Fast Breeder Reactor Technology and the Entrepreneurial State in the UK

Niall G MacKenzie, University of Glasgow[1]
Stephen Knox, University of Strathclyde
Matthew Hannon, University of Strathclyde

Abstract

This article explores the creation, operation, and failure of the UK's fast breeder reactor programme at Dounreay within the context of the development of the nuclear power industry in the UK, and the administration of national and regional economic policy. The UK government maintained total control of the development of the technology including its creation, operation, and attempts at exploitation, corresponding closely to existing definitions of entrepreneurship. We thus argue that the case of fast breeder reactor technology in the UK should be considered a both an example of Mazzucato's characterisation of the state as an entrepreneur and an explanation why it has 'forgotten' how to be entrepreneurial.

Keywords

Nuclear power, Entrepreneurial State, Regional Development, Fast Breeder Reactor, Technology

[1] Corresponding author Prof Niall G MacKenzie, Adam Smith Business School, University of Glasgow, niall.mackenzie@glasgow.ac.uk

Introduction

Throughout the twentieth century governments in Western developed economies took an active role in creating industries, technologies and markets in the pursuit of technological development and economic growth. However, neoliberal doctrine has tended to characterise state involvement in the economy as "intervention", suggesting that government sits by the sidelines watching and regulating the economy, "intervening" only when it sees fit in cases of market failure. Recent work has shown that the state is always present in the economy as both a regulator *and* player and that business historians should recognise this (MacKenzie, 2018). Scranton and Fridenson further argue that "states matter to business historians because they play many roles in building the markets and institutions necessary for enterprise" (2013, pg. 17). Mazzucato explored the role of the state in technological advances and change over the twentieth century, arguing that governments have focused on fixing market failure rather than creating markets (Mazzucato, 2015), and have "forgotten how to be entrepreneurial" (Mazzucato, 2011, pg. 48). Consistent within this characterisation of the entrepreneurial state is the creation (or attempted creation) of markets.

Much has been written on the technological achievements, scientific strength, and focus on science and technology in UK industrial and economic strategy in the twentieth century (Edgerton, 1996 & 2006). However, despite the efforts of the British government to utilise its technological achievements and strength, economic progress stalled in comparison to many of its competitors (Jones & Kirby, 1991). Nuclear power was one technology where the state directly managed the process of bringing new technologies to the fore and attempted to create markets through a combination of strategic direction, explicit policy actions, and financing, based on perceived technological advantages it possessed. Seeking to exploit its achievements and technological strength, in the early 1950s until 1990 the UK state embarked on trying to exploit what it perceived as a commercial opportunity in the nascent nuclear fast breeder reactor technology to pursue economic development aims. The UK state pursued the development of nuclear fast rector technology with the creation of the Dounreay Fast breeder reactor (DFR), followed by the Prototype Fast breeder reactor (PFR) during the period with the specific aim of creating a market, selling the technology, and reaping the economic benefits. Despite this, as many entrepreneurs often do, it failed.

Fast breeder reactor technology has been written about principally by non-historians, or as a subset of wider studies of nuclear power more generally (Lehtonen and Lieu, 2011; Patterson, 1985; 1986). The first fast breeder reactor at Dounreay was part of the first wave of a number of different types of nuclear reactors commissioned by the UK government in the 1950s, including Calder Hall in Cumbria and Chapelcross in Dumfriesshire (both MAGNOX), Windscale in Cumbria, and Winfrith in Dorset on the very southern coast of the UK, all operating different reactor types (HMSO, 1976, pg. 5). Fast breeder reactor technology was a singular venture on the part of the UK state publicly intended to demonstrate nuclear power's potential for electricity production and export abroad, with certain military benefits in the form of fissile material production for weaponry. The Dounreay nuclear power facility was initially an experimental establishment charged with the task of utilising the new technology of fast breeder reactors to explore the possibilities of harnessing the new technology for commercial electricity production.

We argue in this paper that the pursuit of fast breeder reactor technology, despite its failure, was a case of the UK state trying to act entrepreneurially. Fast breeder reactor technology was initially a success in achieving its stated aims in terms of proving the technology could work on a small scale, but subsequently failed to scale up to commercial size as a result of problems with the technology which has been the case in others countries too (IAEA, 2008). Nevertheless, a number of countries are still chasing the promise of fast reactors including India, Russia, Japan, USA, France, Korea, and Italy (IAEA, 2020). Consistent within the argument presented is an analysis of the development of the wider nuclear power industry, the social and political decision-making of various governments in relation to the technology including analysis of the situation in the Scottish Highlands during the reactor's operations, and the numerous technological problems fast breeder reactor technology faced in the UK.

Sources and Approach

Recent work in this journal has called for business historians to articulate their sources and methods more clearly to readers (Perchard, MacKenzie, Decker, & Favero, 2018; Smith & Umemura, 2018). A number of sources were consulted to construct the narrative around fast breeder reactor technology's development in the UK, including the UK National Archives at Kew, the National Records of Scotland in Edinburgh, *Hansard* verbatim records for the House of Commons and House of Lords debates, contemporary newspaper and media articles, promotional materials for the reactors from the United Kingdom Atomic Energy Authority, and a BBC interview with the former Minister of Technology, Frank Cousins, who oversaw the decision to locate the second reactor at Dounreay. Nuclear records are often subject to longer closure periods than more traditional records due to their connections to strategic and military imperatives; the records utilised in this work are all publicly available however and easily accessible. The archive materials were analysed and triangulated with other sources including news reporting, technical reports, and relevant secondary literature to create the narrative, accounting for gaps in the archives (Decker, 2013). Consistent within this we situate fast breeder reactor technology development in the UK within the changing domestic and international context. By taking this approach, we unveil the wider relevance of the technology and illustrate how the micro-level details were impacted by the wider macro environment.

The Entrepreneurial State and the Development of Nuclear Power in the UK

The concept of the state as entrepreneur is based on the argument that where the state seeks to orchestrate and operate resources to exploit opportunity for commercial gain, then it can be considered as acting entrepreneurially. In the 1950s Riggs used the characterisation to describe the role of the state in underdeveloped countries (Riggs, 1956), and in the 1960s Gerschenkron identified it as a feature of Russian economic development (Gerschenkron, 1962). In 1972 Stuart Holland characterized state entrepreneurship as about shareholding and varying levels of control over strategically important businesses and industries in Italy (Holland, 1972). More recently focus has considered the state's direct role in economic development, including characterisations of state ownership and investment in technologies identified across different geographies and the role of state-sponsored capitalism in economic and industrial development (Amatori, Millward & Toninelli; Mazzucato, 2011 & 2015; Musacchio & Lazzarini, 2014). Amatori et al. focus specifically on state owned enterprises and economic development comparing the UK and Italy, and Mussachio and Lazzarini look at how hybrid models of state and business interactions play out under the guise of state capitalism. Mazzucato in particular has sought to debunk the myth of the hands-off state in innovation development by identifying various sectors and technologies where the state has played a key role in their development including jet planes, lasers, biotechnology, and most relevantly for this article, civilian nuclear energy (Mazzucato, 2011. pg 76). The state as entrepreneur thesis has a long history that runs parallel with the development of nuclear technology, although the two have rarely been explicitly connected (an exception to this is the work of Etel Solingen, 1993 & 1996 based on South American nuclear power development).

The main archival based historical work on the early years of nuclear power in the UK was written by the United Kingdom Atomic Energy Authority's (UKAEA) official historians Margaret Gowing with Lorna Arnold in their comprehensive tomes *Britain and Atomic Energy 1939-1945* (1964) and the two volume *Independence and Deterrence: Britain and Atomic Energy, 1945-52* (1974). Arnold followed up this work with her own books focusing principally on the Windscale accident with *Windscale 1957: Anatomy of a Nuclear Accident* (1994), and nuclear weapons development with *A Very Special Relationship: British Atomic Weapon Trials in Australia* (1987), *Britain and the H-Bomb* (2001), and *Britain, Australia, and the Bomb: The Nuclear Tests and Their Aftermath* (with Mark Smith) (2005). Gowing and Arnold's work specifically were official histories, encompassing both civil and militaristic developments, identifying the overlaps between the two, and based on official documentation. What they reveal is the scale and scope of UK nuclear technological development over a long period, starting principally with the immediate period after the second World War.

During the period 1946-51 the UK spent £100m (~£3.085bn in current prices) on the development of nuclear technology (Hansard, 1954a), an enormous sum given the post-war economic difficulties of the country at the time, but paltry in comparison to US expenditure of $7500m (~$59.1bn in current prices) during the same period illustrating the vast gulf in resources between both countries (Hansard, 1954a). Comparing with the US, Gowing and Arnold state "Indeed one of the outstanding features of the enterprise in this period is that so much was achieved with so little resources" (1974b, pg. 38).

The election of the Conservatives in 1951 saw the new Prime Minister Winston Churchill's personal friend and scientific adviser, Lord Cherwell (Professor Lindemann) advise on the creation of an independent body to encourage the development of the new nuclear technology for industrial use by freeing it from Treasury control (Ringe, Rollings, and Middleton, 2004, pg. 218). The UKAEA was then established as a quasi-autonomous body responsible for the industry (and fast breeder reactor development) on the 19th July 1954 under the provisions laid out by the Atomic Energy Authority Act 1954 (HMSO, 1976, pg. 3). Following the US reversing the McMahon Act and opening up again, the UK government announced a more general civil nuclear programme geared towards energy production with a specifically commercial element (focusing on fast breeder reactor and MAGNOX technologies) in a white paper *A Programme of Nuclear Power* in 1955. This was based on the coal shortage of the time and the recognition of the need to diversify energy production (The Electricity Council, 1987, pg. 13).

The white paper contained a number of predictions about the future of the UK's nuclear expertise, with concomitant focus on the commercial and exporting potential therein:

> Other countries will also be helped to build experimental and development reactors which are an essential preliminary to the building of commercial reactors. We are already helping in this way a number of Commonwealth and European countries… We must look forward also to the time when a valuable export trade can be built up. The experience gained by British industry in designing and building nuclear power stations during the next ten years should lay the foundations for a rapid expansion both at home and overseas (HMSO, 1955).

It is important to note here that the commercial angle being posited was by the engineers in UKAEA and communicated to the policymakers, but not private sector voices who were excluded from the discussion. British development of nuclear technology generally was detached from private industry save for contractually based construction, entirely funded at the public expense (Burn, 1967, pg. 113). This caused plenty of frustration with the feeling that "the Authority [UKAEA] did too much detailed design work, and that this could be done equally well and more cheaply by private industry" (Williams, 1980, pg. 85). This was a reflection of the overall approach to developing the technology – UKAEA had both total control and the belief of government in the technology.

The origins of UKAEA's control were a result of the government's belief that nuclear technology was of such national importance that it should remain under state auspices. In 1941 the Ministry of Aircraft Production (through the MAUD Report set up to explore the technical and militaristic potential of uranium and nuclear power) suggested that Imperial Chemical Industries (ICI) be given the task of developing uranium as a source of power. However, the government refused this suggestion (despite ICI being both keen and able to help), arguing that nuclear technology development was of such national importance that it "should not be allowed to fall into the hands of private interests… The responsibility for developments in this country might appropriately be entrusted to the Department of Scientific and Industrial Research." (Gowing, 1964, pp 104-105). This argument came to underpin the development of the technology of the UK and the establishment UKAEA as the monopolistic arbiter of the technology.

The monopolistic position of UKAEA was relatively common amongst countries pursuing nuclear technology development (Rudig, 1987, pg. 416). In the US, Lawrence Halfstad, Director of Reactor Development in the US Atomic Energy Commission (AEC) 1949-1955, felt particular concerns over the public monopoly of fast breeder reactor development in particular in what was a free enterprise system (Hewlett & Duncan, 1969, pg. 495). Halfstad's confidence in private industry in the US stemmed from the interest of a number of private power-producing companies in further developing nuclear technology, who all sought to participate in the development of new reactor technology working closely with the AEC (Hewlett & Duncan, 1969, pp 495 & 512). The American approach evolved quickly into a commercial exporting approach (underpinned by military push and contracts) after Eisenhower's Atoms for Peace speech which reopened American nuclear technology to the world for commercial gain (Drogan, 2016).

The private sector in America were closely involved in the design, construction, and operation of nuclear reactors in an almost diametrically opposite way to the UK's approach. The principal private involvement in early nuclear power in the UK were in construction terms servicing UKAEA's designs, with a number of companies forming consortia for construction of different stations (Williams, 1980, pp 84-85). The model was that for new reactor types UKAEA would choose and develop them into prototypes. Once the prototype was up and running and proven, commercial consortia would then build commercial size versions (Burn, 1967, pg. 86). This led to a variety of reactor types, but no dominant commercial logic in the evolution of UK nuclear power. In part this can be attributed to the prevailing position of nuclear scientists in the development of the technology in terms of how they advised government. David Edgerton argues:

> Scientists in areas like nuclear power and aviation essentially had a monopoly of advice. As Duncan Burn, David Henderson and John Jewkes have so powerfully pointed out, government could only go to its own scientists for advice on these issues; there was not a countervailing set of scientists offering possibly different advice. It was a highly monopolistic system. (Edgerton, 1996, pg. 115).

UKAEA's free reign on the technology development started with Graphite Low Energy Experimental Piles (GLEEP) which evolved via PIPPA (Pressurised Pile Producing Power and Plutonium) into MAGNOX. The latter were gas-cooled and graphite moderated using natural uranium fuel (The Electricity Council, 1987), and produced plutonium for military use. Each of the MAGNOX stations were iteratively different based on new research designs and built by different consortia, meaning that each was effectively a prototype (Elliott, 1978, pp 22-23) and untested by commercial markets. Nobody had experience of developing the reactors except UKAEA meaning their advice and direction were sacrosanct. Because of the early technologies' focus on natural uranium and growing global demand for it, the UK sought to protect its supply of the fuel with international suppliers, with the UKAEA being responsible for its procurement (Berkemeier, Bowen, Hobbs, and Moran, 2014, pg. 13), further strengthening its hand in the direction of nuclear development in the UK. Alongside rising global demand for natural uranium, plutonium was beginning to build up necessitating a solution to the growing stockpile of the latter and the shortage of the former. That solution was to be the fast breeder reactor.

Fast breeder reactor technology and the state

The fast breeder reactor has its roots prior to the end of the Second World War where there was an exchange of knowledge in nuclear research between the USA and the UK when around 40 of the top British scientists went to work in the USA in an attempt to develop the military and civilian aspects of the new technology. This was focused on research into building reactors for domestic power, and atomic bomb development using plutonium (UKAEA, 1979, pg. 3). The experience of working on these projects later gave British scientists the knowledge and technological expertise needed for the construction of reactors at home (HMSO, 1976, pg. 2). However, in July 1946 the introduction of the US Atomic Energy Act (the McMahon Act) put a stop to the exchange of information between both sides of the Atlantic, requiring US scientists to maintain secrecy and cease all interaction with foreign scientists on nuclear matters.

Until the McMahon Act in the US, the British atomic energy programme had stalled due to the unidirectional flow of expertise from the UK to the USA. The introduction of McMahon Act stopped the flow meaning UK scientists remained at home. Following the US, the UK passed the Atomic Energy Act in November 1946, giving the government powers to control the development and use of atomic energy (HMSO, 1976, pg. 2). As part of this move, fast breeder reactor technology became one of the key foci of the UK nuclear power programme, with two main objectives in mind: to utilise nuclear fuel (uranium 235) most efficiently to produce a high outlet temperature from the fission in order to convert it into electric power; and to burn plutonium. It was thought that, if successful, fast breeder reactor technology could be the answer to Britain's energy needs and bring clear economic benefits:

> The prospect of a reactor that would utilise fuel efficiently and also produced additional plutonium was extremely attractive at a time when proved uranium resources were small. The whole of the United Kingdom's electric power consumption might be supplied from

> 80 tons a year. Indeed, without fast breeder reactors an industrial programme might be impossible (Gowing and Arnold, 1974b, pg. 267).

Fast breeder reactors were considered to the 'philosopher's stone' of nuclear technology– if they proved to work then they would produce more fuel than they used (Hall, 1986, pg. 35). This is important as in the 1940s and 50s there was the belief that there would be a world shortage of uranium. The reactors were fuelled by a mix of fertile material (uranium 238) and fissile material (uranium 235 or plutonium) that would 'breed' more fissile material (for military use), providing a net gain of more fuel than it had started with (Williams, 1980, pg. 43). In a secret memo from the Foreign Office to a representative in the British Embassy in Washington in the USA, one official stated "In view of the present difficulties over obtaining the uranium we need for industrial purposes, the breeder if successful will go a long way towards solving our supply problem" (TNA, 1954b). If the new nuclear technology could simultaneously satisfy the needs of both the military and power supply sectors, Britain would find itself in a stronger position politically and economically.

The Minister of Supply took the decision to undertake a programme of nuclear power development in August 1952 and a proposal was put to the Official Committee on Atomic Energy in June 1953 for the construction of a fast breeder reactor to operate a gross output of 200MW (thermal) with a useful power output of 50MW (electrical) on the basis that the knowledge of fast breeder reactors could only be advanced by the building of a large scale reactor (TNA, 1954a). This germinated a thought that if American nuclear scientists were to be bound by secrecy and unable to exchange ideas with others abroad, then the UK would be able to fill a market opportunity for exporting its own nuclear technologies abroad. The UK government pushed ahead on fast breeder reactor technology of its own accord with an explicit intention to export, with one Foreign Office official arguing:

> The whole operation will clearly have an important bearing on our prestige in the atomic world and on our uranium supply position. As you know, from our point of view there was one thing at least to be said for the McMahon act – it gave us an advantage over the Americans in that we could use our technical knowledge abroad to obtain a special relationship with countries hoping to develop power programmes. If the McMahon Act is to be amended and our knowledge to be no longer such a valuable asset abroad, it seems all the more important for us to keep as far ahead of the Americans as we can in the quality of our research. We cannot hope to compete with the quantity of their potential atomic production. (TNA, 1954a)

Ministerial approval was given on the 17th February 1954 for the creation of a fast breeder reactor facility after it was agreed that the reactor should be scaled down in its gross output to 60MW (thermal) (TNA, 1957) with a useful output of up to 14MW (electrical) (UKAEA, 2004). The Minister of Works, Sir David Eccles, announced on the 1st March 1954 that there was to be a new experimental nuclear power station situated at Dounreay. The decision to build the Dounreay experimental fast breeder reactor was explained in a letter from the new Department of Atomic Energy to the Treasury on the 14th April 1954 that stated "there are psychological and political reasons why ability to generate power will be an advantage and an electrical generating plant of 10MW capacity will therefore be coupled to the reactor after initial reactor operating experience has been gained" (TNA, 1954c).

Having gained ministerial approval, the search for a suitable site began. Due to the unpredictable nature of fast breeder reactor research, officials decided that the facility should be sited far away from major centres of population in case of an accident, but close enough to a small town for amenities for those working at the facility, as well as labour supplies (TNA, 1953a). Originally only a fast breeder reactor was envisaged for the site, but upon further discussion it was decided later on that fuel manufacturing and fuel reprocessing would also be required for the site to help process the plutonium produced (UKAEA, 2004). Dounreay, located on the very north coast of the UK mainland, was chosen by the UK's chief nuclear engineer Sir Christopher Hinton of the UKAEA (who became Head of the Central Electricity Generating Board in 1958 and noted for his later ack of enthusiasm for fast breeder reactors), due to its location far from centres of population and concerns over its safety. This was unbeknown to Sir David Robertson, the Member of Parliament (MP) for the area, who was one of the first to write to the Ministry of Supply to express his pleasure, stating,

> The siting of the plant in my constituency is the greatest event that has occurred in the Far North of Scotland and it will transform the economy of the whole region and stop our greatest affliction, depopulation (1953b).

The Marquess of Salisbury announced in the House of Lords on 2nd March 1954 that Dounreay "has the further merit that development on this site should make a big contribution to the economic welfare of this part of the Highlands" (Hansard, 1954b), although the government was keen to play down the economic benefits to the area through further industrial development emanating from the establishment, stating that it was "primarily a research and development establishment" during the first phase of the plant's operation (Hansard, 1959). Nevertheless, given the situation in the Scottish Highlands with long-term depopulation and economic stagnation (Perchard and MacKenzie, 2013), there was much excitement at the prospect of such a technologically advanced development being sited there. The excitement of siting the plant in Dounreay chimes with Hogg's point about

> By aligning national and regional journalistic narrative, we can see that a unified culture was developing around a set of nuclear assumptions. Nuclear narratives were being articulated, reinforced and then normalized into contemporary culture. (Hogg, 2016, pg. 74)

Before construction started the Treasury asked for estimates from UKAEA for the expected construction costs of Dounreay and were told it would cost £15m (~£379.2m in current prices) (TNA, 1954a). However, costs began to rise from the moment construction started due to changes in the design of the reactor and its outlying buildings, the decision to build the Dounreay Materials Testing Reactor (DMTR), and difficulties involved in constructing the plant itself. The 'highly experimental' nature of the reactor led to several revisions and amendments to the cost throughout the construction of the facility (TNA, 1958). The design of the reactor was amended, as was the design of various parts of the plant including the effluent tunnel into the sea and the discovery that the airfield on the site was in a worse state of repair than hoped, resulting in more cost revisions (TNA, 1957). The final July 1958 estimate of £24.5m (TNA, 1958) turned into a total cost of £28.5m (Hill, 2013, pg. 148) (~£596m in current prices), illustrating the level of commitment that the UK government was making to fast breeder reactor technology – it was over a quarter of the total 1946-51 UK spending on nuclear power as a whole.

The challenge of building the plant was huge due to the complexity of the design: engineers in charge wrote "at first sight this fast reactor scheme appears unrealistic. On closer examination it appears fantastic. It might well be argued that it could never become a serious engineering proposition." (Gowing and Arnold, 1974b, pg. 269). UKAEA took the decision to finalise the cost of the construction of Dounreay in 1958 stating "Finally, we have drawn a line to the projects now proceeding on the Dounreay site and any capital improvements or extensions will be treated as separate additional projects" (TNA, 1958). Construction of the DMTR was completed in February 1958, by September Dounreay's famous sphere was completed, and construction of the DFR was completed in December of the same year, followed by completion of the fast breeder reactor chemical plant (for reprocessing) the following July (UKAEA, 2004). Throughout this period, and beyond, the plant was managed from UKAEA's Risley operations in England, several hundred miles away (Arnold, 2016, pg. 99). Unlike various other nuclear power plants that came under the control of the CEGB and other regional electricity boards during the period in the UK, Dounreay remained under the direction of UKAEA creating an exceptionalism in its treatment by various governments throughout the period, particularly in regard of developments around the electricity industry more generally, since it was primarily a research establishment, albeit with grandiose plans of being more.

From DFR to PFR: the regional dimension

The experimental DFR achieved criticality (full reacting operation) in November 1959 having been delayed several times after construction had finished, most notably by a serious fire at UKAEA's Windscale plant. The 60MW thermal output, with 14MW of actual electrical output (often described as 'useful output' by various reporters) was not reached until July 1963 however (Patterson, 1985, pg. 99). Prior to this, problems with using the liquid molten potassium/sodium alloy (which is very flammable and very dangerous if it comes into contact with water) cooling circuits for generating steam had prevented the reactor operating at full capacity (Patterson, 1986, pg. 51). The Queen Mother visited the site on the 14th August 1961 to launch the resumption of experimental work on the fast breeder reactor after a number of extensive modifications had been undertaken (Patterson, 1985, pg. 98). The first electrical output produced by the new reactor was on the 14th October 1962, achieved on a by-product basis of the experiments being run (UKAEA, 2004).

The success of achieving an electrical output prompted calls for a larger-scale fast breeder reactor to be built and an increase in expectation for the technology. The UKAEA undertook a project for a reference design for a full-scale operational fast breeder reactor station with a 500MW capacity, with the intention that the Dounreay reactor would carry out the concepts in the new design on an intermediate scale. The new design was supplemented with other designs that were intended to achieve "higher output and higher 'burn-up' per fuel element" in the new reactor and improve upon the existing technology (Patterson, 1985, pg. 99). By 1962, 37% of UKAEA's 40,000+ staff were involved in fast breeder reactor research (Arnold, 2016, pg. 103; Pocock, 1977, pg. 86), marking it as the Authority's top priority. The commercial potential of the technology was noted again by UKAEA's chairman William Penney in negotiations with EURATOM in November 1962 where "he argued categorically against sacrificing the 'very large and valuable commercial possibilities' of the prototype fast reactor" (Theaker, 2018, pg. 239). Butler details the negotiations thus:

> The FO [Foreign Office]-staffed negotiating team were unable to argue effectively against the PFR's exclusion, noting: 'We deployed without making much impression the arguments that this would involve Euratom in a near-commercial field, which was inappropriate to it…' These rather weak arguments prompted a member of the French delegation to comment that 'the British were "obsessed with the commercial aspect of things".' (Butler, 2014, pg. 336).

The Select Committee on Nationalised Industries stated in its May 1963 report that the "Authority [UKAEA] hope that a prototype will be operating by 1969 or 1970" (Patterson, 1985, pg. 99). Less than four years after producing its first electrical output to the National Grid, the decision was taken to build a new prototype commercial fast breeder reactor (PFR). The UK government's intentions for the fast breeder reactor were not simply the production of extra fissile material (plutonium or uranium 235) for military use or potentially cheaper energy supplies, but also to export the technology for financial gain and retain its position as the world leader in fast breeder reactor research (BBC, 1966). The new large-scale fast breeder reactor was viewed by UKAEA as "an 'essential intermediate step' towards a 1000MW commercial station by 1978" (Williams, 1980, pg. 44). Similar steps were being taken in France and the USSR who had been developing their own fast breeder reactor technologies. The US never developed commercial fast breeder reactors (World Nuclear, 2019).

The creation of the Ministry of Technology in 1964 by the newly elected Labour government brought UKAEA under the responsibility of the new Minister of Technology, Frank Cousins. Cousins' announcement that Dounreay had won the race to become the site of the new reactor on 16th February 1966 was the culmination of considerable wrangling between UKAEA, the Ministry of Technology, the newly created Highlands and Islands Development Board (HIDB), local councils in Scotland and England, the NSHEB (who were to be the potential recipient of the electricity generated if Dounreay won the race), the Scottish Office, Westminster, the Crofter's Commission and the media. Unsurprisingly, given the number of different organisations involved, the decision-making process was complicated and fraught with regional development challenges. UKAEA preferred Winfrith on the very south coast of the UK as it was near its other major nuclear R&D facilities and the Ministry of Technology agreed with them; Dounreay's supporters included the Scottish Office (in particular Willie Ross, the Secretary of State for Scotland), North of Scotland Hydro Electricity Board, and sundry other organisations including the Scottish media who felt it was an important win for the Highlands if it were to be sited there by acting as a 'growth centre' for the area to attract further industry and people to it.

The Scottish case for Dounreay was focused on the industrial benefits that the new fast breeder reactor would purportedly bring to alleviate the social and economic problems of the area. In respect of regional policy at the time, Scottish officials made the point that:

> This over-concentration problem is facing France, Germany, Italy, indeed almost all the modern industrial countries. If the constriction can be removed the whole of the country's resources can be used more efficiently… There are however a few areas where government can act at its own hand and Dounreay is one… The idea of concentrating scientific effort in one area is a current European anachronism. The Americans recognise that with the air transport revolution the benefits of propinquity can be realised together with the benefits of deconcentration (NRS, 1965b).

The point about the dispersal of industry from areas of industrial concentration to other regions was an important one. The DFR had ingrained itself into the local economy, increasing the population in the area from 3,200 in 1951 to around 9,000 by 1966 (Turnock, 1970, pg. 169), with £53m (~£1.05bn in current prices) being spent up until the 31st March 1964 on the facility (NRS, 1965a). However, Winfrith remained the preferred choice of UKAEA and the Ministry of Technology on its technical and economic merits, due to its research expertise in all aspects of atomic research, its proximity to existing grid lines, and recruiting professional grade workers would be easier in comparison to Dounreay and its remoteness (this had been a problem with manning the DFR) (TNA, 1966). Liberal MPs argued "If the new reactor is not sited at Dounreay in Caithness it will be a terrible blow to the Highlands and to the new Government-sponsored Highland Development Board on which the people of the Highlands are pinning so much faith" (NRS, 1965d). Winfrith was overstocked with nuclear reactors and the labour shortage meant there was little or no lobbying for it to be the new site from the area. The entrepreneurial state was being pitted against shifting regional development priorities.

The PFR was intended as a 'showroom to the world', but as a peripheral outpost far away from metropolitan centres Dounreay lacked the facilities to satisfy this particular criterion (NRS, 1965c). Winfrith on the other hand was ideally suited to this, already hosting all four of the reactor types that the UKAEA was developing (the Advanced Gas-Cooled Reactor (AGR), the Steam Generating Heavy Water Reactor, the High Temperature Gas Cooled reactor (this was an international project named the Dragon reactor) and the fast breeder reactor albeit on a far smaller scale), as well as five other experimental reactors and the communication and social facilities that Dounreay lacked (TNA, 1966). The Cabinet then came to the conclusion that:

> The additional cost of establishing the PFR at Dounreay was comparable with that of the different investment grants to private industry in the development regions. Such investment grants were not available for the nationalised industries, partly because their siting could be controlled by the Government as a matter of policy. On these considerations it would therefore be contrary to the Government's policy for the regional development of industry and would cause serious damage to confidence in the Government's determination pursue this policy in relation to Scotland if the PFR were sited at Winfrith (TNA, 1966).

Dounreay had won the battle on the basis of its social and economic arguments, despite the technical advantages Winfrith possessed. The new prototype reactor was to be located in Dounreay with the explicit promise being made by Cousins that it would provide a "restoration of confidence in the economy of the Northern Scottish area" and that it would "provide cheaper electricity" when in full operation (BBC, 1966). The technical and economic considerations of siting the PFR at Winfrith had lost out to economic and social concerns of Dounreay.

The joy was short-lived however with the announcement in 1968 that the DMTR was to be shut down by mid 1969 with its activities moved to UKAEA's Atomic Energy Research Establishment site at Harwell (its principal R&D facility), causing some concern amongst the local population over employment prospects (TNA, 1970a). As a result, the Minister of Technology, the Secretary of State for Scotland and the Prime Minister visited the area to assure the local population the DFR and PFR would continue to provide stability, employing around 2,100 people, as well as inspecting the new PFR and the surrounding facilities (TNA, 1970a).

The PFR at Dounreay was to take five years to construct and supply electric power to the National Grid, and by 1978 was expected to have operated long enough to facilitate the construction of a full-scale commercial fast breeder reactor (TNA, 1966). Delays eventually began to increase in frequency during the PFR's construction due to the difficulties involved in harnessing the new technology. The PFR, as with the different MAGNOX reactors before it, was a fundamentally different design to the DFR, not just a scaling up of technology. It was designed to not breed fuel as much as burn it, and the core was made up of mixed oxide fuel that was both enriched uranium and plutonium suggesting UKAEA was interested in getting rid of its plutonium stockpiles rather than adding to them.

After the PFR officially reached criticality on 3rd March 1974, just under a week before the British Nuclear Energy Society held a major international conference on 'Fast breeder reactor Stations' with delegates from all over the world, including the USA, France, Europe, Third World countries and the Soviet Union. At the end of the conference the French announced that their fast breeder reactor project, the Phenix reactor, had also achieved criticality (Patterson, 1985, pg. 99), leading to the creation of the Super Phenix fast breeder reactor just a year after. The PFR's siting at Dounreay resulted in little extra infrastructural improvement or increased employment, despite the rationale it would. The PFR was viewed as more of an affirmation of the government's commitment to the area rather than an attempt at a whole new development.

Closure

The DFR provided income for the facility for the irradiation of foreign fuel sources of £160,000 in 1967 (~£2.54m current prices), £210,000 in 1968 (~£3.21m), and £860,000 in 1969 (~£12.35m), and a further £40,000 for post irradiation examination in 1969 (~£574,600). This provided a measure of stability for employment in the area, although the intention was that it would cease to operate approximately two to three years after the PFR was started up and employment numbers would be reduced by approximately 3% per year (TNA, 1970a). However, the PFR continued to be problematic. In the period 1974 to 1984 a total of 37 leaks were found, necessitating regular shutdowns (IAEA, 2006, pg. 333). When questioned on the future prospects of Dounreay the Prime Minister, Harold Wilson, could only promise stability into the mid-1970s. As a result, uncertainty over Dounreay, and by extension Caithness and Sutherland's, future began to develop. *The Scotsman* ran an article entitled 'Dounreay: Frontier without a future' that played up the uncertainty over the future of the establishment whilst detailing its success as a 'social experiment' (1969b). The previous week it had run an article entitled 'Dounreay's post-1974 future uncertain, indicates Prime Minister' that observantly pointed out that its future was inextricably tied to the decisions made by UKAEA and the developments of the industry as a whole (1969a).

The DFR closed in 1977 (UKAEA, 2004). The major problem was the instability of the liquid sodium used in the reactor – several leaks in the steam generator in which the sodium was passed caused numerous issues with the PFR, as well as one occasion when a storm in the North Atlantic caused the off-shore cooling-water intake to suck up hundreds of tonnes of seaweed, clogging the system and closing the generators altogether for several weeks in the mid-1970s (Patterson, 1985, pg. 106). In May 1977 there was an explosion in the waste shaft containing plutonium and uranium, the severity of which was not revealed to the public until 1995. In 1988 the PFR cost £105m annually (Hill, 2013), leading to the Conservative government announcing it was to be decommissioned starting in 1994 along with the DMTR, leaving only two small reprocessing plants operational at the development (BBC, 1998 & Munn, 2012). On 21st July 1988, the Secretary of State for Energy, Cecil Parkinson, announced that the fast breeder reactor programme was to be phased out, cutting spending to a "core programme" of just £10m per year, but only to 1994 (Hansard, 1988), marking the end of the exceptionalism which characterised treatment of Dounreay. In 1989 the Conservative government reorganised the nuclear industry along more private lines concurrent with the privatisation of the electricity industry. Establishment support for the fast breeder technology had all but evaporated amidst billions of pounds of investment, the reality of market forces, and a dire safety record including explosions, accidents, and serious health issues related to radiation poisoning (The Scotsman, 2006b). Ownership passed to the Nuclear Decommissioning Authority in 2005, with the intention of turning it into a brownfield site by 2336, 378 years after it opened.

Conclusion

This article posits that in trying to develop overseas markets for the technology the UK state was acting entrepreneurially by seeking to create markets where none existed. By orchestrating resources, the state was seeking to use its technological expertise to exploit perceived opportunity, offering a clear example of Mazzucato's conceptualisation, but one which also answers her question about why the state has 'forgotten' how to be entrepreneurial. The history of fast breeder reactor technology in the UK is instructive in answering this. In the same way that most entrepreneurs fail, the UK government failed to realise its ambitions for fast breeder reactor technology, despite committing 40 plus years and billions of pounds to it, contributing to its move away from large public displays of moonshot technological investments.

Due to the nature and origins of nuclear technology, the state was both innovator and investor, akin to an entrepreneurial inventor using their own funds to pursue a technology to sell. As a commercial play, all the risk was assumed by the UK state (or more accurately, the UK taxpayer) in seeking to exploit its technological advantage in the same way that an entrepreneur seeks to launch and scale technologies. However, the entire energy system was nationalised in the UK during this period (Chick, 2014), meaning the state maintained complete control over the technology and its domestic market with no private sector involvement in important decisions. The intention was to sell the technology abroad leveraging commonwealth and European connections (MacKenzie, 2008; Theaker, 2018). However, with the lack of commercial nous and focus, technological advancement was centred principally on the technical merits rather than the business case for the technology. A charitable interpretation could be that the UK government was attempting to de-risk the technology sufficiently before the private sector stepped in, but there is little evidence of this being the case.

Fast reactor technology was a very expensive failure, promoted by engineers who were facilitated with what amounted to a blank cheque by politicians set against narratives of the national importance of the technology and regional gains. The prize of fast breeder reactor technology – energy security, industrial modernisation, uranium stocks, military applications, and industrial leadership – working well enough to be implemented domestically and sold abroad convinced the UK government of the efficacy of supporting it. It took until the late 1980s to realise the technology was chimeric at best, and a very expensive mistake at worst. The Conservative government was elected in 1979 on a 'no lame ducks' policy of closing down inefficient industries aligned to "anti-state rhetoric" (McGuigan, 2003). Fast breeder reactor was demonstrably inefficient having never made the leap to becoming commercialisable despite the enormous resources ploughed into it. In this sense, the UK state's entrepreneurial intentions were never realised, but the memory lingers on much like the process of cleaning up contaminated land in and around Dounreay. As Lorna Arnold argues, "Misremembering may be as dangerous as forgetting, and memory without history – without understanding or insight - may condemn us all" (Arnold, 2000, pg. 218). It is not that the UK state has forgotten *how* to be entrepreneurial insomuch as it perhaps *chooses not to be* in light of its own fairly dismal experience, and contempt for the role of the state in the economy arising from neoliberal paradigms. (MacKenzie, 2018). Fast breeder reactor technology is an example of why the UK state perhaps chooses not to be entrepreneurial, despite its ability to do so if it wished

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