Physics and nuclear power

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Abstract. Nuclear power owes its origin to physicists. Fission was demonstrated by physicists and chemists and the first nuclear reactor project was led by physicists. However as nuclear power was harnessed to produce electricity the role of the engineer became stronger. Modern nuclear power reactors bring together the skills of physicists, chemists, chemical engineers, electrical engineers, mechanical engineers and civil engineers. The paper illustrates this by considering the Sizewell B project and the role played by physicists in this. This covers not only the roles in design and analysis but in problem solving during the commissioning of first of a kind plant. Looking forward to the challenges to provide sustainable and environmentally acceptable energy sources for the future illustrates the need for a continuing synergy between physics and engineering. This will be discussed in the context of the challenges posed by Generation IV reactors.

1. Introduction
Nuclear Power has always represented a good example of the synergy between Physics and Engineering. In fact, this has also embraced a synergy with chemistry which is reflected by the fact that it is not uncommon in the US for University Nuclear Engineering Departments to be part the Chemical Engineering Faculty. This paper briefly reviews the development of the use of nuclear energy as a means of generating electricity. As with all such developments, as the issues moved from conceptual to the practical, so the lead moved from the “scientist” to the “engineer”. However the physicist continues to have a role. This is reflected in the staffing of a modern nuclear power station, which includes physicists as well as engineers.

The question then arises as to what distinguishes the role of the physicist from that of the engineer? In many cases: not a great deal. Many people who train as physicists smoothly transition into engineers, acquiring the additional skills and knowledge, whilst making less use of the more esoteric aspects of physics. Others supply specialist inputs which are more closely allied to their physics background and training. But, in general they are all working together as part of a team, whose skills and knowledge are being brought together to achieve a common purpose. The Sizewell B project provides an example of this.
Looking ahead the roles of the scientist and engineer have always been most closely allied when considering future projects and this is illustrated when looking at the work needed to bring Generation IV to fruition.

2. A brief review of the development of nuclear power
The identification of the energy potential of nuclear fission came out of work on the investigation of transuranics. This was undertaken largely by physicists and chemists. The discovery that, in addition to creating new elements from the neutron absorption by $^{238}\text{U}$, $^{235}\text{U}$ underwent energetic fission following neutron capture led to the development of both weapons and reactors.

The story of the Manhattan Project is now well known and represents the quintessential example of the synergy between science and engineering. The enormous energy potential arising from fission and the critical mass of $^{235}\text{U}$ was identified by physicists but isotope separation required a huge engineering effort. Similarly once the feasibility of plutonium production in reactors was demonstrated the production and separation of this material required the skills of physicists, engineers and chemists.

However we will focus on the development of power reactors. This came in part as a spin off from the weapons programme and partly from another, initially military, route. Early on, the use of nuclear reactors as a submarine propulsion unit was identified; lots of power, and no need for oxygen, an ideal combination for a submarine. Some preliminary work was done on this by the US Naval Research Laboratories during the war but it did not move ahead until afterwards. The US Navy let contracts with Westinghouse, to develop a water cooled reactor, and General Electric, to develop a sodium cooled reactor. Submarines have been produced using both types but Admiral Rickover preferred the water cooled version which became the mainstream line for development.

The interest in the potential uses of nuclear energy led to the establishment in 1949 of the National Reactor Test Station in Idaho, which is now the US Department of Energy Idaho National laboratory. As its original name implies the laboratory provided a site for a number of prototype, and test reactors. 52 were built over the years including submarine and large ship reactors, nuclear powered aircraft engines, research reactors and prototype reactors of all description. The current laboratory employs 3,500 staff and describes itself as: “Today, the INL is a science-based, applied engineering national laboratory dedicated to meeting the nation's environmental, energy, nuclear technology, and national security needs”. This represents an ongoing example of synergy.

Early on the use of the reactors to generate electricity was looked at and the first reactor to generate a useable amount of electricity, in 1950, was EBR1 (Experimental Breeder Reactor 1). This was a liquid metal (NaK) cooled fast breeder reactor. With an increasing emphasis on the use of “atoms for peace”, the large ship reactors and prototype boiling water reactors were used as the basis for the development of civil nuclear power reactors: Pressurised Water Reactors (PWR) and Boiling Water Reactors (BWR).

In Europe the development of power reactors initially followed a different route. France and UK developed gas cooled plutonium production reactors whilst the Soviet Union developed graphite moderated water cooled reactors similar to those used at Hanford as part of the Manhattan Project. In the UK we initially used air-cooled graphite moderated reactors (Windscale Piles) in which the heat was simply dumped. With the change to closed cycle CO$_2$ cooling the heat was used to generate electricity. Calder Hall was thus the first nuclear power station to generate electricity on an industrial scale requiring connection to the national grid.
The CEGB built and operated a number of “Magnox” reactors based on the Calder Hall design and established its own nuclear laboratories at Berkeley, next to its first Magnox plant. This brought together scientists and engineers, working to support and improve the existing designs, as well as contributing to the investigation of future reactors, which was led by UKAEA.

During this period the UK looked at and developed prototypes for the Advanced Gas Cooled Reactor (AGRs), which became the generation to follow Magnox, the High Temperature Gas Cooled Reactor, the Steam Generating Heavy Water Reactor and Fast Reactors. In addition wide ranging international collaboration in reactor R&D led to involvement in other designs.

Elsewhere the desire to use nuclear power reactors for electricity generation had spread beyond the original countries which developed indigenous reactor designs. The UK exported Magnox reactors to Italy and Japan, but the US were far more successful in exporting their PWR and BWR designs. France abandoned gas cooled reactor technology in favour of PWR in the early 1970s and embarked on a large building programme in response to its perceived dependence on imported oil. In the 1970s the Government undertook a review of the options for the next generation of thermal reactors and in 1978 gave the CEGB the go ahead to pursue the option to build a PWR. This was reaffirmed by the incoming Conservative Government in 1979 and orders were placed for Sizewell B in the following year.

The development of an indigenous nuclear power programme provided a great deal of opportunity for scientists and engineers to work together but this did not change with the importing of technology as will be discussed in the next section.

3. Sizewell B: synergy continues.

One of the important considerations in the decision to pursue the PWR option was the desire to move into the international main stream. This provided opportunities to share R&D, operational experience and good practices with the rest of the world rather than just within the UK fleet. To do this the ideal would have been to adopt a modern standard design and replicate it. The decision was taken to use a Westinghouse NSSS (Nuclear Steam Supply System) and to base the design on SNUPPS (Standardised Nuclear Unit Power Plant System). The SNUPPS utilities (Kansas Electric, Northern States Power, Rochester Gas & Electric, and Union Electric) had got together to design and build 6 standardised units. Due to depressed electrical demand in the US following the oil embargo and the uncertainty involved in licensing new reactors following the accident at Three Mile Island, 4 of the 6 units were cancelled. Kansas Electric and Union Electric, with Bechtel as the architect-engineer and Westinghouse as the nuclear equipment supplier subsequently completed the design, built, and started up the Wolf Creek and Callaway plants.

To build a SNUPPS based plant in the UK would inevitably involve some changes in design, since the frequency of our electrical system was different and Sizewell B would use sea water cooling rather than cooling tower/lake water cooling. In addition CEGB wanted to use standard UK 660 MW turbines necessitating a 2 turbine design. In addition the UK licensing system had somewhat different requirements to that of the US. Added to this were the potential implications of the lessons which were being learned from the accident at Three Mile Island.

CEGB persisted with its application to build a PWR at Sizewell B and set up a joint project team to act as an internal Architect Engineer. The design was modified to meet UK safety requirements, which generally required a greater degree of redundancy and diversity, and the lessons learned from TMI-2 were incorporated into the design. The application was subject to what, at the time, was the longest Public Inquiry in UK planning history (since comfortably exceeded by the inquiry into Heathrow
Consent was given and the plant was built in about 6 years and has operated successfully for more than 10 years.

Reference [1] reviews the history from the design and operational point of view. Many of these issues represent good examples of the synergy between engineering and physics working together, but this paper will touch on 3 aspects to provide illustrations: the development of safety analysis methods, the extension of analysis to "beyond design basis" events and problem solving during the commissioning of new systems.

3.1 Safety Analysis Methods
Traditionally the safety design and safety case for a plant is based on so called “deterministic” methods. For any particular system or item of equipment you identify the most onerous duty that it will be called on to perform and design it for that. This often involves an element of judgement in identifying the “maximum credible accident” but can also, in some cases, bound all possibilities. To ensure a robust design, the conditions resulting from the chosen design basis are assessed conservatively biasing uncertainties to give the worst result. The “biasing” may include artificially combining conditions which cannot physically exist together or making assumptions about equipment failures or ignoring potentially beneficial effects. In the US these standardised methods are set down in their regulations.

The problem with such an approach occurs when you attempt to experimentally validate computer models calculating the complex phenomena involved in such calculations. The methods ensure conservatism, but the degree of conservatism is not always clear and it is impossible to persuade nature to reproduce what are often unphysical assumptions. To cope with this, so called “advanced” codes have been developed and a programme of validation of these was started in the 1970s. For Sizewell B it was decided to use these codes in the licensing process and so extensive UK involvement took place both in the code development and the validation. Both of these exercises turned into international efforts and there was UK participation via agreements with USNRC and through international bodies such as OECD and IAEA.

In addition to the challenges posed by the code development and experimental validation, it was necessary to develop procedures for the use of these codes so that the results, whilst being better based physically, were still sufficiently conservative to be reliably used to support the design.

3.2 Looking Beyond the Design Basis
The accident at TMI-2 raised a number of issues relating to both plant design and human performance and the interplay between the two. The accident underlined the importance of the traditional “defence in depth” approach. An accident occurred which destroyed the core, but the other barriers to the release of radioactivity to the public had sufficient margin built into them that they proved robust enough to contain the accident.

The accident was not caused by one of the limiting design basis accidents (“maximum credible accident”) but by a less significant fault which was exacerbated by other failures (both plant and human). Methods of analysis were available to look at this (i.e. Probabilistic Safety Analysis (PSA)) and these had been routinely used in the UK in support of the design process to check whether a balanced design had been achieved by using the deterministic approach. These methods were applied to Sizewell from an early stage in the design process and generally underwrote the existing UK design rules, but did identify a number of areas in which design changes would be beneficial in reducing the already low risk still further. For Sizewell these “supporting analyses” were formally incorporated into the Safety Analysis Report.
The PSA for Sizewell B was extended to cover the assessment of beyond design basis events, including core damaging events. A great deal of R&D was carried out to improve the understanding of the TMI-2 accident and phenomena which could challenge the containment (e.g. hydrogen burns, steam explosions etc.) as well as the behaviour of fission products under these conditions. This knowledge was incorporated into the Level 2 PSA carried out for Sizewell and because the initial one was carried out early in the design process this resulted in some design enhancements.

This work clearly illustrated one of the traditional synergies between science and engineering with mixed discipline groups working together to design and analyse experiments and then translate the lessons learned into engineered features to provide additional protection. The use of such analyses to influence the design was unusual outside the UK but is now recognised as the norm for the future. IAEA design safety standards now incorporate the concept of supplementing the traditional design basis conditions with the consideration of beyond design basis conditions.

3.3 Problem solving during commissioning

One of the great advantages of building an established design is that you can learn from the experiences of others. This applies particularly during the commissioning phase since whatever problem you encounter, someone else has probably seen it before and can help you solve it. This breaks down when you have unique systems to deal with. This is when the combined efforts of multidiscipline teams comes into play.

Sizewell B has a number of unique systems including the Emergency Boration System (EBS). The EBS provides a diverse fast acting shutdown system to supplement the control rods. (Sizewell also has a further 2 slower acting shutdown systems.) The system is illustrated in figure 1 and consists of 4 tanks containing 7000 ppm boron connected across each of the reactor coolant pumps (RCPs) with fast acting isolation valves on the inlet and outlet pipework. If 2 or more control rods have failed to enter the core, 5 seconds after the receipt of a trip signal, the protection system opens the isolation valves. The high concentration boric acid solution is then swept into the core driven by the RCP pump head. The inertia of the pumps is such that the system will work even if the RCPs are running down as a result of the fault which caused the original trip. Since the system only requires valves to open to operate it is a type 2 passive system.

Since the system is unique to the UK a lot of analysis and flow visualisation rig work was carried out to support the design. The conditions of operation are quite onerous in that the system is normally maintained at containment temperature and ambient pressure but when activated is exposed to full reactor pressure and temperature. The pipe work layout must cope with the expansions stresses. The system is designed to ensure that the tank is emptied efficiently in a "piston" mode. The layout of two of the loops is illustrated in figure 2.

The system was commissioned initially during cold functional testing when the circuit was filled with cold water and was gradually pressurised. It was then tested with the circuit hot (heated by the RCPs alone) and then finally with the core in and the reactor critical to verify the full functionality. However problems were seen during cold functional testing at relatively low pressures. Initially tests were carried out by opening one valve at a time to look at the pressurisation transient. Then both valves were opened together. When both valves were opened the pipework was subject to high vibration, which was absent when a single valve was operated. This was unexpected since the conditions had not changed significantly since there was no flow through the system. The amplitude of the vibration was such that it was approaching the pipework elastic limit at 10 bars. The system is required to operate at 158 bars!
A mixed team was put together to deal with the problem. More instrumentation was put onto the system (as shown in figure 2) and simplified analyses were carried out. After further testing and analysis it was identified that we were seeing a coupling between the pressure oscillations in the fluid and pipework vibrations (see figure 3). The frequency of the fluid pressure oscillation depended on the inertial length of the pipework since that was acting as a driving piston, compressing the water in the tank. The inlet and outlets legs were of different lengths giving different frequencies. When both valves were opened the frequency was set by the average inertial length which was different again and which corresponded to one of the natural modes of oscillation of the pipework and hence the strong coupling seen in figure 3.

The question then arose as to how this was missed during the design phase. The potential for such a phenomenon was recognised and calculations were carried out using complex engineering codes. Unfortunately the design was such that the complete model was so large that it could not be run on the computers available. Two cases were therefore run in which either the inlet or outlet pipework was modelled in detail but the other leg was modelled as an equivalent straight pipe. Since one of the key parameters related to how quickly the fluid flowed into the reactor coolant system the equivalence used was based on the pressure drop, so the flows once established were modelled correctly. This however gave a different inertial length and hence did not predict the correct frequency.

The use of simplified models by the physicists on the team enabled these fundamental relationships to be established far faster than would have been the case if the full detailed engineering models had had to be used. Having established the likely cause, temporary snubbers were fitted to the pipework to change the natural frequencies and the system was retested. Having established that this was successful a permanent design change was engineered and commissioning proceeded.

4. Looking to the future
Operating power stations are supported by a range of disciplines, including engineers and physicists, but what of the future? The recent Government Energy Review concluded that Nuclear Power has a potential role to play in meeting Britain’s future energy needs, in an environmentally acceptable way. Once again the emphasis will be on adopting a standard design but this should be entirely feasible given the probable candidate designs. International standards have developed since TMI and Chernobyl and the current standards against which plants are being designed are not very different from those used by the UK. The use of PSA in support of the design process is now commonplace. Most licensing requirements, including the UK’s, are based on the most recent IAEA Safety Standards and the Western European Nuclear Regulators are seeking to achieve harmonisation across Europe.

Although reasonably priced Uranium is relatively plentiful, optimisation of the fuel cycle and the use of fast reactors will ensure the availability of fuel for the foreseeable future. In the past fast reactors have proved to be less economic than thermal reactors, given a plentiful supply of cheap uranium but there is now renewed interest in the technology for a number of reasons:
- Given increasing fuel costs the economics looks more attractive
- Fast reactors have the ability to burn waste as well as breed fuel. The minor actinides are largely responsible for the long half lives of irradiated fuel. By burning these, the residual fission products decay in a very much shorter time.
- Proliferation resistant fuel cycles are theoretically possible by never separating plutonium from all the other minor actinides.
- Some fast reactor designs can be used to produce very high temperatures for process heat.

A recent paper [3] reviews the work being done as part of the Generation IV initiative [4]. Achieving these aims will once again require the joint efforts of engineers, physicists, material scientists and chemists.
5. References

[1] Buttery N E. 2005 Nuclear Futures, 1 171
[2] IAEA 2000 Safety Standards Series IAEA-NS-R-1
[3] Howarth A 2006 Nuclear Futures 2 79
[4] USDOE 2002 A technology roadmap for Generation IV nuclear energy systems GIF-002-00

Figure 1 Schematic representation of one EBS loop
Figure 2  Isometric showing the layout of EBS loops 1 & 2
Figure 3a  Fluid pressure in EBS tank

Figure 3b  Pipe-work displacement