Decommissioning Nuclear Power Stations

The lecture from David Brown (September 2015) stimulated some reflections about the fortunes of nuclear power in the UK from a different perspective. As it happens, I had a grandstand seat for parts of decommissioning process on Berkeley Power Station, since between 1977 and 1990 I occupied offices at Berkeley Nuclear Laboratories that looked out on to the station. (David Brown told us about the use of the World's largest crane to lower the old heat exchangers to the ground. However, I even remember being seriously impressed by the size of the crane that was used to assemble the larger crane!) I also worked with people who were involved in some of the safety assessments that had kept the station going, and also ultimately, perhaps, contributed to the decision to shut it down.

Why did the station really have to close? A few years previously a number of decisions had been made by the Central Electricity Generating Board (CEGB) to provide investment that should have seen it operating for at least another decade. Those decisions seemed to make sense at the time. What had changed?

Nuclear reactors get shut down for a number of reasons. First of all, there are commercial considerations: are they accumulating cash faster than they are accumulating future liabilities? The second major consideration is "Are they safe?" Safety takes priority, but if we identify a safety deficiency we can usually ask how much it will cost to rectify and whether we are likely to get the money back in the projected remaining plant life. The whole process, overseen by regulators, is driven by the need to reduce safety risk "*as low as reasonably practicable*"[1]. Into this, you must also fold commercial estimates of how likely you are to be right or wrong about the costs. The law requires utilities to operate safely, but only the prospect of profit motivates them to operate at all.

One of the crucial points is that as a nationalised company CEGB investment costs were measured using the Government discount rate – much lower than commercial interest rates. Furthermore its large cash flows allowed investment to be funded internally from current income. Since surpluses were lent back to the Government at discount rate it made good sense to invest back in the business and generally get much better rates of return. There is, of course, a defensible political and economic argument that says that optimum allocation of resources can only occur when such industries operate on the same playing field as everyone else. On the other hand, it would be a brave economist who would argue that the current arrangements have brought us to a position in which electricity generating capacity will match likely demand over the next decade. Capacity margins are low and likely to go lower before new plant comes on stream, and there would already be a risk of load shedding if, for example, an exceptionally cold snap coincided with technical problems on one or more large generation plants. Electricity generation, especially low-carbon generation, requires long-term capital commitments, and does not sit happily with short-term

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[1] This is usually known as the "ALARP" principle by all who work in safety engineering. Loosely interpreted, it means that you are required to spend money reducing risk until the costs of further risk reduction are disproportionate to the benefits. The risks also have to be *tolerable*, which is related to the risk levels that reasonably people show they are willing to accept in different circumstances. The bar for air transport and nuclear power is set rather high, because the public has a low tolerance for aircraft and nuclear accidents. However, for example, in spite of efforts at misinformation by certain parts of the press, the Health and Safety Executive conclude the risk of injury in games of conquers as generally regarded as entirely tolerable to the participants – and even enter teams in the World Championships.

finance and market volatility. The CEGB could take a long-term view and could accept reasonable and necessary risks that would look unpalatable to companies answering to shareholders demanding short-term low-risk profits at low. At present, the only possibility of funding new nuclear generation in the UK is with the backing of foreign governments and their nationalised companies.

The future decommissioning of the nuclear power stations was also intended to be funded out of future CEGB cash flows. After all, it was easy to believe that electricity demand would continue to grow for the long-term, and many engineers believed that the national grid and the generation capacity could obviously best be managed as an integrated operation. (Given that subsequent attempts to devise a regulated market lead to near bankruptcy of some players and excessive profits for others, the case is still arguable. Few people today would claim that current arrangements obviously deliver the lowest feasible prices to consumers.) There was no separate sequestered decommissioning fund, because in the nationalised context it made more sense to put the money into building a coal-fired power station making decent business returns, rather than get poor financial returns via a forced loan to the Government at a low interest. (In any case, the government, as owners, could decide to treat the spare cash as a dividend – and it would not be seen again.) To the potential purchasers of future privatised utilities, however, long-term hard-to-quantify liabilities for decommissioning already old plant with limited future lifespans did not look like attractive propositions.

In that longer term perspective, the earlier decision to continue operation of Berkeley may well have been a good allocation of available investment and technical resources. These, however, were the Thatcher years, and with the prospect of privatisation things began to look different.

The proposed framework for privatising the CEGB originally envisaged off-loading the future decommissioning risks and costs of the nuclear power stations onto the private sector. This might just have worked if CEGB has been floated as an integrated whole, but the Conservative government policy insisted on introducing competition into electricity generation, so an uneven split was arranged with National Power having the nuclear stations, plus a large slide of the coal and oil fired stations, along with the long term responsibility for decommissioning. (Another new company, Powergen, took a smaller part of the non-nuclear generation.)

The Government needed the floatation to be a success. The early Magnox power stations had relatively small generating capacity compared to later stations, but operational costs were not scaled down by the same degree. The remaining lifespans could be curtailed by aging issues, and no one really knew how much decommissioning would ultimately cost, because the process was going to take many decades. It was always clear that the potential investors would do the best they could to avoid the most uncertain liabilities. They could not avoid all of them, but a line would need to be drawn in a place that would persuade them to put hands in pockets. I suspect it became clear fairly early in this process that some of the Magnox stations could not be included in the float.

In addition, major shifts in government policy possible forced by unforeseen events are hard to anticipate decades into the future. The Three Mile Island, Chernobyl and Fukishima accident all led to reassessment of what events might be considered within the bounds of possibility and also what might be tolerable to the public. So, even when one is acting conservatively and adhering entirely to the spirit of the regulatory framework, future events may change the rules. Back in the 1950s few engineers considered the possibility that terrorists might attempt to deliberately pilot an aircraft into a nuclear power station. It would have then been considered very unlikely. That is no longer the case.

A plant's safety argument may also be undermined by deterioration in the plant condition (such as that caused by corrosion) reducing safety margins. The introduction of nuclear technology created conditions that had never before been seen (chemistry in high gamma radiation fields) and that are very difficult to study in laboratories, even today. Hence, some types of corrosion occurred at rates much higher than originally expected.

The safety case might also be affected by a *lack* of knowledge: if we cannot convincingly argue that aging critical components remain in a safe condition then there is gap in the safety case, which is likely to grow larger with time.

The UK's nuclear plants have been affected by all these issues. Materials degradation is one of the most common reasons for reassessing the plant life time. In the case of Magnox reactors, the major corrosion issue resolved around the use of mild steel, which oxidised faster than expected in the environment of a nuclear reactor core. For the early Magnox designs *oxide jacking* was a particularly serious issue. This occurs when corrosion builds up on the surfaces between washers and associated nuts or washers and the steel component that it secures. The oxide forces the surfaces apart, putting stress on the bolt. Early in plant life the ductile steel bolt stretches, later on it becomes brittle and may fracture suddenly because of a process known as radiation embrittlement (discussed in more detail below). The life-limiting factor for the later generation of Advanced Gas Cooled Reactors (AGRs) may well be a slow eating away of the graphite moderator bricks by the carbon dioxide coolant.

Steel also modifies its properties under intense and prolonged neutron bombardment. Much of engineering relies on steels treatments that modify its microstructure to give the right balance of hardness, strength and ductility. However, neutrons can displace atoms of iron out of their normal crystal lattice locations. Such displaced atoms inhibit the sliding of crystal planes across each other that in metals allows them to stretch before they break. After years of neutron exposure ductile steel will get harder and more brittle, particularly at low temperatures. For critical steel components, such as pressure vessels, we would prefer to have material that stretched before it fractured, because brittle fractures probably lead to big holes rather than small leaks. Various methods have been developed to determine whether vital components are approaching safety limits. One of the major techniques with the Magnox stations was to place a number of removable steel samples inside the reactor at the time it was built. These are removed later in life, having been exposed to similar neutron fluxes to the critical components, and tested in laboratories (behind shielding and using remote manipulators). In practice, a large amount of computer modelling is also involved because the sample has been exposed to neutron fluxes at one just point in the reactor and real components are actually exposed to somewhat higher or lower fluxes in a variety of locations. I was involved in the production of computer codes that led to improved predictions of neutron fluxes throughout the reactor spaces, and allowed us to be more confident about the integrity of the components. However, one always had to be conservative whenever there was any uncertainty.

Ingenious techniques were also developed to remotely inspect critical reactor components, but some of the early Magnox designs had bolts in places that were impossible to inspect. (Here, the concern was that a fractured bolt might release an internal reactor component that would block the path of the cooling flow, and lead to overheating fuel.) Mild steel bolts ought to stretch, but after years of neutron exposure they could become brittle and might suddenly fracture. Ultimately, one of the considerations that led to the closure of Bradwell power station was an inability to *prove* that certain bolts had not fractured.

It is interesting to note for the future that some of the main barriers to successful exploitation of fusion power also revolve around materials degradation issues. Neutron fluxes are an order or magnitude higher in fusion reactors than fission reactors, so all the embrittlement issues are correspondingly magnified. While many of the fundamental physics problems of fusion seem to be coming under control, is still by no means certain that the materials issues will ever be overcome. The nuclear physics of fission reactors has been relatively well understood from the early days: it is the chemistry and the materials behaviour that cause the life limiting problems.

One of the particular areas of concern at Berkeley were the external ducts and heat exchangers, since any fracture in this pipework would create a large breach of the primary cooling circuit. If we lose most of the coolant the fuel gets hot and may melt, releasing radioactivity to the environment through the fractured duct. Although fast-acting values were designed to seal off any affected duct, it would always have been hard to argue that these would always operate with high reliability, so one also needed to be able to claim that breaches of the ducts were unlikely. (Later designs with concrete pressure vessel put heat exchangers behind the concrete shields and were much less vulnerable.) However, none the UK commercial gas-cooled reactor designs have a separate external containment (such as the external domes we see on PWRs) so we rely heavily on arguments that large breaches of the primary cooling circuit are unlikely and the consequences are controllable. We can readily make these arguments convincing for reactors with reinforced concrete pressure vessels, but it is much harder for the early Magnox design with their steel containments and exposed ducts.

I was not involved in any of the safety assessments concerning Berkeley (though close colleagues were), but I seem to recall that the issue of external events was being perceived as increasingly important. Given the design of the plant, with exposed duct-work, there is little one can do to mitigate against an aircraft impact, other than reduce the likelihood by keeping them out of the area using air restriction zones. That, of course, is no answer to the deliberate terrorist, perhaps just with a small rocket launcher. Hence, I suspect that the final decisions about Berkeley's continuance could have been influenced by thoughts that new risk scenarios might invalidate the safety case beyond hope of recovery. (The events of 9/11 later showed that such concerns were reasonable.)

In the event, it later became clear that National Power, which has acquired the nuclear stations as a result of privatisation, did not wish to carry any nuclear liabilities at all, and managed to divest them into Nuclear Electric and Magnox Electric. Further re-organisation created British Energy. This latter organisation demonstrated the reality of the commercial risks by requiring a government bail-out to avoid bankruptcy. This event also crystallised a truth that everyone had really known: the UK government could never avoid the ultimate responsibility for nuclear decommissioning. No UK private concern is big enough to carry the long-term risks. British Energy eventually became part of the French government owned EdF, but pays part of its income to the UK government to cover future decommissioning costs of the AGRs which will eventually be undertaken by government agencies.

Decommissioning is always a long-term process, for mainly physics reasons. We remove most of the radiological inventory from the plant when we remove the fuel, which in the case of Magnox fuel has to be sent for reprocessing because it degrades relatively rapidly. (With AGRs and Pressurised Water Reactors (PWRs) there is at least the possibility for long term storage of the fuel elements, which has the advantage that plutonium is not separated from other highly radioactive components and so presents no nuclear proliferation risk.)

The remaining reactor structure remains moderately radioactive because of neutron activation of the materials. The principle problem with steel is that some useful alloys contain cobalt which becomes extremely radioactive. (Later designs avoid cobalt steels as far as possible to simplify decommissioning.) There are two possibilities: use robots to disassemble the structure and remove the radioactive components to safe storage in the short term, or simply wait for 50-100 years, by which time it will be possible to do much of the work using human labour. (Highly radioactive isotopes tend to decay away relatively quickly. What remains will stay mildly radioactive for a long time, but can be reasonably handled at low-level waste repositories.) At the time Berkeley was closed it was clear that the lowest cost option involved waiting, even taking into account the costs of long term maintenance of the site. It may well be the case, however, that on-going advances in robotics may mean that earlier final disassembly will become feasible and become the best cost option.

Many people, of course, do not like the idea that our generation enjoyed the benefits of nuclear generation, but we will expect future generations to pay for the decommissioning. Nor do such people like the idea that we will leave nuclear waste repositories that will at least need to be avoided, even if they do not generate on-going maintenance costs, for a very long time. It is a defensible moral position that each generation should clean up after itself, and avoid practices that create long-term liabilities for future generations. Of course, none of our fore-fathers paid any attention to this, but they just did not have the capability to muck things up on a really extensive scale. It is also arguable that at least nuclear waste does decay away with time. If our generation uses up a finite resource, then every future generation will suffer the impact of not be able to share the benefit. It remains hard to see whether the net benefits of the Magnox programme will outweigh the ultimate costs, but it should be remembered that those who conceived and authorised the programme were not counting benefits purely in monetary terms. Our current perception of values may have changed, but hindsight decisions are always so much more reliable that decisions about the future. We might wish things had been done differently but should not criticise those who did the best they could with the information available at the time.

All these opinions are purely my own, and are based on personal and possibly inaccurate recollection of events that occurred twenty to thirty years ago. I do not believe that I have been seriously misleading, but I am certain that other people who were involved (possibly more closely involved than me) might give differing emphasis to the importance of the various technical, economic and political issues. That is why, unlike science, history rarely reaches definitive conclusions.

Michael McEllin, September 2015