall's steam [15], [17]. This was not however the first example of nuclear district heating in the UK; engineers on the AERE Harwell campus were already using the hot air from one of Calder Hall's progenitors, the BEPO British experimental pile, to produce "atomic hot water" to heat the site's offices well before Calder Hall was commissioned [18].

A full discussion of the Calder Hall reactors would not be complete without also mentioning Chapelcross and the reprocessing facilities in Sellafield buildings B204 and B205. Located in Dumfriesshire (Scotland), Chapelcross, was virtually identical to Calder Hall and began construction in 1955. Its four reactors were the UKAEA's second plutonium factory. From 1980 Chapelcross also allowed Britain to become self-sufficient in tritium when BNFL completed a treatment plant there allowing separation from lithium irradiated in the Chapelcross reactors [19].

FIGURE 2: The Sellafield site showing the location of Calder Hall and relevant facilities.

Neither Calder Hall nor Chapelcross would have been able to serve their intended purposes without such separation facilities. At Sellafield, the Windscale Reprocessing Plant B204, was originally built to service the Windscale Piles and allowed fission products, plutonium and uranium to be separated from irradiated material using Butex solvent extraction [20]. B204 employed counter-current exchange which required enormous 250ft tall towers to operate effectively [20], [21]. This operated as a reprocessing plant in its own right between 1951-64 before being absorbed into and superseded by the Magnox Reprocessing Plant (B205) which operates to this day. The construction of these reprocessing plants was considered by some as more impressive than Calder Hall itself; in particular B204 was built without a prototype and was based on chemical knowledge gleaned from only a few milligrams of Pu at the Chalk River labs in Canada by Harwell's head of chemistry Bob Spence [20]–[22].

The needs of plutonium production are somewhat different than those for electricity production. Upon irradiation Pu-239 breeds from U-238 through capture of neutrons produced during fission. If nuclear fuel is left in the reactor too long, the Pu-239 can itself undergo further neutron reactions reducing its usefulness for weapons production. Consequently, the residence time of fuel in a reactor is much lower during Pu production than in civilian power reactors (where the aim is to generate as much electricity from a given mass of fuel as possible). The Calder Hall reactors were well suited to Pu production as individual fuel channels could be accessed from the pile-cap using a special fuelling machine – increasing the rate at which material could be moved through the reactor. These attributes and the availability of facilities capable of isotope extraction made Chapelcross and Calder Hall suitable for producing radioisotopes for peaceful purposes.

Civil isotope production on the site had started with the Windscale Piles with the manufacture of isotopes such as radiocaesium for medical applications [23]. This bolstered the radioisotope production that had started at Harwell with the GLEEP graphite low energy experimental pile in 1947 [24]. This type of activity expanded with the opening of Calder Hall and Chapelcross. A particularly significant isotope obtained from both sites was cobalt-60 which is a strong gamma emitter that has the advantage of a relatively long half-life when compared to similarly intense sources (5.27 years). It has a number of uses such as in radiotherapy for cancer treatment, agriculture (pest sterilisation), industrial thickness gauges, weld inspection (industrial radiography) and sterilisation of medical equipment and other materials. This final use gave rise to one of the more unusual examples of nuclear co-generation with cobalt-60 sources produced in Calder Hall being used to sterilise goat hairs for use in the manufacture of carpets [20]. Cobalt-60 sources were produced using cartridges which were then irradiated in the reactors. These took the form of Co-60 pencils surrounded by Magnox alloy cladding [25]. The scale of isotope production can be gauged by considering there were 842-1122 Co cartridges still in the ponds at Sellafield in 2013 [26], [27]. These were amongst 1500-1800 other isotope cartridges with an overall mass of 6600kg [26]. Another important isotope produced in Calder Hall and Chapelcross was carbon-14. This was sent to the Radiochemical Centre in Amersham for incorporation in radioactively labelled organic compounds [20]. These are used in tracer studies in medicine and biological experiments. Carbon-14 was produced in the reactors by irradiating cartridges of aluminium nitride [28]. Plutonium-238 emits significant amounts of heat during radioactive decay. This makes it suitable for use in radiothermal generators (RTGs) where it is converted into electrical current. RTGs can be incorporated into devices requiring very long lived power sources for use in applications such as heart- pacemakers [23] and ocean navigational buoys [29], [30]. This isotope was produced in the Windscale Piles and there is evidence to suggest that the production of Pu-238 continued after the closure of the Piles: from 1967 a section of the original Windscale Reprocessing Plant (B204) was used to extract Np-237 from reprocessing waste. This isotope is a precursor for the production of Pu-238 and when irradiated in a thermal nuclear reactor, it captures a neutron to become Pu-238. The extraction of Np-237 continued until 1973.

Lessons learned from the operation of the Calder Hall reactors for a future cogeneration facility include:

- A secure and guaranteed supply of electricity was generated that directly supported the Sellafield industrial reprocessing site over many decades.
- A secure supply of both high and low pressure steam was generated that directly supported the Sellafield industrial reprocessing site, including heating of buildings and process steam for industrial processes.
- A continuous supply of electricity was generated for
- commercial sale into the UK national grid.
- Plutonium was produced to underpin the UK's nuclear deterrence programme.
- Specialist radionuclides were manufactured for medical and
- industrial applications, e.g. C-14, Pu-238 and Co-60.

3. CONCLUSIONS

Cogeneration, making use of the unique capabilities of nuclear reactors above and beyond simply electricity production, is not new as illustrated in this article. With modern capability new nuclear reactors can be used to support a range of technologies including, in particular, energy intensive user industries, industrial chemical generation including hydrogen, ammonia and synthetic fuels, radioisotopes for medical and aerospace applications in addition to district heating and desalination. All of these can be done while producing low carbon outputs with massive environmental benefits.

Acknowledgements

The authors would like to thank Tim Tinsley of the National Nuclear Laboratory and Dr Simon Middleburgh (Bangor University) for help in preparing this paper.

References

[1] Nuclear Cogeneration: Civil Nuclear Energy in a Low-carbon Future. *London: Royal Society*, 2020.

[2] M. J. D. Rushton and W. E. Lee, "Co-generation in the Early Days of Nuclear Power in the United Kingdom. Part 2: Metal Production," *Nucl. Futur.*, 2020.

[3] J. Mahaffey, Atomic Accidents. P*egasus Books*, 2015.

[4] C. Hinton, "The place of the Calder Hall type of reactor in nuclear power generation," *J. Br. Nucl. Energy Conf.*, vol. 2, pp. 43-46, 1957.

[5] "The Calder Hall Pile," *Nature*, vol. 177, p. 1016, 1956.

[6] K. L. Stretch, "Operational experience at Calder Hall," *J. Br. Nucl. Energy Conf.*, vol. 3, p.109, 1958, doi: 10.1049/pi-a.1958.0086.

[7] "Calder Hall Completed," *Nature*, vol. 182, p. 1708, 1958.

[8] H. G. Davey, "Commissioning and operation of A' Station, Calder Works," *J. Br. Nucl.Energy Conf.*, vol. 3, p. 101, 1958.

[9] Nuclear Power Reactors in the World (IAEA-RDS/2/39). Vienna, Austria: *International Atomic Energy Agency*, 2019.

[10] R. V. Moore and B. L. Goodlet, "The 1951-53 Harwell design study," *J. Br. Nucl. EnergyConf.*, vol. 2, no. April 1957, pp. 47-60, 1957.

[11] C. N. Hill, An Atomic Empire: A Technical History of the Rise and Fall of the British Atomic Energy Programme. London: *Imperial College Press*, 2013.

[12] S. E. Jensen and E. Nonb0l, "Description of the Magnox Type of Gas Cooled Reactor (MAGNOX)," Roskilde, Denmark, Nordisk kernesikkerhedsforskning NKS/RAK-2(97) TR-C5, 1998. [Online]. Available: http://www.nks.org.

[13] "Modification of Existing Plant: Highly Active Liquid Evaporation and Storage (HALES) Operating Rule (OR) 20," Office for Nuclear Regulation, Project Assessment Report ONR-SDFW-PAR-17-002, 2017.

[14] "Planning Application for New Steam Generation Plant and Demolition of Existing Combined Heat and Power Plant," Copeland Borough Council, 4/17/2256/0F1, 2017.

[15] "Nuclear heat applications : Design aspects and operating experience," Vienna, Austria, I*nternational Atomic Energy Agency*, IAEA-TECDOC-1056, 1998.

[16] E. Jeffs, Greener Energy Systems: Energy Production with Minimum Environmental Impact. Boca Raton, FL: *CRC Press*, 2012.

[17] (Atkins), "NDA Calder Hall Nuclear Power Station Feasibility Study," Nuclear Decommissioning Agency, Report 5048027.12.002, 2007.

[18] J. Cockcroft, "British Nuclear Power Developments," *Br. Aff.*, vol. 3, p. 43, 1959.

[19] R. Edwards, "Never mind the tritium, watch the plutonium," *New Sci.*, no. 1978, 1995.

[20] J. Cockcroft, "British Experience in the Technical Development of Nuclear Power Reactors," United Kingdom Atomic Energy Authority, DPR/INF/261, 1961.

[21] N. L. Franklin, J. C. Clarker, D. W. Clelland, K. D. B. Johnson, J. E. Littlechild, and B. F. Warner, "The Contribution of Chemical Engineering to the U.K. Nuclear Industry," in History of Chemical Engineering,

W. F. Furter, Ed. ACS Publications, 1980, pp. 335-365.

[22] J. Hill, "Some reminiscences and lessons of 50 years of the nuclear industry," *Nucl.Energy*, vol. 39, no. 3, pp. 143–148, 2000.

[23] “Pile Fuel Storage Pond,” *Sellaf. Mag*., no. 02, p. 16, 2015, [Online]. Available: https://www.gov.uk/government/publications/sellafield-magazine-issue-2.

[24] J. Mallard and N. G. Trott, "Some aspects of the history of nuclear medicine in the United Kingdom," Semin. Nucl. Med., vol. 9, no. 3, pp. 203-217, Jul. 1979, doi: 10.1016/ S0001-2998(79)80034-3.

[25] "NDA Waste Inventory 2013 - Waste Stream 2C31," Nuclear Decommissionng Authority, 2013.

[26] “Ponds Solids Legacy Isotope Cartridges : Encapsulation , CVD and pre- treatment options (Conceptual stage) Summary of Assessment Report," Nuclear Decommissioning Authority, 2013. [Online]. Available: https://rwm.nda.gov.uk/ publication/summary-of-assessment-report-for-ponds-solids-legacy-isotope- cartridges-encapsulation-cvd-and-pre-treatment-options/.

[27] “Insight into Nuclear Decommissioning - 19th Edition,” Nuclear Decommissioning Authority, 2015. [Online]. Available: https://tools.nda.gov.uk/publication/insight-into- nuclear-decommissioning-19th-edition-december-2015/.

[28] J. Hastings, C. Zimmerman, P. Little, R. Mills, J. Clifford, and M. Wise, "Preparation of Waste Fingerprints for the Miscellaneous Beta Gamma Waste Feeds to the Box Encapsulation Plant at Sellafield - 16080," *Proc. WM2016 Conf.*, 2016.

[29] D. M. Rowe, "Thermoelectric power generation," *Proc. Inst. Electr. Eng.*, vol. 125, no. 11R, p. 1113, Apr. 1978, doi: 10.1049/piee.1978.0247.

[30] B. Flowers, Sixth Report of The Royal Commission on Environmental Pollution: Nuclear Power and the Environment, vol. 6. London: Her Majesty’s Stationery Office, 1975.