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Nuclear Lessons Learned

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Nuclear Lessons Learned

Published by The Royal Academy of Engineering on
behalf of Enigineering the Future

ISBN 1-903496-60-8

October 2010
The Royal Academy of Engineering
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Registered Charity Number: 293074

A copy of this report is available online at
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Foreword by Rt Hon Charles Hendry MP

Minister of State for Energy and Climate Change

We need to be proactive in the fight against climate change and must provide a secure, stable future energy supply. New nuclear power stations will be firmly part of this Government's energy strategy and the future energy mix alongside other low carbon technologies. Nuclear power will be crucial in ensuring we decarbonise our electricity supply and reduce our carbon dioxide emissions by 80% by 2050.

I am happy to confirm that we are fully supportive of new nuclear power in the UK but will not be subsidising it. We are under no illusions however, that to attract the inward investment necessary will require significant commitment from Government. I see it as my job to remove unnecessary barriers to investment in nuclear power and endeavour to provide a landscape that facilitates private sector investment. Government has already taken active steps to enable new nuclear by publishing for consultation the draft Energy National Policy Statements including a list of potential nuclear sites and making a decision on Regulatory Justification. We will also be taking forward a detailed appraisal of the electricity market that will support the delivery of a secure, low carbon, affordable electricity mix for the future.

We are therefore very pleased to have commissioned this work on lessons learned for nuclear new build. The report will help all project stakeholders to understand and limit risk, and to minimise potential overruns and delays, which are both expensive and reduce public confidence.

This report highlights the lessons learnt from design and construction experience, and those learnt from reflection during operation. This results in a comprehensive report that highlights key factors influencing the successful development of a new build programme for the UK.

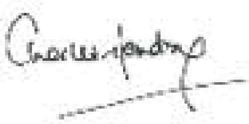
This Government is committed to facilitating a smooth process for nuclear new build and continuing the work of the Office for Nuclear Development (OND) which is already focused and progressing on many of this report's recommendations. For example, OND's facilitative actions on Generic Design Assessment support key recommendations from this report that tested technology should be used with design well developed before construction commences.

We must attract private sector investment into this technical and capital intensive technology. This report provides a valuable insight to policy makers in understanding the landscape that we need to create to facilitate efficient new build and highlights the lessons to be adopted by those wishing to build and operate reactors in order to minimise commercial risk and achieve a successful nuclear new build project outcome.

In this context the report's conclusions and recommendations are expressed with three audiences in mind:

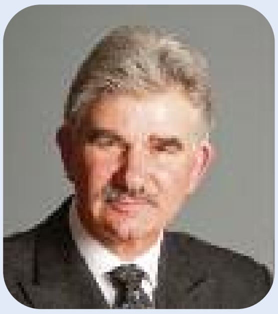
- **Government**; the high level recommendations aimed at establishing policy,
- **Developers**; wishing to reduce commercial risk and see timely revenue streams from successfully completed plants
- **Supply Chain**; with detailed conclusions aimed at more specific task focussed issues to enable more successful contract delivery.

The report also promotes the important aspects of supporting relevant research and skills development which has already been a feature of Government action. I look forward to engaging with industry on the implementation of the lessons identified in this report.



Foreword by Tom Foulkes

Director General, Institution of Civil Engineers



Building the UK's future low carbon energy system will entail many challenges and the engineering community must lead the way. It appears increasingly likely that nuclear power will play a central role in responding to this challenge. However, with the last British nuclear reactor plant completed over 15 years ago, much of our relevant experience in this field is dwindling.

Engineering practice builds on experience. This is especially crucial for complex projects such as nuclear power plants where the risks, both economic and material, are large and require careful management. If the new build programme is to be successful, all available experience must be gleaned from around the world. This will help prevent delays and inefficiencies being repeated and will make the UK plants exemplars of global best practice.

On behalf of Engineering the Future, I welcome this report and endorse its findings. I congratulate the authors of the report and thank all those involved in compiling it, especially the engineers from around the world who contributed so much. Commercial considerations can sometimes get in the way of disseminating information but the more the engineering community is able to share experience, the better chance we have of building the infrastructure society needs. This is the aim of the Engineering the Future alliance which will continue to help the engineering community speak with one voice.

Nuclear Lessons Learned

Nuclear Power Station Construction Lessons Learned Relevant to New Nuclear Build in the UK

Executive summary

Background

This study was overseen by a steering group of Engineering the Future member organisations at the behest of the Office of Nuclear Development (OND) and conducted by Lancaster University with support from the Institution of Civil Engineers R&D Enabling Fund and the Department of Energy and Climate Change. It constitutes the first phase of a larger project that will investigate the lessons to be learned from recent and current nuclear build projects that are relevant to new power station projects in the UK. In this context, the current report represents the academic summary of literature and information available to date.

A full summary of the detailed lessons learned in this review is provided in the Conclusions section of the main report. The most significant lessons identified in this review are as follows:

1. **Follow-on replica stations are cheaper than first-of-a-kind**. A statement of the obvious perhaps but the implications for electricity supply planning, investment and politics are huge. A secure electricity supply will be cheaper to build with less financial risk and uncertainty about completion dates if a firm commitment is made to a fleet of identical stations rather than one at a time.
2. **The design must be mature and licensing issues resolved prior to start of construction.** This was the case for Sizewell B and is the purpose of the Generic Design Assessment for new designs in the UK. It has not been the case in all countries. Permission to start nuclear construction does not always imply that the regulator is satisfied that the design can be licensed for operation.
3. **Establish a highly-qualified team to develop the design, secure the safety case, plan the procurement and build schedule in detail in collaboration with main contractors**. This emphasis on highly-qualified teams and collaboration is essential for large, capital intensive, complex and technologically sophisticated projects. It does not necessarily imply less competition except when specialist skills are in very short supply. A commitment to collaborate and provide a high quality team for the duration of the project must be a requirement of the competitive process with contract and procurement strategies to achieve this.
4. **Ensure that sub contractors are of high quality and experienced in nuclear construction or are taught the necessary special skills and requirements for quality, traceability and documentation.** This requires investment by industry and educational institutions and the inspiration of students to commit to an intellectually challenging and specialised career. This requires an unequivocal commitment and encouragement from government.

5. **Establish and maintain good communications with the community local to the site.** A nuclear station will be part of the community for a century. It is important that the local community is kept informed and involved, that concerns and fears are addressed and the station is perceived as bringing benefits as well as being in the 'national interest'.

In preparing the report an almost inexhaustible legacy of nuclear plant could have been investigated, given that generation capacity currently exceeds 400 reactors worldwide. However, the time frame of the planned new-build expansion in the UK means that only a few of the projects completed recently and those that are current are of direct relevance to future build projects in the UK. The Generic Design Assessment has resulted in two specific reactor designs going forward for consideration in the UK, the EPR and the AP1000. As these are both PWR systems, the focus of this report is limited to these plant, and related ongoing nuclear projects in both Europe and Asia. Furthermore, a variety of significant, technologically-challenging non-nuclear construction projects could have been investigated but this has not been attempted. Recently, the Department for Business, Innovation and Skills commissioned a relevant report in this area, the Gibson Review; readers are referred to that for related, non-nuclear project evidence.

The methods adopted in the preparation of this report focussed on the research and collation of evidence from the literature, combined with the interview of numerous experts from the nuclear construction field, past and present. During the course of the research for this report, the authors became aware of a relative dearth in the availability of archived information associated with recent nuclear build projects. This has occurred despite the best intentions of project authorities on various nuclear builds in recent times and numerous conference activities, but has perhaps been exacerbated by some projects preceding the advent of the Internet. Furthermore, there are understandable constraints relating to security and commercial confidentiality that limit the information available with regard to more recent projects. Thus, the ability to interview relevant experts was an essential part of the report's preparation.

Whilst many 'lessons' often arise as a result of learning from mistakes, several of the key lessons that follow have arisen as a result of reflection on the best practice and experience carried out at the time. There are thus several lessons identified as a result of the research for this report that were considered best practice by project teams in the past, and where on reflection the benefit of taking such approaches has either been confirmed or has been modified now that the outcome of the specific project is known. Further, whilst many important lessons arise during construction, significant learning is also often made during operation and maintenance.

This report discusses the lessons learned from:

- Sizewell B (a PWR completed in 1995),
- The installation of waste processing facilities (at Sellafield),
- Olkiluoto 3 (the EPR plant under construction in Finland),
- Flamanville 3 (the EPR plant under construction in France),
- Taishan units 1 & 2 (the EPR plants under construction in China),
- Sanmen and Haiyang (the AP1000 plants under construction in China).

From cursory examination of the lessons learned from previous and current new nuclear build projects, it is possible to envisage a set of characteristics that a successful project in the UK would have We cannot say that all of these need to be in place to guarantee a successful project because if the lessons identified in the study are learned effectively, the solutions could take a number of forms. The following attributes of a successful project can therefore only be indicative:

- Governmental involvement and public acceptance from an early stage with strong public engagement throughout ensuring effective communication is maintained between the project and the local community
- Appreciation among the project team that many lessons are generic across a wide range of related projects and related issues arise time and again
- Focus on proven technology and established design
- Planned series build from the outset
- Investment in appropriate technology to aid the design and build
- Maintenance of a commercial risk register reviewed at senior levels in the organization
- Establishment of a relationship to ensure regulatory issues are resolved ahead of the program's critical path
- Establishment of staff project teams with high-calibre managerial and engineering people, dedicated to the project objective and led by a person with the authority to act
- Quality control and assurance processes throughout the whole supply chain

The process of learning lessons from previous experience is well understood and formal processes to collect, disseminate and learn safety related lessons exist in a number of industries. Within the nuclear industry, mechanisms are in place to collate reports of incidents and disseminate lessons learned for nuclear operators and the overwhelming majority of world nuclear operators subscribe to this system.

Current safety related reporting schemes in the nuclear industry come into effect at the time a nuclear plant is commissioned. There are often lessons for reported incidents that are of relevance to the construction phase, and while the dissemination of this knowledge to the nuclear supply chain is encouraged by the database owners, the effectiveness of the dissemination is not fully understood.

The culture of learning lessons from past experience is embedded within the vendor companies and their supply chains, but to date, the dissemination of those lessons beyond individual projects does not happen as often or as effectively as it does between nuclear operators.

An expansion of this culture and style of incident reporting from the nuclear operators' community into the new nuclear build supply chain would be of immense use not just for the companies involved in the nuclear supply chain but in ensuring that the nuclear plant operators take delivery of plant built and commissioned with the benefit of that critical knowledge exchange.


Photo supplied courtesy of British Energy.

1. Introduction

This report focuses on the lessons that are of particular relevance to the construction of new nuclear power stations in the UK. Interviews have been conducted with experienced members of new build teams from Westinghouse UK, EDF and AREVA, members of the project teams that built Sizewell B and are constructing a new Evaporator at Sellafield as well as companies supplying nuclear components, to obtain their views on the key lessons relevant to new construction in the UK.

Given the need for new base load electricity generation, a UK government commitment to support a nuclear contribution to the national electricity supply and a commitment to streamline the UK planning processes, the key determinants for a successful new build programme in the UK are the financing, the organization of the build, and the risks associated with licensing and construction. Options for financing the new build have not been addressed in this report.

The organizational arrangements for build in the UK are still evolving and may differ depending on the operating customer. These arrangements are likely to be different from the arrangements selected in other countries that are building EPR 1600 or the AP1000 reactors. In Finland AREVA has a turnkey contract to build Olkiluoto 3 and in China both AREVA and Westinghouse have nuclear component supply contracts. As a result some of the specific lessons learned on these plants, which are relevant to replica builds in those countries, may be less directly relevant to build in the UK. Both AREVA and Westinghouse have considerable experience of introducing new PWR technology into a country for the first time and are well aware of the uncertainties associated with regulation and site construction, which can be very country specific. Manufacture of the main nuclear components is an international business so that the application of lessons learned in this specific area can be much less country specific.

This report discusses the lessons learned from:

- Sizewell B (a PWR completed in 1995),
- the construction of a new evaporator at Sellafield,
- Olkiluoto 3 (the EPR1600 plant under construction in Finland),
- Flamanville 3 (the EPR plant under construction in France),
- Taishan Units 1 & 2 (the EPR plants under construction in China),
- Sanmen and Haiyang (the AP1000 plants under construction in China).

Olkiluoto 3 is a relevant example of an advanced PWR being built outside of the countries which developed the design The EPR design is a derivative of the Framatome N4 and the Siemens Konvoi designs. The supplier AREVA has extensive knowledge and experience of working with the French and German but not the Finnish licensing authorities. The Finnish Regulatory Authority has published extensive information on the lessons they have learned.

Sanmen and Haiyang are examples of the construction of the Westinghouse AP1000 where the build programmes were, at the time of writing, at an early stage.

Taishan Units 1 & 2 are examples of EPR projects underway in mainland China and these are currently behind the Sanmen and Haiyang projects.

The Sellafield evaporator installation is an example of a current nuclear project in the UK.

Sizewell B construction was completed some 15 years ago however many of the lessons are relevant to new build. Sizewell was built after the Three Mile Island (TMI) and Chernobyl incidents and so the design had to include developments based on the lessons from them. It also qualifies as an advanced PWR. Many of the lessons learned reflect the licensing and construction culture that is still relevant to nuclear build in the UK today. The two issues which had major impact on the programme, the difficulty of pouring concrete into the dense rebar necessitated by seismic requirements and the difficulty of verifying the reliability of microprocessor based protection and control systems, are very similar to issues experienced at Olkiluoto 3 and which were raised by the Nuclear Installations Inspectorate (NII) Generic Design Assessment (GDA). It is also the case that Sizewell B will be a benchmark against which the new projects will be judged. This is likely to be the case for operator dose targets and activity discharges, and also for site 'good neighbour issues'. Economic and performance issues such as construction programme and electricity cost will be compared with the alternative available technologies for power generation. The context in which lessons arise is important to their relevance to other situations so the design, construction and commissioning of Sizewell B has been summarized.

2. Background

For the past 40 years the international nuclear industry has had an improving record of learning from experience and sharing that experience so others in the industry can benefit. The need to learn from the experience of others was evident from the beginning of civil nuclear power operation. Vendor companies established Owners Groups and utilities formed or expanded trade associations to collate, analyse and distribute experience from the operation of nuclear plant. The corrosion problems experienced on light water reactor designs[1] extended this collaborative process to include substantial research and development programs. The successors to these organizations such the Electric Power Research Institute (EPRI), VGB (www.vgb.org) and the National Utility organizations in France, Japan, Korea and Russia provide the repositories for the many lessons learned and provide operators and vendors with advice and guidelines based on the continuously expanding operational experience data base.

The need to freely exchange information and experience that could have an impact on safety was underlined following the accident at Three Mile Island Unit 2 on the 28th March 1979 when it was found that a similar set of circumstances had been experienced earlier at the Davis Besse plant. Had the operational experience at Davis Besse been passed on then the TMI accident could well have been avoided. In the US at that time the anti-trust legislation designed to promote commercial competition had been cited as a reason for not passing information from one organization to another. The nuclear industries in Western, Central and Northern Europe, as well as those in Japan, Korea and the developing countries took the lessons from TMI and other operating stations to heart and this led to the development of advanced PWR designs that had greater protection against external hazards and more robust containment measures for protection in the event of core damage. In the US the nuclear industry set up a national organization, the Institute of Nuclear Power Operations (INPO), to improve operating safety and established systems to collect, evaluate and exchange reports on nuclear incidents at all their plant. Following the accident at Chernobyl on 26th April 1986 the World Association of Nuclear Operators (WANO) was founded in 1989. The WANO mission is "to maximise the safety and reliability of nuclear power plants worldwide by working together to assess, benchmark and improve performance through mutual support, exchange of information, and emulation of best practice". Through the WANO programme of peer reviews, Significant Operating Experience Reports (SOERs), Significant Event Reports (SERs) and technical support & exchange, members can learn from the experiences of other operators. The willingness of WANO members to openly share their operating experience for the benefit of other nuclear operators is fundamental to the success of this programme.

Following the revival of international interest in new nuclear construction, WANO is actively promoting the transfer of information to support new build. They propose to do this by undertaking pre start-up peer reviews prior to integrated testing and by identifying and classifying SOERs and SERs that indicate that design modifications would eliminate or mitigate any issues identified. They are in discussion with all the major designers and constructors around the world. The project is in the pilot stage at present and, if shown to be useful, will become an integral part of the WANO activities[2]. INPO has already undertaken many reviews of nuclear construction projects in the US and this activity will be integrated with the WANO initiative. There are likely to be benefits in shared construction experience, as is long established in plant operations that should not be compromised by traditional concerns of the loss of competitive advantage.

The International Atomic Energy Agency (IAEA), founded in 1957, had long been trying to establish an international system for reporting nuclear incidents with analysis of cause and recommendations for reducing the chances of similar incidents but had run into resistance on the grounds that such information was proprietary or confidential. In 1978 the Nuclear Energy Agency (NEA of the OECD) took the first steps to setting up its own Incident Reporting System (IRS). The TMI accident gave impetus to both agencies and in January 1980 the IRS began a two year trial. NEA members formally approved the system in 1983 and the IAEA extended IRS to all interested member states. The UK joined the IRS in 1986 and by 1996 virtually all member states' operating nuclear power plants are in the system[3]. Today the IAEA operates the International Nuclear Information System (INIS) and a Nuclear Knowledge Management (NKM) section[4] and is actively promoting the exchange of information to improve the performance of new construction projects[5].

The opportunities for lessons learned to improve efficiency and generate economic savings on new-build projects are greatest for follow-on replica stations particularly when the follow-on stations are built by the same organization in the same country. Companies therefore create and maintain knowledge management systems to help ensure that lessons and experience are captured and acted upon. These data bases can be very detailed and much of the information is regarded as commercially sensitive. The most effective way to transfer 'know-how' and experience is by transferring experienced personnel. Most stations are constructed by consortia of companies and the composition and allocation of responsibilities of these groups can vary widely particularly between countries. The timely transfer of both information and staff can therefore be more difficult between different consortia particularly if in different countries.

The Nuclear Industry Association (NIA) and the Nuclear Institute have made considerable efforts to ensure that potential suppliers to the UK new-build programme are informed of what is required to qualify as suppliers of nuclear equipment and services. They have arranged conferences and seminars to inform potential new entrants to this market[6]. Westinghouse UK and AREVA/EDF have engaged with over one hundred potential UK-based suppliers.

In the area of lessons learned as a result of large-scale, general construction project, not limited to nuclear, the Department of Business Innovation and Skills (BIS) commissioned Mark Gibson to review productivity and skills in the UK industry and compare this with international performance[7].

3. Lessons Learned from the Sizewell B project

The first commercial Pressurised Water Reactor, PWR, to be built in the UK was completed within budget and achieved full load in 82 months just 4 months beyond the official programme of 78 months committed to the Central Electricity Generating Board (CEGB) executive and 2 months ahead of the 84 month commitment made to Government and which was the basis for the business case. Sizewell B (SXB) won the prestigious British Construction Industry Award in 1994 in the civil engineering category and also the Supreme Award selected from all the competition categories. In 1995, when it achieved full commercial load, SXB was the only design in operation that met the state-of-the-art requirements for an Advanced Light Water Reactor as defined by the US Electric Power Research Institute (EPRI)[8].

The CEGB issued an Enquiry Specification for Sizewell B in April 1980 and the request for section 2 consent and deemed planning permission to build the first of four identical stations was submitted in January 1981. They also applied to the Nuclear Installations Inspectorate (NII) for a revision to the Site licence. In March 1987, almost exactly two years after the longest ever Public Inquiry had finished taking evidence, the Secretary of State granted planning consent for a 1200MW PWR power station to be built at Sizewell alongside the still operational Magnox station, Sizewell A. Following the accident at Three Mile Island Unit 2, on the 28th March 1979, and the change of Government, the decision to build a PWR was revisited. In December 1979 the decision was taken to proceed subject to the normal assessment and licensing processes.

Figure 1: Sizewell B PWR

Sizewell B was sanctioned by the CEGB in April 1987 and its total budget was set at £1,691M. When the CEGB was privatised the three follow-on stations planned for Hinkley Point, Sizewell and Wylfa were cancelled. This had a profound effect on the cost as Sizewell B had to carry all the up-front, first-of-a-kind engineering costs. The revised capital cost estimate was £2,030M at 1987 prices. This was confirmed by Nuclear Electric plc following its inception in November 1989. The final cost at 1987 prices was £1,989M. The station first went critical in January 1995, started operation in February, achieved full load in June and formally entered commercial operation on 22nd September that year. In retrospect the overall programme was judged to be ambitious by comparison with similar plants elsewhere. Sizewell B is an example of a very successful large, technologically-challenging project.

Since that time both the UK electricity supply industry and the nuclear power industry have changed significantly and nuclear technology has advanced; nevertheless there were lessons learned during the planning, construction, commissioning and operation of Sizewell B that are relevant to the construction of new PWRs today.

In 1995 John G Collier FREng FRS, the first Chairman of Nuclear Electric plc listed the following lessons learned in the Christopher Hinton Lecture to the Royal Academy of Engineering[8];

- The application of proven technology based on established design. This must be complemented by a high level of design completion in advance of construction, and in the case of nuclear plant the licensing basis for the plant must be secure before commitment to construct.
- Project management arrangements must reflect the allocation of risk between client and constructors. Sizewell B demonstrated that a unified organisational structure works well for such a complex and interactive project; the selection of the right person as project director is crucial; and the management systems, QA, planning, cost control; and information systems must be of high quality. An effective industrial relations approach must be adopted.
- The contract strategy must be sound and reflect the risk being carried by the parties. The contracts must clearly define the scope and responsibilities of contractors and, most importantly, the work must be placed with quality contractors.
- Contract management must instil a disciplined approach, for example, by the use of the *key dates* procedure. Further, a good working relationship between the client and the contractors is crucially important – it has to be a partnership creating a win–win situation.
- There is still room for improvement in the way in which consent applications are processed and Public Inquiries are conducted. On Sizewell B it took over six years from application to consent and for the proposed station at Hinkley – a replica plant, over three years.

Collier's paper pointed out that the design development cost was of the order of £700M. This included the establishment of the detailed design and safety case and project infrastructure necessary to construct plants. This sort of investment only makes sense if a family of replica plant are built. Sizewell C was planned to be a two-reactor unit. This design, with many shared services, would have been more cost effective and quicker to build than the single unit SXB station. It would have benefited directly from all the experience and lessons learned on SXB[9]. In 1992 the Taiwan Power Company announced its intention to build a twin-unit Light Water Reactor (LWR) using the EPRI requirements for an evolutionary ALWR as the design specification. The joint Westinghouse/Nuclear Electric bid based on a twin unit "Sizewell C" design was one of the final three considered in the ultimate commercial evaluation. The Advanced Boiling Water Reactor (ABWR) was finally chosen. One can only speculate about what the UK nuclear industry might have achieved if Sizewell C had been built. Cancellation of the follow-on stations had a devastating effect on the UK nuclear power industry but many of the UK sub contractors did build on the experience gained at SXB to develop as suppliers of components to nuclear plants internationally[6].

Sizewell B and the three follow-on stations were to replace the ageing Magnox plant and so maintain the nuclear percentage of electricity generation, not to increase it. At privatisation the government wished to encourage new entries to the electricity generation market. These new entries were all gas fired and because of the widespread use of 'take or pay' gas contracts, these wanted to be base-load stations. The base load market became saturated so no one was building base load stations[10]. Efforts to raise private capital to build Hinkley C were abandoned and the planning permission was allowed to lapse.

This section summarises the experiences which generated these lessons, how lessons learned from previous international experience was incorporated into the SXB design and reports the reflections, insights and recommendations of the following key contributors to the Sizewell B Project after 15 years of SXB operation;

- Brian George, the Sizewell B Project Director;
- Richard Waite, who was the SXB Commissioning Manager and recently the Divisional Director Strategy and Technology of the Nuclear Decommissioning Authority (NDA) and now Managing Director, Commercial Nuclear, Europe & Middle East for CH2M Hill;
- Nigel Buttery, who was the Safety Manager on the SXB Project Management Team and until recently was the Licensing Manager for the Station.

Pre-construction Activities

The long Public Inquiry process extended the time between the submission of the planning application and the start of work on site to six-and-a-half years. However effective use of that time was made to:

- Transfer the technology from the US;
- Develop the design to meet UK requirements in particular to meet the stringent safety requirements set by the CEGB and the NII and incorporate lessons learned from international light water reactor operating experience[11];
- Establish a first-class project organisation[12];
- Establish contracts with mainly UK contractors, many of which had to upgrade their facilities and introduce quality assurance programmes that were far more demanding than UK industry had been used to[13];

- Plan the construction process using three-dimensional modelling and involve contractors in the production of detailed, integrated schedules to eliminate or de-risk potential interface issues.
- Conduct research, development and testing on a number of plant items where the design or manufacturing route had been changed significantly and to improve the data bases and safety analysis methods which formed the basis of the plant safety case[14];
- Further develop the safety assessment processes applied by the safety regulator, the NII.

Rapid strides were being made in the concept of quality assurance and its application to nuclear power plant which resulted in the publication of very demanding quality assurance requirements by the US Nuclear Regulatory Commission (NRC) and the British Standards Institute. SXB was the first major project in the UK to apply a comprehensive QA programme through all aspects of the project including design and engineering.

The UK conducted an extensive R&D programme and participated in the growing number of international programmes that supported light water reactor design and safety. Test facilities were built for example the main circulation pump test facility at Weirs and the valve test facility at the CEGB laboratories at Marchwood. Equipment qualification facilities were built to test equipment that was called upon to operate under severe environmental conditions.

There had been major advances in the development of fracture mechanics and non-destructive testing. Concerns had been expressed about the ability to detect defects in pressure vessels which could lead to failure of the component. In 1974 a Light water reactor Study Group had been set up chaired by Walter Marshall (Chairman of the AEA and later Lord Marshall and Chairman of the CEGB) to examine the factors which determined the integrity of the pressure vessel. The group reported its findings in 1976 and the Report was updated in 1981[15]. Because of the importance of ensuring the absolute integrity of the pressure vessel an Inspection and Validation Centre (IVC) was established by the AEA. The centre undertook validation of inspection techniques and certified the inspectors who undertook manual inspections thus improving the reliability and confidence in non-destructive testing methods and procedures used for high integrity pressure components[16].

Nuclear Regulator processes, procedures and in-depth understanding of light water reactor technology and operating experience benefited from the Public Inquiry and the additional time. The CEGB's Design Safety Guidelines[17] and the NII's Safety Assessment Principles[18] were modified as a result of discussions at the Inquiry and in particular the NII document on the tolerability of risk from nuclear power stations was produced in direct response to the deliberations at the Inquiry[19].

Design

The CEGB, following many years of experience of introducing innovation with almost every new nuclear project, wanted SXB to be based on mature and proven technology with the minimum of innovation necessary consistent with meeting the requirements of safety and performance. A Task Force, chaired by Sir Walter Marshall was set up in 1981 with representatives from major interested parties to evaluate the basis for the Sizewell B Design.

The basis selected for the development of the Sizewell design was the Standard Nuclear Power Plants (SNUPPS) that was developed by Westinghouse and Bechtel as a standard for series ordering in the US. In the event only two SNUPPS were built (Calloway and Wolf Creek). In the late 1970s and early 1980s when SXB was being designed there was a rapidly expanding data base of light water reactor operating experience and rapid development of manufacturing methods and safety assessment methodology16. The most memorable experience was of course TMI-2 in 1979 where lessons learned had to be incorporated in new designs but there was plenty of other experience, much of this already accommodated in the CEGB Design Safety Criteria and Guidelines that drove design development[11].

TMI highlighted the need for comprehensive instrumentation, the vital importance of the nuclear power station operators and the importance of the man-machine interface. This had a profound influence on control room design and design for ease of maintenance. The need for highly-trained operators was re-enforced and SXB had a full scope, high-fidelity simulator available for training well in advance of the commencement of plant operation. This also led to the development of so called symptom-based procedures to meet the need for procedures capable of dealing with multiple faults and misdiagnosis.

The fire at Browns Ferry in 1975[20] showed the need for design development to demonstrate that plants could withstand both internal and external hazards. This led to SXB having a number of four-train systems compared with the two-train systems in the SNUPPS design. In particular, the essential electrical systems are arranged as four separate groups, each supported by a 100% back-up diesel generator, separated by fire and hazard barriers.

The requirements for diverse as well as redundant equipment called for by the CEGB Design Safety Criteria lead to additional equipment and systems; examples are the microprocessor-based Primary Protection System backed up by the magnetic logic Laddic Secondary Protection System, the Emergency Boron Shutdown System (EBS) as a diverse backup to the control rods, and two 100% steam-driven auxiliary feed-water pumps backed up by two 100% electrically-driven pumps with separate nozzles on the steam generators to provide feed routes diverse from the main feed lines.

The CEGB Design Safety Criteria and Guidelines evolved with the gas reactor programme, from Magnox through to AGR. They were influenced by both UK and international developments. Both the CEGB Criteria and the NII safety Assessment Principles were based on fundamental principles established by the International Commission for Radiological Protection (ICRP). Although the basic design criteria were deterministic, probabilistic analysis was used in support of these in the early 1970s. For SXB Probabilistic Safety Assessment (PSA) formed an integral part of the safety case. A level 1 PSA was carried out in support of the initial design process to ensure that the application of deterministic criteria had produced a balanced design. Because of the criteria relating to offsite consequences (a requirement prompted by the Windscale fire in 1957), a level 3 PSA was produced and this meant that severe accident issues were addressed during the design process10.

Increased awareness and understanding of the earthquake risk required development of the seismic design and qualification of buildings. The interaction of seismic loads with the high pressures and temperatures postulated for possible accidents created an extremely onerous loading regime for the reactor building making it one of the most complex civil structures then designed[21].

The development and increased application of PSA demonstrated the need for highly-reliable safety protection systems with adequate diversity and redundancy to achieve high reliability. Rapid evolution in control and instrumentation technology had a major impact on the design development[22]. The use of microprocessors in the reactor protection system produced a step change in the approach to rigorous software verification and quality control[23],[24].

UK requirements relating to radiological protection drove changes in control and instrumentation area. There is a requirement that no immediate off-site evacuation is required for any design-basis accident[i] and this places limits on the radioactivity that could occur at the site fence in the event of such an incident. This required a secondary containment to be built at SXB[25]. At the time of the Public Inquiry the average operator dose from US PWRs was significantly higher than on the AGR stations[26]. The Inquiry regarded the collective dose target set for SXB at 2.4man Sv/yr, as very challenging. Design effort was focused on materials specification, detailed pipe-work design, shielding, plant layout and plant water chemistry control to reduce operator dose. The actual collective dose peaked at 0.635man Sv/yr after the 3rd fuel cycle and declined to below 0.3man Sv/yr after the 5th fuel cycle, demonstrating the success of the design provisions and the administrative controls[10].

Many light water reactors around the world were experiencing stress corrosion problems with pressure boundary materials at the time SXB was being developed. In the late 1970s and early 1980s all US PWR plants were suffering from major losses of capacity factor because of steam generator corrosion[27]. A few late design changes were made where a convincing case was presented and the risk to the budget, timescale and the safety case were understood and small. An example of one of these was the use of thermally-treated Alloy 690 rather than Inconel 600 tubing for the steam generators. Inevitably there was experience that came too late to be incorporated into the design; an example was the stress corrosion failures of Inconel CRDM penetrations in the reactor vessel head which were first observed in French plant in 1985. The lessons did feed into the inspection strategy for the vessel head at SXB. The head was later replaced with one with Alloy 690 rather than Inconel 600 CRDM penetrations.

There were also UK specific requirements that were different from SNUPPS. The CEGB wanted two turbines based on the then standard 660MW units. The electrical frequency of 50Hz rather than 60Hz meant that rotating

i A postulated accident that a nuclear facility must be designed and built to withstand without loss to the systems, structures, and components necessary to ensure public health and safety.

machinery was generally larger with knock-on consequences for the station lay-out. Changes were required also because Sizewell was a coastal site and the two SNUPPs plants were inland sites.

The design development of the SNUPPS design to meet UK requirements was undertaken by a dedicated team of engineers from the CEGB and NNC, supported by the civil contractors Taylor Woodrow and Sir Robert McAlpine, using information provided by Westinghouse and Bechtel through technology transfer and licensing agreements. In the initial design phases Westinghouse and Bechtel engineers were embedded into the design team to ensure full benefit was gained from their experience. At its peak this team had over 1000 engineers.

The SXB project required a high level of design completion at an early stage to ensure; accurate costing; a realistic programme; detailed contract specifications and advanced availability of design information to support the construction programme. The long lead time that resulted from the planning process was a help in this respect.

The design and later the construction programme were supported by detailed models from a full-scale mock-up of the control room to a highly detailed 1:20 scale model of all the main buildings. Virtually every item down to the 12mm pipe-work was modelled with an accuracy of 1mm. It was an essential design tool, used daily, to ensure that the maze of 217 km of pipes, ducts and cable trays did not foul seismically-qualified primary circuits, to ensure that fire-segregated cable routes were not compromised and that access for construction through to operation and maintenance was acceptable. A 1:10 scale model replica of the pre-stressed concrete reactor building primary containment was tested to destruction to help validate the computer analysis of safety factors. Now, of course, such models would be based on computer aided design models and finite element analysis but no less valuable.

Licensing

It was important to secure a safety case agreed with the NII in order to minimise the risk of delays during construction caused by problems with the licensing authority. The Pre-Construction Safety Report (PCSR) and reference design were issued in May 1982, as it turned out, some 5 years before the start of construction. This gave time for outstanding safety issues with the NII to be resolved and to incorporate any changes into the design and related contracts. The NII issued the amendment to the Site Licence necessary for work to start in 1987.

Issue of the licence has conditions attached (35 at the time of SXB construction, now 36) and arrangements must be in place to comply with these at all times. During construction and commissioning the most significant controls are via consent points which are defined activities in the programme when NII permission is required to proceed further. These are listed in table 1. On previous projects these ‘hold points’ had been used to review general licensing progress and this proved unwieldy. Instead, a licensing group was charged with ensuring timely submission of documents to the NII and early resolution of any problems. A program of work to clear the outstanding licensing issues was developed and a process for monitoring progress and resolving differences was established. The licensing activities were divided into about 15 general areas and a Licensing Activities Summary

Programme (LASP) was formulated for each. A program of meetings was established. Level 4 meetings were for the provision an discussion of new information, level 3 progress meetings, held every 6 months, were between the licensing manager and the appropriate NII Inspector to clear licensing issues and resolve differences, level 2 meetings were between the project director and the Deputy Chief Inspector to resolve any issues referred up from level 3 and Level 1 policy meetings were with the Chief Inspector if matters were not resolved at level 2. This separation of licensing activities from the construction progress helped both whilst providing the NII with the means to exercise required controls. It also provided a mechanism for resolving concerns before they became critical to the construction program.

One of the requirements for the final construction stage (fuel load) was the delivery of the Pre-Operational Safety Report one year before this point. It was delivered in November 1992 on a timescale consistent with construction.

There were many detailed lessons learned from the licensing experience on SXB concerned with documentation, risk criteria and ALARP, the use of PSA, design change control, reactor pressure vessel integrity assessment, radiological protection, the primary protection system and filtered venting. These were reported to the HSE in 1994[28]. The overall lesson was "talk to the regulator early and often".

Sizewell B Construction Consent Points

1	Mass Concrete
2	First permanent Structural Concrete • Construction of tunnels and cooling water culverts • Construction of reactor and radwaste building foundations • Construction of the reactor building dome • Completion of reactor building
3	Not used
4	Install reactor coolant pump support legs
5	Access for mechanical plant construction and radwaste building
6	Install reactor pressure vessel
7	Start containment pre-stress
8	Start of site primary protection system functional test
9	Start of simulator training
10	Primary hydro test
11	Deliver fuel to site
12	Load fuel

Table 1: Construction Consent Points

Project Management

The CEGB had recognised that the performance of projects such as the Isle of Grain and Dungeness B had been poor and changes were needed[29]. The changes made in the late 1970s lead to the Drax B (coal) and Heysham 2 (nuclear) projects were successfully completed close to budget and programme. SXB built on this experience but, in a departure from past practice, adopted a unified approach to the design, contracting and construction of the project, with the CEGB leading the project. This decision was made because of the risk carried by the CEGB on a large unitary investment in a project that could not be allowed to go wrong.

From the mid 1950s the Magnox and AGR construction was dominated by five nuclear construction consortia. They were awarded complete design, supply and build turnkey contracts. This approach was initially successful but repeated construction cost increases and programme overruns dented profits. Successive mergers resulted in the five being reduced to one, the National Nuclear Corporation (NNC), formed in 1973[30]. For the construction of the last AGR, Heysham 2, the CEGB offered NNC a management rather than a turnkey contract. With a cost-plus-with-incentive-bonus arrangement with this management agency, most of the risk was with the client.

The CEGB were concerned about the lack of competition in this arrangement and for SXB, after first considering a joint CEGB/NNC project group, established a PWR Project Group (PPG) with CEGB firmly in the lead. 100 key NNC staff moved over to be directly employed by the CEGB. NNC was given several specific design contracts. Continuity for outline design was retained by Taylor Woodrow and Sir Robert McAlpine, splitting away from NNC to form Nuclear Design Associates, who became the lead civil engineering contractor. The PPG had direct responsibility and control of all aspects of the Sizewell project and easy access to the expertise available in the NNC, UKAEA and CEGB engineering and research organisations that had been built up to support the UK civil nuclear programmes.

The PPG was responsible for: compiling the safety case; determining the station layout; acting as architect/engineer for the station systems; specifying equipment; managing procurement; managing the construction site; commissioning; and managing the overall project. This was the first time all these functions had been combined for a UK nuclear station project. The management arrangement was scrutinised at the Public Inquiry and Sir Alistair Frame, who was called as an expert witness, stressed the need for high quality leadership and the importance of the task of Project Director. This post was filled by Brian George FREng who had led the project from its initiation and into the Public Inquiry. Sir Alistair also stressed the importance of having a supervisory board to oversee the project team. This approach was adopted with the establishment of the Project Management Board.

This cohesion of effort, concentration of skills, short direct lines for communication and decision making, and the elimination of traditionally difficult interfaces was a major contributor to the success of the project.

The PPG invested time and money to ensure high quality planning, progress monitoring and cost control arrangements. It also established a single project database, "Total Project Information", coupled with a robust information system to provide access to a common set of information from the start. A quality assurance programme was established covering the design as well as manufacture and construction. This was backed up by detailed procedures on all aspects of the project. This assurance of quality and traceability throughout the design, manufacture and construction process was an essential element in meeting the stringent safety and licensing requirements.

Particular attention was paid to industrial relations. This included robust support for the National Agreement for Engineering Construction Industry (NAECI) and its National Joint Council with an SXB Joint Council, and setting up a Management Group with Nuclear Electric and the contractors to produce guidelines for harmony of wages and conditions. This ensured a consistent application of industrial relations policy across the project.

Contract Strategy

Work on SXB was divided into 110 contract packages. Negotiated contracts were employed for the primary circuit contract because Westinghouse, as developer and owner of the design, was in a unique position to offer the necessary warranties and performance guarantees, and for the high integrity pipe-work where it was necessary to use three UK contractors with the experience of the design, manufacture and erection of such pipe-work. This precluded competitive bidding. Where possible contracts were placed by a competitive bidding process and lump sum, firm price were adopted which covered design detail, manufacture, erection and testing. Where work was logistically complex and the design incomplete firm rates and estimated quantities were used. This was the case for the major civil works and cable installation.

Emphasis was placed on getting high quality contractors with the necessary resources to undertake the work and a record for delivering a quality product to time. The target programme was set 9 months ahead of that promised to Board and, where appropriate, incorporated penalty and incentive arrangements. Payments to contractors were linked to achievement of milestones. A key date (see Table 2) procedure in which cash flow and resources were discussed at director level was an important part of the management of contractors.

KEY DATES	
January 1981	Planning application
January 1983	Start of Public Inquiry
March 1985	End of Public Inquiry
March 1987	Planning approval granted
June 1987	Site Licence
July 1987	Start preliminary works
August 1988	First permanent structural concrete
May 1991	Polar crane installed
August 1991	Reactor pressure vessel installed
November 1992	Pre Operational safety Report to NII
December 1993	Reactor building structural overpressure test
January 1994	Reactor building integrated leak rate test
January 1994	Primary circuit hydro test
February 1994	Completion of main civil works
April-May 1994	Hot functional testing
September 1994	Fuel loading
February 1995	Commercial operation

Table 2: Sizewell B Key Dates

Incentive arrangements were set early and reviewed with the contractor to achieve the best mutual advantage for the project management and the contractors to achieve a win–win situation. There were times when circumstances dictated a flexible and innovative approach to contract strategy. The example of most significance was the civil contract with Laing. The rapidly developing seismic design was generating an equally rapid increase in materials quantities. Rebar tonnage rose by 58% and volume of concrete rose by 25%. The contractor would have been entitled to major claims and time extension which would have completely destroyed the programme. The solution negotiated by the Project Director was to free the contractor of his responsibility under the original contract and enter more into a partnership deal. The basic lump sum and re-measure ICE Fifth Edition contract remained in place but with an innovative amendment. A line was drawn under possible claims, with a single settlement payment and further payments changed to a cost reimbursable basis. There was a fixed fee for overheads, a target cost to completion and significant bonus payments linked to some of the contractor's 400 key handover dates. No further claims would be entertained and some rescheduled key dates assumed significant acceleration, crucially the installation of the polar crane was put back only 8 months rather than the year that it otherwise would have been. This revised polar crane installation date was met[21].

Construction

The construction programme is shown in figure 2. However, preparation for construction had started nearly three years before first permanent concrete with the construction planning process. The 3D model was used to develop detailed schedules, for example, to route piping and cabling; identify access requirements and locate embedments and size holes in walls so they could be in place well ahead of piping and cabling installation. Contractors were involved with the project management and design teams in the production of integrated programs and detailed schedules. All prime contractors were contractually obliged to form a Joint Planning Team. This team would collectively sign off the integrated programs which were the basis for detailed schedules. This substantially reduced the likelihood of later arguments at interfaces between contractors during construction. The design clearance and construction methodology clearance programs identified key dates which the contractors were incentivised to meet. This effectively de-risked the program. This detailed planning also allowed the required labour force to be estimated and facilitated the planning of associated logistics such as transport and accommodation.

When the teams went to site, this collaborative working arrangement carried over and facilitated reference back to the design when problems were encountered. There was a strong focus on meeting milestones on the critical path. There was relentless attention to maintaining the program and identifying and rectifying problems early. A key feature was interface management by the client team with rigorous attention to quality assurance. This ensured that a facility or piece of equipment was complete and fit to pass on to the next contractor, such as the hand over from mechanical to electrical to instrumentation contractors. This ensured that errors were not compounded.

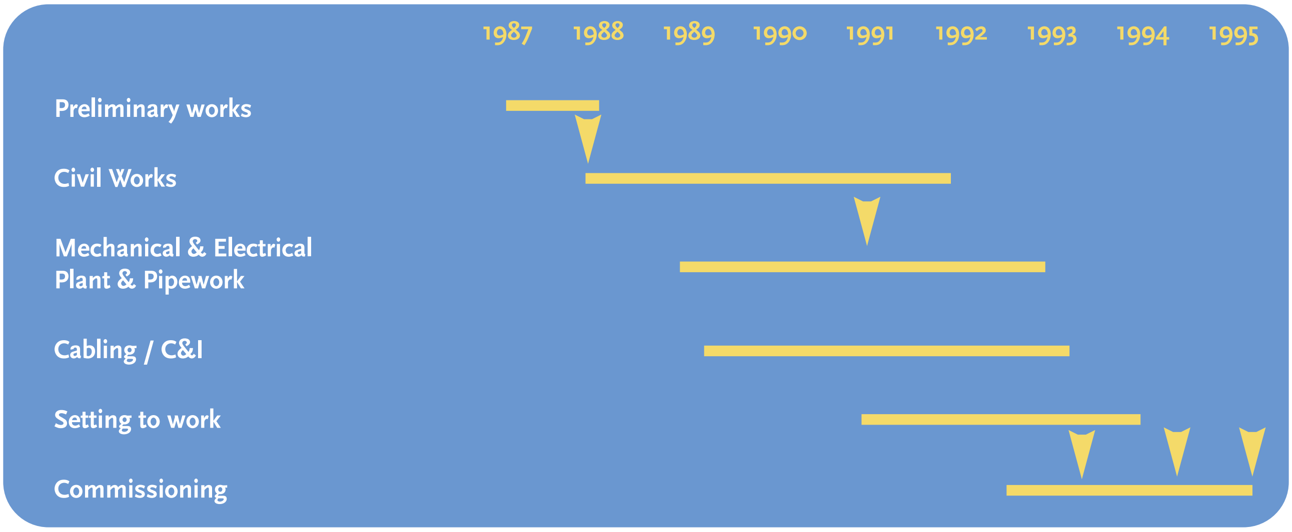


Figure 2: Sizewell B construction programme[16]. Milestones (arrows) indicate (from left to right): First permanent concrete, start of nuclear steam supply system, hot functional testing, load fuel and full load.

Preliminary works started in July 1987 and ran until August 1988. To properly drain and dewater the site a diaphragm wall was constructed. This extended 50 metres down through the sand to the London clay strata and extended around the site perimeter. At the time it was the deepest ever built in the UK[31].

The civil works were a huge undertaking and proved extremely challenging. When John Laing Construction started on site in September 1987 the detailed design of the main structures including the reactor building were just starting. As the seismic analysis progressed it became apparent that the construction of the reactor shell, especially the lower section, was far more complex than originally anticipated. The rebar density in the base of the internal shield wall increased to 7%, as high as any density for a concrete structure anywhere. The steel fixers had to be given 3D computer generated drawings as the usual plans were too complex. Cleveland Structural Engineering started construction of the 65m high cylindrical, gas tight, liner for the reactor building in mid 1988. The liner barrel also acted as the inner shuttering for the 1.4m thick concrete wall of the containment building. It was fabricated on site from 9m x 3m panels that were 6mm thick. There were more than 200 penetrations and 400 embedments and also large access ways in this flimsy 45m diameter self-supporting structure. The contractor later admitted that the complexity of the interface problems has been underestimated[21]. Slow progress on the containment wall threatened the installation of the huge polar crane on the circumferential rail track near the top of the building. The renegotiation of Laing's contract, reassessment of the handover process to mechanical and electrical contractors, the instigation of accelerated working with triple shifting and a substantial increase in labour on site, together with an enhanced degree of collaborative working brought the programme back by 4 months[21]. It has been estimated that this effort cost about £60M. Had a follow-on station been built, the lessons learned would have lead to much more off-site pre-fabrication of rebar cages and the liner[9].

The huge sea water cooling intake and outfall culverts, which extend into the North Sea for 750m, were installed in 1990, by Kier Construction, a full 12 months ahead of the contract programme. The 3000t concrete tunnel sections were constructed offsite in Teeside and floated down by sea and sunk into trenches cut in the sea bed at Sizewell[32].

The civil engineering works were completed in the summer of 1992 and the reactor primary containment building was subjected to its structural over pressure test in December 1993. A detailed account of the construction of Sizewell B from a civil engineering perspective was published as a special issue in the proceedings of the Institution of Civil Engineers[33].

The reactor pressure vessel (RPV) was installed in April 1991. It had been manufactured by Framatome from forged rings made by Japan Steel. The RPV had been subject to considerable analysis and was rigorously inspected at every stage of manufacture and installation[16]. The cost of this analysis and inspection doubled the price of the component. Many of the other major mechanical components were made in the UK. The four steam generators were manufactured by Babcock Energy under licence from Westinghouse and the main circulation pumps were built by Wier Pumps.

Installation of mechanical and electrical services was completed towards the end of 1993. High levels of productivity had been achieved. Main cable laying and termination was the best ever achieved on any UK power plant construction, demonstrating the value of early planning and interface scheduling[34]. The lessons learned by N G Bailey & Co Ltd, the main contractor, were recorded in a paper at a conference focused on the electrical and control aspects of the project in 1992[35].

A major challenge to the programme came in early 1991 when it became clear that the control system for the station, the Integrated System for Centralised Operation (ISCO) could not be delivered to programme. The system ordered was that being developed by CEGELEC for the French PWR, Chooz B, which was running some 18 months ahead of the SXB programme. However the development was way behind and in December 1990 EDF cancelled the contract. Westinghouse had supplied a state-of-the-art microprocessor-based system for the Primary Protection System (PPS) and had been working on an ISCO system[22]. In June 1991 they were awarded a contract for their WISCO system. The task involved 2 years of intensive development and much back fitting on the station. The construction programme was maintained.

Priority was given to providing information to, and fostering good relations with, the local community from before work started on site and throughout the construction and operation[36]. The Construction Consultative Committee was established, chaired by the Site Manager, with representatives from the councils, police and community groups. There were also a number of residents' committees. Throughout construction NE published 'Sizewell News' and distributed it to 19,000 local homes to explain all about the station. A Visitors Centre was built that was attracting 50,000 people a year in the mid 1990s. The disruption and annoyance caused by traffic to and from the site was alleviated by the strictly enforced requirement for road traffic to use a designated route to and from the site and not use side roads. The majority of heavy loads including everything from aggregate to the reactor pressure vessel were brought in from the sea via purpose-built beach landing facility.

The Station had been built in the middle of the Suffolk Heritage Coast, a site of special scientific interest. One requirement from the Public Inquiry was that

NE signed a number of 'conditions and undertakings' which ranged from maintaining public access to the beach at all times, reinstating any disrupted sand dunes and obtaining local authority and Royal Fine Art Commission approval for the station's finished look. The architect YRM was commissioned to develop the design which resulted in the sparkling white dome and steel cladding in grey and blue with red detailing, in stark contrast to the drab concrete grey of most PWRs around the world.

Commissioning

A cautious approach to commissioning was adopted as this was a reactor type new to Nuclear Electric and there were also a number of problems encountered with the conventional, non-nuclear side, of the plant which extended the program beyond that planned. Commissioning started in January 1994 with the mandatory hydro test of the primary circuit. Fuel was loaded in September 1994 and first criticality was achieved in January 1995. Power raising began in mid-February and full power was achieved in June 1995[37],[38].

Contractors were responsible for setting to work their equipment and were contractually required to rectify any deficiencies before the commissioning teams took over. Strong interface management and quality assurance throughout the construction program ensured that equipment and systems were checked ready for commissioning. Commissioning was therefore not about finding design or construction faults it was about testing and proving complete systems. Both the commissioning teams and the station operating staff were on site from early on in the construction. Draft procedures were produced early. Commissioning staff supported contractors during setting to work and station staff were responsible for energizing systems during commissioning. This arrangement smoothed the transfer of responsibility from contractor to commissioning staff to the station team. There was an active communication link to the design and safety teams at headquarters so that if a test identified any differences in performance from that expected, this could be reviewed and rectified or accommodated efficiently. This helped to ensure Regulator safety hold points were always cleared before any impact on the critical path.

Operating Rules were replaced by Technical Specifications (Tech Specs) for the operation of SXB. Tech Specs had been developed by Westinghouse for PWR operations at power. The innovation at SXB was to introduce them for start up, shutdown and other operating states in addition to full power. These procedures were those first required for SXB commissioning and some problems were inevitable. This did mean that Tech Spec approval by the Regulator came close to the critical path on occasions.

Great attention was paid to keeping foreign material out of the plant circuits, particularly the material removed during valve seat lapping and to ensuring that circuits were effectively flushed out. This helped reduce radiation fields and hence the dose to operators that results from the activation of these materials during reactor operation. The other major initiative taken to reduce operator dose was to take time to ensure that the primary circuit metal surfaces were effectively passivated and potentially soluble oxide material was removed during hot functional testing[39]. This has had the long term benefit of reducing operator dose throughout station operation[40].

The key interface between the project team and the station operators was managed via the weekly Test and Commissioning Panel which was chaired by the commissioning manager with the joint working groups that reported to it being members.

Lessons Learned

The interviews with key members of the Sizewell B team produced the following list of lessons that are relevant to the new nuclear build today.

- Nuclear power stations are capital intensive and suited to base load operation. Stations can load follow but are not designed for conditions that require frequent or unplanned shutdown or start up. Commitments are very long term with up to 60 years of operating lifetime and up to a further 100 years of responsibility for spent fuel prior to final disposal. Privatisation and the "dash for gas" experience showed that; ***Government commitment to nuclear power and a willingness to recognise its requirements with respect to planning consent, the National Grid, market stability and spent fuel/waste disposal, are essential to attract the necessary private capital investment.***

- ***New stations should be based on the application of proven technology and established design. This must be complemented by a high level of design completion in advance of construction, and the licensing basis for the plant must be secure before commitment to construct.*** It is not possible to produce a fully developed and fully licensed design prior to construction for the first of a kind in any country and 'replica stations' may differ for site-specific reasons. Developments in technology are inevitable and when a station design is first built outside the UK, differences in Regulation and the electricity grid means that comprehensive replication of an overseas design in the UK is not credible. However, design development does involve risk of delay and price escalation and should be resisted. There must be a rigorous, efficient and auditable design change process in place, indeed this is a requirement of the nuclear site licence, and a culture established that recognises that even seemly small changes can have unexpected implications and therefore require formal review.

- The design and safety case development that culminated in the production of the Pre Construction Safety Report and beyond design basis assessment, together with the process for obtaining a Site licence, reduced the uncertainties in the SXB licensing process during the construction phase. The Generic Design Assessment will likewise reduce the uncertainties associated with the licensing of new nuclear station designs in the UK. However there will still have to be a process to debate and resolve outstanding licensing issues throughout the construction and commissioning program for each station built. ***It is essential to establish a program and a process for resolution of licensing issues throughout the build program that is agreed with the regulator and administered to ensure, as far as possible, that such issues are resolved before they approach the construction program critical path.***

- ***Follow-on replica stations are cheaper and take less time to construct than the first-of-a-kind.*** It is inevitable that lessons will be learned and experience gained that can reduce the program time and the cost of a replicated station. Experience has shown that follow-on replica projects can catch up and even overtake the 'lead' project. The interval between the lead and follow-on stations is important as the most effective way of passing on lessons and experience is to transfer people. There are clear industrial relations benefits if skilled construction staff rundown on the lead site is matched by a requirement for a build up of that skill on a follow-on site.

- ***Comprehensive, early and open engagement with the local community in a structured and formally managed way, a good neighbour policy, pays dividends in terms of local support and cooperation.***
- ***Project management arrangements must reflect the allocation of risk between client and constructors - SXB demonstrated that a unified organisational structure works well for such a complex and interactive project; the selection of the right person as project director is crucial; and the management systems, QA, planning, cost control; and information systems must be of high quality. An effective industrial relations approach must be adopted. The project director must have the full backing of the client organization and be given the necessary authority to act.*** Many decisions are taken daily and must be delegated to the appropriate team members. The director can only do this with confidence if he/she has the authority to do so without reference to a committee. It is important that the director is appointed early and is committed to remain until the completion of the project. This helps to build loyalty within the project team, the contractors and the site workforce generally and fosters collaboration.
- ***The contract strategy must reflect the risk being carried by the parties. The contracts must clearly define the scope and responsibilities of contractors, and most importantly, the work must be placed with quality contractors.*** Competitive tendering works well for the procurement of many goods and services but is not a panacea. For some of the more complex and technically challenging tasks which require a range of special skills an arrangement is required which provides for incentives for specialist contractors to collaborate and innovate.
- ***Comprehensive pre-planning and detailed scheduling with designers and support from main contractors, using three dimensional models, prior to start of construction will save time during construction, reduce rework, help avoid disputes between contractors and identify labour and related logistic requirements on site.*** By contractually requiring main contractors to collaborate as a Joint Planning Team to produce integrated schedules it is less likely that there will be interface problems and disputes on the site. If there are problems on site there is an established process for reference back to the design teams.
- Sizewell experience demonstrated the value in comprehensive scale modelling. 3D computer modelling has now largely superseded actual models. ***It is important that these models are accessible to all from designers through to maintenance engineers and radiation protection officers and that the status of the model is controlled and clear to users at all times.***
- ***Contract management must instil a disciplined approach. Contractors should be incentivised to meet agreed milestones.*** The focus on meeting

program milestones should be relentless with daily, weekly and monthly meetings at all levels up to and including director level to ensure problems are identified and addressed early and program dates are met.

- ***Interfaces require active management with a rigorous QA program to ensure that when a hand-over occurs between one contractor and another the job is complete, correct in all respects and ready for that hand over.*** This will help to ensure that errors do not accumulate and when commissioning takes place the activity is about setting to work and checking performance against expectation rather than discovering and rectifying construction and installation errors.

- ***The transfer of responsibility and knowledge from construction teams to commissioning teams and on to the station operations staff can be facilitated by appointing commissioning and station operations teams early and actively encouraging collaboration.*** Making equipment suppliers and installers responsible for setting to work and having commissioning staff as members of their team ensures that the right expertise is made available in a timely way, experience is gained and knowledge transferred. Similarly station staff should be participants of the commissioning process.

- ***Operators should be trained early in the project schedule to ensure smooth commissioning and hand-over from construction to operation.*** This implies the establishment of a simulator, preferably on-site to facilitate easy collaboration between designers and operators on commissioning matters. There are also benefits in this training activity extending beyond the immediate team of operator personnel, to senior station staff, so that all are introduced to operational issues facing the project.

- ***Ensuring that foreign material is prevented from entering the Primary Circuit and taking measures, prior to nuclear power generation, to reduce the circuit material oxides that could circulate through the core, will reduce radiation fields and operator dose that arise from subsequent operation of the plant.*** There have been considerable developments in the understanding of the control of radiation fields since the commissioning of Sizewell B and 'good practice' has been incorporated into Operator Guidelines and Quality Assurance requirements.

4. Lessons Learned from the Installation of Waste Processing Facilities at Sellafield

Reprocessing at Sellafield is supported by three existing evaporator units, to treat the highly radioactive waste liquid produced when spent fuel is dissolved in nitric acid. These units are reaching the end of their life and need to be replaced with one or possibly two new evaporator units and associated equipment. The contract to build a new unit was awarded to COSTAIN Ltd. The project started in April 2007 and the target completion date is July 2013 which is one year ahead of the contract completion date. The plant will operate with non-active materials for about one year to prove all systems prior to active operation. To date the program is on schedule to meet the contract completion date. The Project Director Clive Loosemore, Stuart Campbell, the Project Manager, and Mike Napier the COSTAIN Ltd Strategy and Business Director were interviewed to solicit their views on lessons learned so far.

This is one of the largest current nuclear construction projects in the UK and is typical of the facilities which have helped maintain nuclear skills during the gap in reactor construction. At a contract value of £297M it is perhaps a tenth of the size of a power station but includes very similar and equally complex engineering. The system includes a number of high integrity stainless steel vessels, pipework, control and protection systems, and is to be housed in a heavily reinforced cellular concrete structure adjacent to operational reprocessing plants at Sellafield. The building has to be seismically qualified and withstand other external impact requirements, and is in turn enclosed within a seismically designed steel frame overbuilding. The site is surrounded by buildings containing radioactive material and related equipment so that use of cranes for heavy lifting, that could swing or topple was not an option. The plant was designed to be constructed in large modules that would be transported to the Sellafield site coast by sea, then by road and lifted and skidded in place by a seismically-qualified gantry lift. The largest module which contained the evaporator and 7.5 km of associated pipe-work and other equipment weighs 500 tonne. The modules are fabricated in factory conditions some 120 miles down the coast from the plant, shipped by barge to Sellafield beach, landed at high tide, off loaded at low tide from the beached barge then transported to the construction site by road. This required a temporary bridge to be built to take the total load of 800 tonnes. The gantry straddles the road adjacent to the building allowing the modules to lifted, and if necessary up-ended, and then skidded into the building without any risk to adjacent buildings in the event of a dropped load or gantry collapse.

The project adopted the Front End Loaded (FEL) process originally developed by BNFL, for the design, licensing and preconstruction planning phase. Stage 3 of this process requires the design to have reached a high level of maturity, the safety-related analysis and documentation to be of a high standard and approved by the Regulator, the cost estimate to be credible within 10% of the outturn value and the schedule credibly within

6 to 12 months of eventual outturn. This process took 18 months. It requires constructive interaction between and the eventual approval of the stakeholders, which in this case, included the Government and the Nuclear Decommissioning Authority and the appointment and participation of the main contractors. The design acceptance and safety case require first internal approval and then approval by an independent safety assessment authority, before being presented for acceptance by the NII. The completed process substantially reduces the risks of delays during subsequent construction and provides stakeholders with a level of confidence. A disadvantage of this detailed forward planning and rigorous quality assurance from a construction program perspective is that a significant degree of flexibility is sacrificed. Many relatively minor changes in design detail or construction method, which otherwise would be approved by the project manager, will require formal reference back for regulator and/or stakeholder for approval. There is also an enhanced risk of cost escalation and delays associated with changing a contractor or equipment supplier. The FEL and QA processes are regularly reviewed and where appropriate have been simplified for smaller nuclear projects on the Sellafield Site.

Manufacture of the evaporator presented particular challenges because of the special steel with a restricted range of chromium content to resist attack by nitric acid, and stringent controls on vessel profile and weld quality. The civil structure also presented challenges and demonstrated the need for detailed planning and the value of the 3D computer model in the placement of penetrations and embedments.

Lessons Learned

- The FEL process took a long time but the resulting maturity of the design, the quality of the safety-related documentation and the detailed costing and scheduling have paid dividends in enabling the subsequent program to be met.
- The 3D computer model produced early in the design and construction planning process has been invaluable as a tool for design, planning, operability and safety validation and in explaining the project at all levels in the organization.
- Modular construction has reduced construction times and improved quality.
- The client, main contractor and key subcontractors must develop shared goals and work collaboratively.
- It was evident that initially the several stakeholders and contractors had differing expectations, interpretations of safety and quality requirements and methods of working based on past experience and culture. It was essential to eliminate these differences which took time and patience.
- The project director has to command the support of the stakeholders and have the necessary authority to act and take decisions on a daily basis.
- Scheduling and cost control must be detailed and actively managed.
- The involvement of steel fixers with practical experience of assembling rebar structures, at an early stage in the rebar design, substantially reduced rebar fixing changes on site.

- High quality is essential so that quality assurance programmes must be comprehensive and documentation must be detailed and complete at all stages. It was necessary to appoint more quality inspectors and to undergo quality training programs.
- Shortage of trained and experienced personnel was a problem in a few areas; in addition to quality inspectors there was an acute shortage of pipe stressing engineers.
- Engagement with the local community has been managed via the local authority. Open and detailed explanation of the project and active engagement with the local community has paid dividends in that initial scepticism has been transformed into active support.

5. Lessons learned from the Olkiluoto 3 EPR project

The process of nuclear new build in Finland is currently under way with the construction of a new nuclear power plant at Olkiluoto, the site of two existing reactors, and the investigative digging for a deep geological repository. In addition to this, a further two proposed power plants are currently going through the licensing process with the Finnish government forwarding a positive Decision in Principle (DiP) to parliament for ratification in May 2010[41],[42].

The process of building the Olkiluoto 3 reactor started in June 1998 with the submission of the Environmental Impact Assessment (EIA) to the Finnish Ministry of Trade and Industry for two sites Olkiluoto and Loviisa, by the electricity generation company Teollisuuden Voima Oyj (TVO). Whilst the EIA does not come under the Nuclear Energy Act, it provides useful information that is used to inform the Finnish government when TVO applied for a Decision in Principle (DiP) in November 2000. The DiP is part of Finnish nuclear law and is granted by the government if a new nuclear power plant "is in line with the overall good of society"; there are no safety issues that can be foreseen as assessed by the Radiation and Nuclear Safety Authority (STUK) and the host municipality agrees to the site of the new power plant. A positive DiP was made by the government in January 2002 and was ratified the following May by parliament.

Figure 3: Positioning and installation of the steel containment liner dome on the EPR, Olkiluoto, Finland[43].

Following the final ratification of the DiP, TVO put out a call for bids for a nuclear power plant unit equipped either with a boiling water reactor (BWR) or pressurised water reactor (PWR) with an electricity output of 1000-1600 MW. This call was put out in September 2002 with a March 2003 deadline for tender submission with the aim of selecting plant type and location by the end of 2003. The final location of the new nuclear power plant was selected to be at Olkiluoto in October of the that year with the contract for the plant being signed on the 19th December 2003 with the vendor consortium Framatome ANP (currently Areva NP) – Siemens AG for an EPR 1600 MWe pressurised water reactor, on a turnkey contract. The aim was for the Olkiluoto 3 power station to start commercial operation in 2009.

The next stage of the licensing process prior to the start of construction was to gain a construction licence from the Finnish government, with STUK ensuring that the design of the EPR meets the required safety standards. The construction licence application was submitted in January 2004, with the licence being finally granted February 2005, including several reservations such as "The detailed design of the systems and structures of the new plant unit shall be continued and further specified during the construction phase. STUK has required that TVO submit detailed, system-specific pre-inspection documents to STUK for approval"[44].

Construction

The construction of the Olkiluoto 3 EPR power plant is currently ongoing and, due to delays, the initial target for commercial operation of 2009 has not been realised. TVO now estimates that the start-up of the plant may be postponed beyond June 2012, which is the current schedule confirmed by the supplier[45,46].

Prior to the government granting the Construction Licence, work was started to prepare the site of the new power plant in preparation for the hand over to construction consortium of Areva NP-Siemens AG. The preparation of the site was not within the scope of the turnkey contract with the plant suppliers and, as such, TVO awarded these contracts accordingly. The site preparation started in December 2003 with the aim of completion during 2004. The initial work involved forest logging and construction of the required access roads to the site. The contacts for these were awarded by TVO to UMP Forest for the removal trees in an area of 15 hectares, for the actual site of the reactor construction, and a further 20 hectares to allow for a storage area for excavated rock and soil. The contract for the building of the access road to the construction site was awarded to Jalonen-Yhtiöt. The first of a number of staged contracts for the site excavation was signed on 28th January 2004 with Maanrakennusliike E. Hartikainen Oy and the excavation works starting in mid-February[47,48]. By the end of 2004, the rock excavation and site preparation was almost complete with a total of 500,000 m^3 of rock being removed and approximately 700m of water-cooling tunnels being excavated. The site was handed over, on schedule, to the construction partners Areva NP-Siemens AG on the 1st February 2005[49,50].

Contracts were awarded for the construction of the reactor building, the safeguard buildings and the fuel building to the French company Bouygues Travaux Publics together with several Finnish subcontractors. The turbine plant building construction contract was awarded to the German company Heitkamp GmbH as the main contractor again utilising several Finnish subcontractors. The concrete requirement for the entire construction was supplied by Forssan Betonituote Oy, who set up batching plants in the vicinity of the Olkiluoto 3 construction site. The base slab for the construction was contracted to Hartela Oy[51,52,53,54].

Base slab

The construction work started in June 2005 with the levelling of the rock surface and installation of the reinforcement for the 3m-thick base slab, the pouring of which started later that year. During the course of the base slab construction, a number of non-conformancies, including the variation of the concrete composition and the disappearance of test samples, were detected by TVO and Hartela Oy. These ultimately resulted in Framatome ANP discontinuing the operation of the batching plant on the 24 January 2006. The batch plant restarted on the 30 January 2006 only for it to be discontinued once again on 6th February 2006. Following this, Framatome ANP developed a set of corrective actions for both short- and long-term that were in turn approved by TVO and satisfied the regulator STUK. Once the corrective actions had been implemented and the batching plant was inspected by TVO, FANP and STUK and a report was signed by TVO and FANP with both parties stating that the short term actions had been implemented. STUK had no further comment and as a result the concrete batching plant resumed operation on the 15th March 2006. Due to this and other issues, discussed below, STUK began an investigation into the procedures used in selecting subcontractors, their prerequisites for meeting set requirements and the supervision of their operation. The result of this investigation was published on the 10th July 2006 with the English translation published by STUK on the 1st September of that year[55]. The main conclusions from this report with respect to the construction of the base slab were reported as follows:

"The construction of the base slab was impeded by the following factors:

- *No appointed responsible manager at the site unambiguously in charge of the base slab fabrication, with authority to issue orders that are binding to all parties.*
- *The base slab delivery chain did not share a common perception of the safety significance of the quality of concrete.*
- *In the selection of the concrete supplier, the special quality requirements applied in a nuclear power plant construction were not brought up in the tender invitations, whereas cost factors were strongly emphasised in the selection.*
- *No training was provided to the staff involved in the fabrication of concrete concerning practices in the nuclear field and the safety significance of their own work.*
- *The division of the concrete supply contract resulted in interfaces, the management of which failed.*
- *In quality control, too much trust was placed on the responsible attitude of the parties in the elimination of the detected problems.*
- *Responsibilities were unclear and problems existed in communication with respect to the design of the mix composition, fabrication of concrete and quality assurance.*
- *The problems observed in previous concreting operations did not result in effective corrective actions implemented in time.*

- *The approved composition of concrete and the concreting specifications were not adhered to in concrete fabrication.*
- *Quality related non-conformances connected with the composition of concrete and concreting were not handled without delay and in an open manner.*
- *The handling of quality problems in the base slab concrete has been characterised by a search for guilty parties instead of focusing on developing the practices."*

The testing of 91-day old concrete samples from the base slab indicated that the majority of samples taken fulfilled the specified strength-class requirement, with only one area being slightly below the value of the require strength class. However, further improvements in compressive strength are gained over time and, as a result, it was considered that the base slab would meet the requirements for compressive strength. The durability of the slab was also assessed and whilst it met the required durability with respect to carbonates and chlorides, it failed to meet the requirements for chemically-aggressive substances, as a result of the higher-than-designed water content of the concrete. However, due to the high amount of blast furnace slag used, the chemical resistance was deemed to be very good in practice and, as the slab aged, the strength and density of the slab would increase further which would further improve the chemical resistance. The high proportion of blast furnace slag as a binder in concrete is normally used in extremely-demanding environmental conditions where the risk of concrete corrosion is considerable and to reduce the heat of hydration in thick pours. Nevertheless, TVO announced that an additional layer of concrete would be added to the base slab as a protection against humidity[56,57].

Work continued during the time when the operation of the batching plant was discontinued on the construction of the turbine building by the installation of formwork and reinforcement and in the cooling water pump station with the installation of reinforcement for the topping concrete.

Once the batch mixing plant was once again under operation work progressed to the preparation of the base for the installation of the first section of the steel containment liner.

Steel containment liner

The contract for the design and supply of the steel containment liner was award by FANP to Babcock Noell Nuclear GmbH (BNN) who in turn sub-contracted the manufacture of the liner to Energomontaz-Polnoc Gdynia (EPG); a Polish engineering works.

The reactor building was constructed to ensure the containment is maintained in all possible situations. The containment in the EPR reactor design is based on a cylindrical double-walled construction with the outer wall being a massive, reinforced-concrete structure designed to withstand the significant collisions such as airplane crashes. The inner wall is composed of pre-stressed concrete with an internal steel liner and is designed to remain air tight, even in accidental situations that result in greatly-elevated temperature and pressures. The inner containment will be 60m high and has a diameter of 45 m.

The steel liner is constructed from 6mm-thick structural steel and the plates are welded together to form 30° segments which are then finished by sandblasting and coating. This work was completed in the engineering works and the 30° segments were transported to the port for shipping. Prior to shipping the 30° segments were welded together to form 180° segments that were shipped to the Olkiluoto 3 site. On site, the sections were welded together to form rings which were lowered into position and welded together to form the containment liner, with the entire liner being composed of nine such sections. Prior to the fabrication of the steel liner, EPG was audited by FANP, TVO and STUK with any issues that were raised being addressed before manufacture of the liner was approved to proceed by STUK. After this, quality controllers from FANP and BNN supervised the manufacturing possess in Poland. In addition, TVO undertook weekly quality checks and STUK performed construction inspections on the prefabricated components prior to coating.

During the manufacture of the liner, inspectors from both TVO and STUK noticed excessive root gaps in the welds of the steel plates as opposed to the 2-5 mm root gap specified, this resulted in delays to production at the manufacturing plant until the problem was addressed. Additional problems regarding the root gaps of weld were also detected when the 30° segments were assembled prior to shipping. As a result of this, additional quality tests had to be performed on the welds with the increased root gaps which were then approved by the regulator. Repairs to the liner sections were welded using a non-approved method and, due to this, the welds had to be removed and re-welded using the approved qualified method. The welds between the anchor plates and the steel liner also had to be removed and re-done. Further problems were encountered due to the ongoing design modifications to the liner and the use of non-approved plans. The information about the changed location of holes in the liner did not reach the manufacturer, EPG, before the work started. The construction of the respective parts of the liner was authorised by FANP before the design documents had been approved and the errors in hole locations were detected by TVO control inspectors. The holes were patched using the approved methods and the repair was verified by X-ray.

The final issue reported[58] with respect to the steel containment liner concerned the base section of the liner. This part of the liner had to be as flat as possible to ensure that there are minimal air pockets between the liner and the concrete, once installed, as to avoid corrosion issues. There was a clear deviation from the specification for the waviness of the bottom of the liner. However, once it was filled with water, to mimic the effect of the concrete that would be poured into it once it was in position, it was concluded that the load would flatten the liner base. Nevertheless, a further design change was introduced in order to eliminate the possibility of air pockets. As a result the underside of the liner base had groves milled into it to allow the injection of concrete once it was in position at the Olkiluoto 3.

Once the bottom section of the steel liner was completed it was delivered by sea to the Olkiluoto construction site and installed on the 11th May 2006[59]. Following this, reinforcement was installed and concrete was poured into this section to form a foundation for the reactor pit and subsequent structures. The sequential installation of the steel containment liner, reinforcement and concreting operations continued on the reactor building to form the doubled-walled structure. The last vertical section of the steel liner was installed in March 2009[60]. This was followed by the installation of the polar crane and the fitting of the cover to the equipment hatch in the reactor building. Once these items were installed the final section of the steel liner, a 14m-high dome, was fitted to the reactor building in September 2009. Once the welding was complete, this provided a weather-tight seal to the reactor building that allowed the internal work to proceed[61],[62]. Currently the construction work is continuing with the dome of the reactor being covered by a thin layer of concrete during April 2010 and it is to be followed by a thicker reinforced layer, for which the reinforcement is currently being fitted. Once this second layer of concrete is poured the inner wall of the reactor building will be completed and work will start on the dome of second, much thicker, impact-resistant wall[63].

Figure 4: Reinforcement being fitted to the reactor dome at Olkiluoto 3 (May 2010)[64].

The construction of the turbine building and other buildings, such as the water pump building and the switch gear building, was undertaken alongside the reactor building construction and these have progressed well. Many for these buildings and associated plants are well advanced, for example the turbine building is current entering the commissioning phase of the project with all the large components being installed. The installation of piping and electrical equipment was nearing completion in September 2009[65].

The progress of the installation of the reactor has been reliant on the reactor building construction and now the dome of the reactor building has been fitted, the emphasis of the project is moving toward the installation of the reactor components.

The reactor pressure vessel was manufactured at Japan Steel Works and Mitsubishi Heavy Industries in Japan. The manufacturing began in October 2003. A TVO inspector supervised the work with STUK also performing inspections during the manufacturing. The pressure test of the finished component was carried out successfully in October 2008 and it was shipped to Finland where it arrived at the Olkiluoto 3 site in early January 2009.

The steam generators, pressuriser, reactor coolant lines and coolant pumps were manufactured by Areva in various facilities in France. Manufacture started in 2004 and the four steam generators and pressuriser arrived at the Olkiluoto site in November 2009. During the manufacture of these reactor components there were very few reported issues except for the main coolant lines. TVO reported in December 2006 that the plant supplier had decided to recast a part of the pipe forging[66]. The issue with the original castings was that the grain size of the steel was larger than specified and it was decided to re-manufacture to reach the specified grain size, as required for in-service testing[67]. A further minor issue was also detected by STUK regarding the pre-assembly welding of the coolant lines. They detected micro-cracking of the welds that the manufacturer had not faced previously. However it was shown that grinding and re-welding removed the issue[68],[67].

Lessons Learned

The lessons learned presented here are from the viewpoint of the Finnish Radiation and Nuclear Safety Authority STUK and were presented by J. Laaksonen (STUK Director General) at the 20th International Conference on Structural Mechanics in Reactor Technology[67]. The lessons learned were grouped into several areas as outlined below:

- Changed Nuclear Power Plant Construction Environment:
  - In planning and scheduling a new build, it is necessary to recognize that circumstances are quite different from 1970s when most of the currently operating plants were constructed: Vendors of 1970s had large experienced organizations, incorporating comprehensive in-house capability for design and manufacturing and as a result had less need for subcontractors; there was sufficient skilled manufacturing capacity in the market; designs were often based on work done earlier in similar projects; experienced project managers were available.
  - Vendors have lost much knowledge and skills when experienced experts have retired and new types of competence are needed for new technologies. Thus good reputations earned in the past are no guarantee for success and the experience and competence of persons assigned to the project are more important.
  - Vendors need to establish a subcontractor network from companies with proven skills; awareness of nuclear quality and understanding of nuclear safety culture must be taught to companies that have no previous nuclear experience; management of work conducted by subcontractors is a challenge in its own right.
- Preparation of Project:
  - Early contact between vendors, licensee and regulator.
  - Feasibility studies of several designs in early stage of the project were found to be very useful and facilitated the subsequent licensing process. These involved:
    - Technical discussions between potential vendors, license applicant and regulatory body.
    - Allocation of adequate regulatory resources to the safety assessment of each alternative design.
    - Identification of crucial safety issues before and during the DiP process; these issues were addressed by the licensee and the potential vendors during bidding.
    - Each design proposed in bidding was improved from the original version that was reviewed tentatively during the DiP process.

- Making safety requirements clearly understood:
  - European Utility Requirements were used to present most of the technical requirements to potential bidders, but these did not include all necessary national safety requirements. The licensee and the regulator need to discuss how the national safety requirements are best presented in the call for bids in good time. Just making reference to national requirements and regulatory guides is not adequate to ensure that requirements are correctly understood by vendors.
  - Discussions in preparing for the Olkiluoto 3 project should have been more extensive to better clarify all national safety and quality requirements and the regulatory process to the bidders.
- Understanding of regulatory practices
  - To ensure the smooth progress of the project, the vendor needs to understand and take national regulatory practice seriously. In Finland, regulatory practice is different from what Areva had met elsewhere.
- Preparedness of parties for project implementation
  - In order to avoid delays and difficulties in the project implementation, it is necessary to allocate sufficient time for the planning stage and to assess the preparedness of each party before starting construction. Before starting, each of the parties (vendor, licensee, regulator) should conclude that:
    - licensee's capabilities and resources are adequate,
    - vendor's capabilities and resources are adequate,
    - the design stage is adequate for a controlled construction start and for smooth implementation,
    - qualified subcontractors are available as needed, and plans and contracts exist for managing the subcontractor chains.
- Importance of timely completion of design
  - Inadequate completion of design and engineering work prior to start of construction is detrimental to the implementation of the project as per the schedule,
  - it delays the start of construction activities at full speed,
  - it leads to attempts to reschedule manufacturing and construction steps, thus making project management complicated,
  - it causes continuous time and cost pressures to all organizations involved.

In the Olkiluoto 3 project, it was concluded that the detailed design had been done too late. Consequently, delivery of Construction Plan (CP) to STUK's review has often been delayed relative to the planned schedule. The CP has also been split to many batches; this has made the inspection complicated and time consuming. Fixing the sometimes inadequate quality of design and engineering has caused major difficulties for project management, for example:

- There has been a need to revise and resubmit the initially poor Construction Plans for corrections and reassessment, and this is time consuming,
- Insufficient CP quality has also caused numerous unnecessary comments; this has required extra time in the approval process,
- Several successive document revisions have made subsequent inspections at vendor's premises complicated.

• Management of Subcontractors

- To ensure good management of the subcontractor chains, it is important that in each call for tender for subcontracts the vendor clearly indicates and emphasizes the nuclear specific practices, such as:
    - a requirement to provide design documentation well in advance of planned manufacturing,
    - multiple quality controls and regulatory inspections to be conducted during manufacturing, and
    - expectations of safety culture.

If the nuclear-specific practices are not recognized and understood by the subcontractors at the time of signing the contract, difficulties are to be expected in a later stage. It has been noted that the real competence of manufacturers and subcontractors is not easy to judge through auditing only, and the evaluation of the manufacturer's ability at the shop floor is important. The licensee needs to have means to ascertain that the issues specific to nuclear safety and quality management, and the respective controls, are properly agreed in each contract between the vendor and its subcontractors.

• Communication within the Vendor Consortium

- If design work is conducted by different organisations and in different places (or even in different countries), good coordination and communication is vital for a successful outcome. The licensee and the regulator should audit and carefully assess the communication approach and the adequacy of communication between those designers who are expected to interact during the design process.
- Lack of coordination and communication within the vendor consortium has been a problem area especially in the early stage of the Olkiluoto 3 project and throughout the I&C design process.

• Mastering the Manufacturing Technologies

- New advanced safety features are not easily implemented. Qualification of a new construction or a manufacturing method may take time if it has not been done before the project start. For instance:

- new welding solutions were a challenge during RPV manufacturing, and additional evaluation and some repair welding were needed,
- preassembly welding of main coolant line legs showed microcracking that had not been faced by the manufacturer before (it was demonstrated that the indications can be removed by grinding and re-welding),
- a number of components for Olkiluoto 3 had to be remanufactured to achieve acceptable quality and to ensure a 60 year lifetime such as some main coolant pipe sections and some main circulation pump casings.

- Licensee Responsibility
  - The Licensee is responsible for the safety of its plant when it starts to operate, and therefore it must have strong control of the project also at the turn-key and fixed-price project stage,
  - The respective roles and responsibilities of licensee and vendor need to be specified accordingly, and also for the construction phase. The Licensee should:
    - conduct its own safety assessment to verify that the plant and its SSC's are licensable,
    - have its own requirement management system and an independent capability to verify and prove that all requirements are met, with support of third party where necessary,
    - have a system for reporting and resolving all non-conformances identified in quality controls,
    - have an opportunity to require use of proven, state-of-the-art technology in manufacturing and construction (not only to accept final products that meet minimum agreed quality requirements).
- Safety Culture during construction
  - Strong message and transparent actions and decisions are expected from the management of the vendor and the licensee to promote safety culture: *"safety and quality have higher priority than costs and schedule"*. This needs to be demonstrated for instance in:
    - the choice of qualified subcontractors,
    - state-of-the-art tools and methods,
    - uncompromising compliance with the agreed requirements,
    - walk-downs by management.
  - A questioning attitude is needed on every level and organisation: licensee, vendor and subcontractors.
  - Safety concerns and questions raised by workers need to be responded to properly. Each person attending the project needs to understand the safety significance of his / her work, to promote personal responsibility.

- Importance of Regulatory Oversight of Construction
  - Throughout the project there have been multiple quality controls, carried out by manufacturers themselves, Areva, and independent 3rd parties: TVO and STUK. Therefore the product deviations have generally been detected with high sensitivity. Nevertheless, in some situations the QC inspectors by the manufacturer, vendor, and licensee have faced too much economic pressure, and may not be in a position to enforce stopping of work to making necessary corrections. Even when the work is not progressing as expected in such situations an intervention by a regulatory inspector is needed.
  - A stringent regulatory approach and inspections are thus needed to verify that new manufacturing techniques and new type of equipment meet the specifications set by the designer.
- Construction Schedule
  - The schedule for the Nuclear Island at Olkiluoto 3 is now about three years behind the original plan. The main reasons for the delay are:
    - The original schedule was too ambitious for a plant that is first of its kind and larger than any NPP previously built,
    - Inadequate completion of design and engineering work prior to start of construction,
    - A shortage of experienced designers,
    - A lack of experience of parties in managing a large construction project,
    - A worldwide shortage of qualified equipment manufacturers.
  - The construction of Turbine Island has progressed much better. There is close cooperation between the Turbine Island vendor and an experienced construction company, resulting in good integration of design and construction work.

6. Lessons Learned from Flamanville 3

The French authorities and utilities are involved in a nuclear renaissance program with the view to replacing the country's original fleet of nuclear power plants that will start entering the decommissioning phase in the year 2020[69]. As a result the Flamanville 3 power plant is an EPR reactor that is currently under construction in the Lower Normandy region of France and a second EPR is being authorised at the Penly site in Seine-Maritime. The Flamanville site currently houses two operational PWR reactors (1300MWe each) that became operational in 1986 and 1987.

The board of directors of the utility Électricitê de France (EDF) decided to instigate the process of building a new reactor at the Flamanville site in 2004, with the design contract for the new unit being awarded to Areva NP in September 2005. The public debate for the proposed power plant ran from October 2005 to February 2006 with a favourable opinion being obtained from the Commission Nationale de Débat Public (CNDP) in May 2006. The preparation of the site started in the summer of 2006 with the construction permit being granted in April 2007[70] and the first concrete being poured during December 2007. The original completion date for this project was 2012 at an estimated cost of €3.3 billion[71]. However, this date and estimated cost has been recently revised to 2014 and €5 billion, respectively[72].

Figure 5: Flamanville 3 under construction[73].

The construction of the EPR at Flamanville is conducted under the supervision of the French regulatory body Authorité de Sûreté Nucléaire (ASN) with technical support from the French Institute for Radiation Protection and Nuclear Safety (Institut de Radioprotection et de Sûreté Nucléaire – IRSN). During the supervision and inspection of the construction activities for the EPR at Flamanville a number of issues have been raised by ASN, these are outlined below.

Site layout

Issues were raised by ASN regarding the site layout and, in particular, the consequences of crane failure and the possibility of certain cranes being able to fall on the auxiliary building of the existing reactor Flamanville 2, which is adjacent to the construction site. This was remedied by EDF arranging for the construction of concrete stacks around the cranes in question[74].

Concrete operations

Several issues concerning the concreting operations for Flamanville 3 have been highlighted by the regulator during the course of the build program, the first being the cracking of the concrete block making up the foundation of the nuclear island. This foundation raft was poured in December 2007 and was one of the first concreting operations in the construction program. The cracking phenomenon is frequently observed in large-scale concreting operations and is often due to shrinkage as the concrete hardens. EDF proposed to remedy this problem by injecting pressurised resin into the cracks and, after considering IRSN's opinion, ASN accepted the solution proposed by EDF[74].

During the routine inspections on the 5 March 2008, ASN found that certain rebars for the foundation raft of the future spent fuel storage building were not arranged as indicated in the associated drawings. These non-conformances were remedied before the concrete was poured. Further issues were reported to ASN concerning the rebars in a part of the foundation raft of a building designed to house some of the reactor safeguard systems by EDF in May 2008[74,75].

ASN stated that while these recurrent anomalies have had no negative impact on safety, they point to a lack of rigour from the operator regarding the technical supervision of construction operations, difficulties in monitoring the work of external service providers and organisational shortcomings. Under current conditions, it considers that concrete pouring activities on the site do not guarantee a standard of quality control in compliance with the requirements of a nuclear facility.

As a result of these observations ASN asked EDF to:

- Firstly, to suspend concrete pouring operations on safety-related structures, as announced by Thomas Houdré, the Head of ASN's Caen Division, at the regional press conference held on 27 May 2008,
- Secondly, to analyse the malfunctions observed and the corrective action required. More particularly, the Authority has asked EDF to tighten up not only the technical controls carried out by service providers working on the site, but also its own monitoring activities and discrepancy management procedures.
- However, this suspension did not apply to concrete pouring work on non safety-class structures or on reinforcement operations, which continues[75]. Following this suspension in concrete pouring EDF prepared an action plan to tackle the concerns raised by ASN and the response of the regulator to the action plan was as follows:

“The main points of the plan encompass the concerns expressed by ASN, namely:

- More stringent technical controls by service providers working on the site and closer monitoring by EDF of their activities,

- Closer monitoring of concrete reinforcement operations on safety-related buildings, based on a supplementary technical inspection by a third-party organisation,
- Clearer management of deviations, highlighting in particular those activities concerning reinforcements and those concerning concrete pouring,
- Training all those working on the site with a view to improving individual safety culture,
- Strengthening of the Bouygues quality team.

In ASN's opinion, this action should improve the performance of the quality management system in construction activities."[76]

After a 23-day break in concreting operation ASN allowed it to recommence, with EDF being asked to submit a monthly report on the actual implementation of the plan and to assess its effectiveness after 6 months' application on site. Further inspections by the regulator in December 2008 appraised the effectiveness of the plan and noted an improvement in the quality of performance and more stringent technical inspections of concrete reinforcement work[77].

As the concreting activities on the Flamanville 3 progress three further issues were raised by ASN.

The first was highlighted during an inspection in May 2009 examining the preparatory work for the concreting of the foundation raft for the internal structures of the Reactor Building. The inspectors and their technical support agency alerted EDF that a significant number of tasks still had to be completed before going ahead with the concreting operation. Following this inspection, and after the concreting work had been carried out, ASN found that a number of non-conformance files had been opened. ASN considered that the problems found by EDF and the Contract Holder, notably an insufficient volume of concrete poured in places and modifications to the formwork during concreting operations, do not impact on the safety of the structure. These problems do, however, highlight a major source of pressure related to satisfactory progress on the schedule and that is liable to have a negative impact on the quality of the works. ASN asked EDF to take adequate measures to avoid repeating this type of problem-generating situation[78].

The second issue concerned the treatment of construction joints i.e. the area of contact between two layers of concrete placed at different times. In order to ensure a sufficient degree of adhesion these joints must be prepared to have a minimum level of surface roughness. However, during ASN inspections in August 2009 it was noted that, on several occasions, that there was inadequate levels of surface roughness. In addition to this they also discovered the use of a chemical not specifically designed for the treatment of construction joints. As a result, ASN asked EDF to stop using this product and a comprehensive qualification procedure to be carried out on all the methods used for treating construction joints on the Flamanville 3 site. ASN also asked EDF to analyse the consequences of the use of this chemical in the areas concerned[79].

The third issue concerning concreting operations reported to date by the regulator was the positioning anomalies of pre-stressing sheaths for the reactor building inner containment wall. Before pouring the first concreting lift for the inner containment wall in November 2009, EDF reported to the ASN inspectors that the position of the pre-stressing sheaths within the reinforcements for the Reactor Building inner containment wall were outside required tolerances. After consultation with its design and engineering department EDF decided to leave the sheaths as they were and pour the concrete for this lift. On ASN's request, EDF forwarded a fuller subsequent demonstration proving that this non-compliance with required tolerances was not detrimental. Following this ASN requested that it must be informed of all subsequent concreting lifts for the inner containment wall. This enabled ASN to make spot-checks and check beforehand that EDF has implemented provisions to prevent the repeat of anomalies, and to check subsequently the measurements made after the concrete is poured[80].

Steel Containment Liner

During inspections by ASN in June 2005 it was noted that there were deviations in the welding method for the liner from what was originally specified in the EDF technical specifications. As a result, ASN asked EDF for an impact analysis on the use of a different liner plate welding method and EDF replied by sending a document setting out the technical aspects of the problem and suggested performing additional tests to guarantee weld quality using this method. After reviewing with its technical support organization, IRSN, ASN informed EDF on 28 August 2008 that it had no objection to liner manufacturing continuing under the present conditions, provided the proposed additional tests were performed[81]. However several inspections of liner welds during the last quarter of 2008 revealed:

1. Deviations from liner technical requirements concerning, in particular, the welding methods used, the climatic conditions during welding operations and the welding data package available to welders,

2. Inadequacies in the application of the Order of 10 August 1984 relating to the quality of the design, construction and operation of basic nuclear installations, particularly with respect to the qualification of the liner pre-manufacturing shop on the Flamanville 3 site, monitoring of welding operations and non-destructive testing of welds and, lastly, the quality management system of the company responsible for liner welding.

ASN considered that the high rate of repair on some welds was an indication that liner welding conditions were not adequately controlled and consequently asked EDF to demonstrate that the liner could guarantee containment safety under such conditions and, if necessary, propose additional tests and inspections. In the meantime, ASN asked EDF on 12 December 2008, to suspend any irreversible operations that would be incompatible with additional weld inspections.

On 4 February 2009, following an in-depth examination of the supporting material provided by EDF and after consulting the IRSN, ASN asked EDF to take the following steps[82]:

For welds already completed:

- Provide additional data to that already transmitted, in particular concerning tests to be carried out on welds representative of those found on the site,

- Inspect 100% of certain types of weld. ASN considers that the proposals already submitted by EDF for the other welds will avoid any impact on the liner's containment function.

For future welds:

- Submit an action plan aimed at making a significant improvement to the quality of these welds, with a monthly report on the actual implementation of the plan, and make an assessment of its effectiveness after 6 months' application on site,

- Inspect 100% of welds until a significant improvement in their quality has been confirmed.

The action plan designed to significantly improve the quality of welding was submitted by EDF and the contract holder to ASN on the 15th April 2009. The key points of this action plan involved the optimising the weld process and the conditions in which welding is performed, improving training for welders and stricter monitoring on weld operations. This action plan was provisionally approved by ASN but would be reviewed once sufficient feedback was obtained. Pending the assessment of how effective the action plan was, radiographic tests were performed on 100% of the welds already done. In July 2009, EDF submitted evidence to ASN of controls performed on weld operations. The results of the radiographic shots performed over a period of one month of welding mainly showed acceptable repair rates (less than 10%). On this basis, EDF has decided to suspend radiographic tests, while maintaining closer monitoring over weld operations[83].

On 23 June 2010, EDF informed ASN of an increase in the number of faults detected in a weld in the liner. Amid recurrent concerns over the issue, ASN inspectors paid a visit on 7 July 2010 to validate measures implemented by EDF to improve weld quality. During this visit, ASN inspectors observed that the ergonomics of the welding position of the horizontal weld in question was the primary cause of the new problems. They also observed that radiographic testing was not performed as welding work advanced: the delay in performing an inspection prevented quick detection of inferior weld quality. On the day of the inspection, EDF had already temporarily suspended new welding activity, reminded those concerned of the 2009 action plan and begun radiographic testing of all questionable welding. Repairs of areas showing faults were then completed.

Welding difficulties caused by the ergonomics of the welder's post had already been identified as one of the main causes of the 2008-2009 events. ASN also determined that EDF's treatment of the anomalies detected in 2008 and 2009 was not performed correctly and requested that EDF apply this operating feedback to all welding activities at the site.

ASN however took steps to emphasize EDF's proactive response in implementing preventive measures following detection of the deviation in June 2010[84].

Sea Outfall Tunnel

Soletanche Bachy France (SBF) was contracted by EDF to construct the underground water cooling outlet works consisting of 160m deep x 5m diameter land shaft, 63m deep x 5.85m diameter marine shaft and interconnecting tunnel. Fugro Seacore Ltd (FSCL) was sub-contracted by SBF to construct the marine element, consisting of drilled shaft, installation of 300t internal steel liner and 450t top r/c diffuser. The installation of the diffuser was completed in June 2009[85].

However, technical difficulties were reported to ASN by EDF in the last quarter of 2008. The issues were resolved by an alteration in the path of the sea outfall tunnel and a change to a new tunnel digging technique i.e. using a tunnel-boring machine. Given the proximity of the existing Flamanville 2 reactor, ASN asked EDF to check the analysis of safety risks for this reactor (for example the possible impact of mine blasting operations and vibrations induced by the excavation work, and checking that the mass of rock does not suffer any deformation, etc.)[86,82].

Intermediate cooling system

Following inspections in July 2008 by ASN on the intermediate cooling system for the safety-related equipment of the new reactor EDF carried out some additional investigations that resulted in the scrapping of certain pipes that were not up to production standards. After this activity the pipes in question were deemed to be acceptable by ASN and that EDF had taken adequate steps to ensure the safety of the system[82].

Reactor components

ASN conducted numerous inspections in the second half of 2009 during the manufacturing of the components for the nuclear pressure equipment at AREVA NP site and those of its suppliers and subcontractors. Where deviations were observed, ASN ensured that suitable corrective action was taken for each case.

One issue that was raised by AREVA NP concerned the manufacture of one of the one of the steam generator components which was found to be defective. At the end of 2009, ASN reached a decision on the corrective action proposed by AREVA NP. Based on the results of the requested tests and completed inspections, it was decided to accept the AREVA NP proposal to replace the defective component by another which had already been manufactured, but did not present exactly the same characteristics.

During its review inspection of AREVA NP nuclear pressure equipment manufacturing activities, ASN observed that key production quality assurance procedures were satisfactory, but noted that the various tasks of those responsible for quality needed to be made clearer. ASN asked AREVA NP to make improvements in decision-making procedures and supplier approval and monitoring, and to move forward in the area of regulatory documentation[79].

Instrumentation and Control systems

ASN along with the UK nuclear safety regulator (HSE's ND) and the Finnish nuclear regulator (STUK) have all raised concerns regarding the instrumentation and control systems for the EPR reactor as outlined in the joint statement from these bodies issued on the 2nd November 2009. The joint statement is as follows[87]:

"1. The UK nuclear safety regulator (HSE's ND), the French nuclear regulator (ASN), and the Finnish nuclear regulator (STUK) are currently working to assess the EPR Pressurised Water Reactor.

2. In carrying out individual assessments, we have all raised issues regarding the EPR Control and Instrumentation (C&I) systems, which the proposed licensees and/or the manufacturer (AREVA) are in the process of addressing.

3. Although the EPR design being developed for each country varies slightly, the issues we raised with the current C&I system are broadly similar, our aim being to collectively obtain the highest levels of safety from the EPR.

4. The issue is primarily around ensuring the adequacy of the safety systems (those used to maintain control of the plant if it goes outside normal conditions), and their independence from the control systems (those used to operate the plant under normal conditions).

5. Independence is important because, if a safety system provides protection against the failure of a control system, then they should not fail together. The EPR design, as originally proposed by the licensees and the manufacturer, AREVA, doesn't comply with the independence principle, as there is a very high degree of complex interconnectivity between the control and safety systems.

6. As a consequence of this, the UK nuclear safety regulator (HSE's ND), the French nuclear regulator (ASN), and the Finnish nuclear regulator (STUK) have asked the licensee and manufacturer to make improvements to the initial EPR design. The licensees, and AREVA, have agreed to make architectural changes to the initial EPR design which will be reviewed by the regulators.

7. It is for the licensees and the manufacturer, AREVA, to respond to its regulator's issues. However, as designs are similar, it is likely that the solution will be similar, although not necessarily identical, taking into account individual licensees' requirements and national regulatory requirements or practises. As an example, in providing defence-in-depth, different solutions could be proposed to back-up safety systems. In all cases, however, the solutions will lead to equivalent high levels of safety.

8. This is a good example of how independent regulators working closely together can promote a shared understanding and application of existing international standards, and promote the harmonisation of regulatory standards and the build of reactor designs with the highest levels of safety."

The development of the instrument and control system is still ongoing and on 24th August 2010 ASN issued the following Information notice[88]:

"In order to improve the robustness of the instrumentation and control (I&C) system of the EPR reactor, ASN asked EDF to modify one of the reactor's control platforms. EDF had already considered this modification towards the end of 2009 in response to ASN's request on 15 October 2009.

On 15 October 2009 ASN had infact pointed out to EDF that the safety of an item of equipment in the I&C system of the Flamanville 3 EPR reactor

(SPPA T2000 platform) was not demonstrated and had particularly asked EDF to provide additional information and to examine different design options.

Since then EDF has worked hard to comply with ASN's requests. Its initial response and additional information were sent to ASN at the end of 2009 and subsequently.

The I&C system (see diagram) of the Flamanville 3 EPR comprises two associated platforms:

- *the Téléperm XS platform, specifically developed for the nuclear industry and designed to protect the reactor during incidents or accidents;*
- *the SPPA T2000 platform, of 'conventional industrial' origin, used for functions associated with normal reactor operation and for some functions designed to protect the reactor during incidents or accidents.*

Once ASN and its technical support agency IRSN had examined the initial information provided by EDF, ASN concluded in a letter to EDF dated 9 July 2010 that the ability of the SPPA T2000 platform to accommodate certain reactor protection functions still had to be demonstrated. ASN therefore asked EDF to modify the SPPA T2000 platform in order to improve its robustness and enable it to be used for EPR-type reactors. This modification involves duplicating on the Téléperm XS platform some reactor protection functions accommodated by the SPPA T2000 platform.

To enable ASN to complete its examination of the documentation on the I&C system, EDF must submit detailed information about this design improvement and its impact on demonstrating reactor safety to ASN before the end of 2010."

7. Lessons Learned for Taishan Units 1 and 2

In November 2007, AREVA and CGNPC signed an €8 billion contract for the delivery of two EPR units and fuel supply for 15 years in mainland China, which will be Taishan Units 1 and 2. In August 2008 EDF finalised an agreement with China Guangdong Nuclear Power Holding Company (CGNPC) to construct and operate the two nuclear power plants. They formed Guangdong Taishan Nuclear Power Joint Venture Company Limited (TNPC) that will own and operate the two EPR reactors at Taishan in Guangdong province. EDF has a 30% stake in the company for 50 years (the maximum permitted for a joint venture in China). The first unit is scheduled for commissioning at the end of 2013 and the second in 2015.

In October 2008 AREVA and CGNPC established an engineering joint venture as a technology-transfer vehicle for development of EPR and other PWR plants in China and later aboard. The AREVA stake in the joint venture is 45%. It will engineer and procure equipment for both the EPR and the CPR-1000 (CPR-1000 is based on the French-derived three-loop units). AREVA are building the nuclear islands for the Taishan plants.

CGNPC authorised construction of Taishan Unit 1 in July 2008 and first concrete was poured on 28th October 2009. The official inauguration ceremony took place on 21st December 2009. Construction of the second unit started in April 2010. AREVA will fabricate the major components for both units. The Arabelle steam turbines and the 1750 MWe generators are being purchased separately from Alstom and Dongfang Electric Co.

CGNPC and the French nuclear industry have had a long association. The two Daya Bay reactors in Guangdong province are based on a standard three-loop French PWR supplied by Framatome, with GEC-Alstom turbines. EDF managed the construction with the participation of Chinese engineers, starting in August 1987. The two units achieved commercial operation in February and May of 1994. The Lingao phase 1 reactors are virtually replicas of Daya Bay. Construction started in May 1997 and Lingao 1 started up in February 2002. Lingao 2 entered commercial operation in January 2003. These two reactors use French technology now supplied by AREVA with some 30% of Chinese technology and are designated as CPR1000.

The reference design for the Taishan EPR is the Flamanville 3 plant currently under construction in France. The EPR design is a derivative of the Framatome N4 and the Siemens Konvoy designs. EdF have taken the lead in the licensing process with the Chinese regulatory authorities and the process continues to benefit from the licensing process for this reactor in Europe (both in Finland and France) and experience gained from Daya Bay and Lingao.

Early phases of construction have also benefited from European experience. Indeed, AREVA has gathered and analysed more than 1,000 lessons learned from its ongoing projects, most of them coming from Finland, and has been able to leverage these lessons by utilisation of experienced staff. For example, in the case of Taishan, the following have already participated in either Olkiluoto 3 or the Flamanville 3 projects:

- 50% Management Directors & Managers,
- 50% Engineering staff,
- 90% Procurement workforce.

The base mat concrete pour was successfully completed in a single pour on Unit 1, halving the time from two months to one month in comparison with Flamanville 3 and Olkiluoto 3. Moreover, initial pouring was done in 68 hours for Taishan 2 as compared to more than 80 for Taishan 1, showing that improvement is continuous across these plant developments.

Of note is that construction is not the only part of project delivery that sees improved performance since engineering for the electro-mechanical scope of the Nuclear Steam Supply System has seen its productivity increased by a factor of 4 between Olkiluoto 3 and the Taishan projects.

Figure 8: The EPR site in China: Taishan 1(left) and Taishan 2 (right) in July 2010

8. Lessons Learned from the Sanmen and Haiyang AP1000 projects

Four Westinghouse AP1000 PWRs are being built in China, two in Sanmen, Zhejiang Province, and two in Haiyang, Shandong Province. The first of these is planned for operation in 2013. Ten more AP1000s are planned; three pairs at in-land sites, Dafan, Pengze and Tachuajiag; and two pairs at the existing costal sites. China plans to achieve 80GWe of nuclear generation by 2020 and more beyond.

Figure 6: First Concrete at Sanmen Unit 1 March 2009.

Following the TMI 2 accident Westinghouse together with other nuclear power plant suppliers and the Electric Power Research Institute (EPRI) initiated the United States Advanced Light Water Reactor (ALWR) programme. The objective of this programme was to design new plant with levels of safety significantly greater than earlier designs by building on the lessons learned from the previous thirty years of operating experience. For Westinghouse this culminated in the AP600 design, an advanced and passively safe PWR with a nominal output of 600 MW. The design intent was to provide greater protection against external hazards, improved containment, less reliance on external power supplies by use of passive systems and greater reliability and reduced cost by greatly simplifying the whole system. It was intended to be the safest, simplest, least expensive nuclear plant on the world market however the projected price per unit of electricity generated was not competitive in the US compared to natural gas fired plants.

To reduce the price per kWhr to be competitive with gas the output of the plant had to be increased to 1000MWe resulting in the AP 1000 which was based closely on the AP600 design. The nuclear island footprint was maintained by increasing the height of the reactor pressure vessel and the containment structure, while maintaining their diameters, thereby avoiding the need to repeat most of the structural and seismic analysis[89]. The design incorporates many lessons learned; components with a good operation record have been incorporated, such as core internals, control rod drive mechanisms and fuel and components with a poor record such as the steam generators have been developed based on the lessons from the previous problems with this component. Materials of construction have been selected on the basis of experience in operation, for example Inconel

600 has been eliminated. The digital instrumentation and control systems used have been back-fitted into operation plant which provides evidence and practical experience and extensive computer software verification and validation.

Figure 7: Reactor Coolant Pump Casing Shipping from Sheffield Forgemasters (UK)

The AP1000 design has a smaller number of safety components and has adopted a fundamentally modular approach with the objectives of reducing construction and fabrication quality risks, optimizing plant construction time and reducing overall schedule and cost risks. The design has received Design Certification from the U.S. Nuclear Regulatory Commission (NRC). The Westinghouse modular approach builds on the experience of General Dynamics Electric Boat for the construction of nuclear-powered submarines, Hitachi-GE Nuclear Energy and Mitsubishi Heavy Industries. The EPRI have produced a report, (restricted to EPRI members), *Modularization of Equipment for New Nuclear Applications – Benchmarking (1019213)* which details the types of modules each company makes, the test procedures used, and how to protect them in transit[90]. Modularization has the potential to dramatically reduce construction programmes by allowing work in parallel and improving quality by enabling more factory build and validation in controlled conditions rather than on site inspection. It is possible that it could also lead to changes in the safety arguments but this aspect will be part of the NII's Generic Design Assessment and there will surely be lessons learned during that process as well as from the construction of the AP1000 in the US and in the Far East.

Sanmen Unit I is being built by China's State Nuclear Power Technology Corporation (SNPTC), Sanmen Nuclear Power Company, the main civil contractor is the China Nuclear Industry Fifth Construction Corporation (CNF) and the Shaw Group are contracted to provide engineering, procurement, commissioning, information management and project management services. The Construction Permit was issued on 26th March 2009 following submission by Westinghouse of the preliminary Safety Analysis report (PSAR) and first permanent concrete was achieved on 31st March 2009. The Chinese companies have built fabrication facilities at Haiyang capable of producing modules and containment vessel sections for 4 AP1000s per year. The containment vessel bottom head was successfully set on 21st December 2009. The operation took just over 3 hours to complete. The second containment vessel (CV2) ring was set on the 2nd June 2010. The schedule date for this was set in 2007 at 31st May 2010.

Haiyang Unit 1 was issued a construction permit on 23rd September 2009 and first permanent concrete was completed on 26th September 2009. The

Sanmen Unit 2 basemat was successfully completed on 17th December 2009. This activity involved pouring 5,156 cubic metres of concrete within 42 hours.

The First-of-a-Kind activities for Sanmen 1 and AP 1000 equipment design and manufacture have produced a number of lessons learned which have benefited the follow-on units, for example[91];

- The nuclear island basemat at Haiyang 1 and Sanmen 2 were laid in less time than at Sanmen 1.
- The ultra large steam generator and reactor pressure vessel forging lead times were reduced for the 3rd and 4th units.
- The auxiliary building module fabrication for Haiyang 1 took far less time to build that for Sanmen 1.
- The containment vessel bottom head welding at Haiyang was performed in a fully-enclosed building.

The general lessons have been similar to those from Sizewell B and other large nuclear projects.

- Design must be mature.
- Safety documentation must be of high quality and a comprehensive understanding of the safety case and any outstanding issues must have been reached with the Regulators prior to start of construction.
- Partner Organizations and main contractors must have shared goals and work collaboratively together.
- Schedules must be detailed and actively managed.
- Quality is paramount so subcontractors need to be experienced and Quality Assurance arrangements must be comprehensive and robust.
- The modular construction of mechanical/electrical systems is well established and the use of civil/mechanical/electrical modules has been demonstrated to save construction time and improve quality, by having module fabrication and testing carried out off-site in more carefully controlled conditions. This also allows work on many different parts of the plant to be carried out in parallel.
- In circumstances where the modular approach requires novel construction or manufacturing techniques to be used, there may be a requirement to do additional work with the regulatory authorities in order to demonstrate full compliance with accepted regulatory standards.

9. Discussion

The proposed resumption of a programme to build nuclear reactors in the UK poses issues of the long-term consequences of nuclear power. These issues include the uncertainties concerning waste disposal, the long-term storage of spent fuel and waste at each power station site, the long term potential threat to nuclear sites from climate change, the threat posed from terrorist attack (post the New York World Trade Centre attacks of 11 September 2001), and the question of who pays in the event of a major nuclear accident (the BP issue). There are also some design specific issues such as the use of high burn-up fuels and the adoption of designs accepted in other countries which may have different standards of safety compared with the UK. Whilst outside the specific remit of this study, these issues pose important questions for Government as they mirror the concerns of the general public. This does however illustrate why any decision to generate electricity from nuclear power cannot be made without Governmental involvement and public acceptance.

Lessons learned in this report have been identified from a literature search and interviews with a several key managers who are or were working on the projects discussed. The authors of this report are very conscious that the victors write the history'. Not all the key stakeholders in these projects are willing or able, for commercial or cultural reasons, to publish their analysis of lessons learned. The sources of information are therefore not comprehensive and do not provide a balanced perspective on the circumstances that lead up to, or reasons for, the generation of a lesson on a particular project or necessarily identify all the lessons. This report is concerned with identifying lessons that are relevant to new nuclear build and not about reaching judgements about why they arose on a particular project.

Although the current discussion has been limited to recent PWR projects in the UK, mainland Europe, China and the new evaporator project at Sellafield, there are nonetheless some striking similarities the arise from this analysis. In particular, the long history of civil nuclear infrastructure design and development throughout the world has resulted in a global network of commercial designers and constructors that, in the main, deliver excellent quality to exacting standards. All of the examples studied in this report provide examples of these successes. Conversely, where there have been difficulties, unforeseen challenges and delays to programme schedules, these are often the result of common factors.

These common factors have arisen in the research across most if not all of the examples studied here. For example, the essential reliance on the 'application of proven technology and established design' is a feature that has been debated in the context of both SXB and Olkiluoto 3; the need for a 'efficient and auditable design change process in place' is relevant to both the Sellafield evaporator and Olkiluoto 3, essentially paraphrasing elements of the FEL process; and licensing issues feature significantly in all of the projects, from both the perspectives of successful resolution of concerns and the difficulties that arise otherwise; issues associated with C&I (microprocessor system dependability), mass construction activities (huge volumes of concrete with complex rebar systems to meet challenging environmental, seismic and impact specifications) and innovative use of modular construction methods are common areas for issues to arise across these projects.

Follow-on replica stations will benefit from the lessons learned from the construction of a first-of-class design in any country and so are cheaper and quicker to build. Knowing that more than one station will be built will provide confidence and encourage subcontractors to invest in manufacturing facilities and nuclear skills training. This and the statements that the design should be mature and licensing issues resolved prior to construction may appear to be obvious but complying with them for nuclear build is not so simple. The lesson from the privatisation of the UK electricity supply industry is that the fact that follow-on stations will be cheaper is not enough to get the necessary investment. There was no doubt that Hinkley C would have been cheaper that SXB, the planning consents were in place, the licensing position was clear, subcontractors had made the investment in facilities and skills and British Energy had the necessary management and engineering skills, but the deregulation of the market resulted in base load stations burning gas and the project being terminated.

The investment needed to secure a mature and licensed design and make a commit to building a fleet of stations is vast. For the private sector to invest such sums there must be a significant degree of certainty about planning consents, grid requirements, electricity supply market stability and the disposal of spent fuel and waste over the six decades or more that these stations will supply electricity. Investment on this scale has to be viewed in the international context; why invest in low-cost, low-carbon electricity supply in the UK rather than elsewhere in the world? EDF have proposed a fleet of four stations which would be a very substantial investment but it is modest compared with the number of nuclear station China is proposing to build. This confidence, stability and reason for favouring the UK can only come from a Government commitment. The UK Government have made progress with the identification of suitable sites, proposals to simply the planning consents process, and the instigation of the Generic Design Assessment (GDA) process which will clarify the nuclear Regulatory position. However UK utilities are under no obligation to provide security of supply or low-cost, low-carbon electricity. Will the prospect of higher gas prices in future be enough to encourage this level of investment in nuclear power? Does the Government need to do more to ensure investors select low carbon options for future electricity generation?

There are other common and perhaps obvious lessons, for example, the benefits of using detailed computer modelling to aid design and construction and linking these with project management and documentation control systems. In the nuclear area there will be security and confidentiality issues which must be considered and would preclude web-based information sharing systems. It is important to ensure that the investment in the modelling technology matches the complexity of the design and construction that is to be undertaken. Inadequacies in the computer-based modeling technology early on were a contributor to the considerable delay and cost escalation on the Astute nuclear submarine programme[92],[93].

The lessons learned that relate to procurement, project management and commissioning will be familiar to anyone who has been involved in a large, complex engineering project and they will know that achieving ideal arrangements where all these lessons are applied is never that simple. Each project will throw up a unique set of circumstances that require taking commercial risks in the hope of saving time and money. It is important

Photo supplied courtesy of British Energy.

that these risks are acknowledged, communicated to key stakeholders and contingencies are put in place. An example from SXB was the procurement of the pressure vessel. It had to be ordered early if a sensible program was to be met and this was well ahead of the date when the issues of critical crack size raised by Sir Alan Cottrell could be answered to the satisfaction of the Regulator. There was thus a real risk that the 'incredibility of failure' safety case could not be made for the vessel as ordered. To make clear to all that the vessel may not be used for SXB it was called a 'research vessel' until the safety case could be established. Each project will have to take commercial risks related to the circumstances at the time. In order to identify and track the progress of these risks and ensure both adequate contingency and that contingency made against a particular risk is only released in the event that that risk is realized, projects should maintain a 'risk register' that is regularly reviewed at senior levels in the organization.

New nuclear build in the UK will present a unique set of circumstances which are very different from those that generated lessons in Finland, France and China. For the EPR 1600 design at least one of the operators and licensees will be EDF incorporating the skills and experience of British Energy so the skills and experience to evaluate the design, meet all regulatory requirements and incorporate lessons from operating experience will be in place. The basis of the nuclear design is an evolution from the Framatome N4 and the Seimens Convoy plants so by the time the Generic Design Assessment is complete the nuclear design will be mature and the licensing issues should be resolved subject to satisfactory progress through construction. Concerns have been expressed by operators, through organizations such as WANO that lessons learned in the first year or so of operation are not picked up by the designers. In the UK these lessons should be picked up by the utilities and fed back to the designers of the EPR and AP1000 during the GDA process. There will be ongoing detail design development, the need for validation of certain safety case issues and safety case issues which cannot be presented to the Regulators until the station is virtually ready to receive fuel for the first time. It will therefore be important for the licensee to establish procedures and a working relationship that enable regulatory issues to be resolved ahead of the construction program critical path. The AP1000 has yet to be selected by a UK operator/licensee however that Company will have considerable nuclear operating experience and the design and its safety case will have been scrutinized via the GDA. If approval is given the design will also qualify as 'mature' and have Regulatory permission to start construction. The outstanding issues will be different from the EPR and the need for an ongoing procedure and working relationship with the Regulators will be as important.

The Government has pledged to simplify and rationalize the planning consents process. This will mean that issues which relate to national policy and the generic designs and their safety cases will not be reopened for each individual site but local issues will be as pertinent as ever. The lessons relating to local site liaison, the importance of controlling heavy road traffic, the advantages of delivery of heavy or bulky loads via the beach, the infra structure provision for the influx of the site workforce, the preservation, restoration of wildlife habitat and the need for effective communication between the project and the local community are as relevant as ever. At some of the identified locations, such as Wylfa, the local population may welcome the continuity of employment that the new stations will provide but at others the concerns over dislocation in the community during construction make alternative futures for the area appear more attractive. The new proposals are for multiple reactor sites; this will mean a longer period of construction at the site. Is it time to look again at the question of specific compensation for this period of dislocation as has been the case with construction of nuclear stations in France?

The owner/licensees for these proposed new stations are very large organizations with a wide range of interests and priorities. It will be essential that the project teams are staffed with high calibre managerial and engineering staff dedicated to the project objective and that the team head has the authority to act on all matters concerned with the project and can expect support from the wider organization when necessary. Brian George was 'Mr Sizewell' and Murray Easton was 'Mr ASUTE': who will be 'Ms or Mr Hinkley C', 'Mr Sizewell C' and 'Mr Wylfa B'? There will be a particular need to consider the implications of a multi-station program and the need for special skills development and succession planning that will be required.

It is equally important that the facilities and management infra structure is built up in the vendor and key contractor organizations. The lessons from Olkiluoto and Sanmen are important here and will not have been lost on the owner/licensee and vendor organizations or the Regulators. For nuclear build, where the range of specialist skills is large and in some cases in short supply it is appropriate to emphasize the need to promote and nurture a collaborative approach between key contractors were risks and rewards are shared and the project success is a shared objective. For nuclear projects as for other complex engineering build programs, where component integrity and system performance is critical to the implementation of the safety case, the importance of quality control and quality assurance throughout the whole supply chain cannot be over emphasized.

Interestingly, as a result of considering projects that span the last 30 years of civil nuclear plant design and implementation the effects of changes in the global nuclear business are also now becoming apparent in the experiences of projects across this era. Whilst this period of time coincides with the advent of the only PWR in the UK, and is therefore critical to this report, it also represents the longest period of decline in the civil nuclear business in the west. Meanwhile, elsewhere in the world, and predominantly in the Far East, China and India, significant expansion of the civil nuclear sector has occurred. This has resulted, at least in part, in the distinction between lessons learned we observe from the SXB story and the lessons derived to date from the Olkiluoto 3 development, in particular. For example, recommendations from earlier projects such as SXB tend not to elude to tensions in expertise, competence, quality and culture but rather to the beneficial effects that appropriate resource in these areas had on these programmes. In later programmes, and especially Olkiluoto 3 explicitly for the reason that it is amongst the only example of its type thus far, a new realm of lessons has become apparent associated with:

- The influence of shortages in expertise and skills in specific areas, and amongst subcontractor groups,
- The requirement for new competences amongst individuals and subcontractors,

- The requirement to 'teach' aspects of nuclear quality and safety culture to subcontractors that are on a nuclear project for the first time,
- Anticipating and absorbing the implications of the variation in regulator practice across national boundaries,
- The implications of new approaches used on nuclear construction for the first time, such as new welding methods, and making allowance for learning of such approaches.
- Select manufacturers and subcontractors on the basis of quality rather than price.

10. Conclusions

The nuclear projects reviewed have identified similar lessons which will be no surprise to those who have worked on large technologically-complex projects. The most obvious lessons are:

1. Follow-on replica stations are cheaper than first-of-a-kind.
2. The design must be mature and licensing issues resolved prior to start of construction.
3. Establish a highly-qualified team to develop the design, secure the safety case, plan the procurement and build schedule in detail in collaboration with main contractors.
4. Ensure that sub contractors are of high quality and experienced in nuclear construction or are taught the necessary special skills and requirements for quality, traceability and documentation.
5. Establish and maintain good communications with the community local to the site.

To implement or benefit from these lessons a very large investment is required a decade or more before there is any prospect of revenue.

Legislation, Regulation and Planning Consents

Nuclear power stations are capital intensive and suited to base load operation. Stations can load follow but are not designed for conditions that require frequent or unplanned shutdown or start up. Commitments are very long term with up to 60 years of operating lifetime and up to a further 100 years of responsibility for spent fuel prior to final disposal. Privatisation and the "dash for gas" experience showed that; ***Government commitment to nuclear power and a willingness to recognise its requirements with respect to planning consent, the National Grid, market stability and spent fuel/waste disposal, are essential to attract the necessary private capital investment.***

New stations should be based on the application of proven technology and established design. This must be complemented by a high level of design completion in advance of construction, and the licensing basis for the plant must be secure before commitment to construct. It is essential to talk to the regulators early and often. The UK Generic Design Assessment Process should achieve this objective.

A design must be mature for it to be accepted as licensable by the NII but there will be details about the method of fabrication and construction and outstanding licensing issues that cannot be resolved prior to construction for the first of a kind in any country and 'replica stations' may differ for site-specific reasons. Developments in technology are inevitable and when a station design is first built outside the UK, differences in Regulation and the electricity grid means that comprehensive replication of an overseas design in the UK is not credible. However, design development does involve risk of delay and price escalation and should be resisted. ***There must be a rigorous, efficient and auditable design change process in place, indeed this is a requirement of the nuclear site licence, and a culture established that recognises that even seemly small changes can have unexpected implications and therefore require formal review.***

In the case of new nuclear build in the UK, both the licensee and the vendor are very likely to be from overseas and will be required to adopt the UK safety licensing regime. This is likely to be a key challenge in that the licensee needs to both 'own' the safety case and be the 'intelligent customer'. ***It is essential to establish a program and a process for resolution of licensing issues throughout the build program that is agreed with the regulator and administered to ensure, as far as possible, that such issues are resolved before they approach the construction program critical path.***

Comprehensive, early and open engagement with the local community in a structured and formally managed way; 'a good neighbour policy'; pays dividends in terms of local support and cooperation.

Design, Planning and Procurement

Follow-on replica stations are cheaper and take less time to construct than the first-of-a-kind. It is inevitable that lessons will be learned and experience gained that can reduce the program time and the cost of a replicated station. Experience has shown that follow-on replica projects can catch up and even overtake the 'lead' project. The interval between the lead and follow-on stations is important as the most effective way of passing on lessons and experience is to transfer people. There are clear industrial relations benefits if skilled construction staff rundown on the lead site is matched by a requirement for a build up of that skill on a follow-on site. The projects currently ongoing in mainland China indicate how significant improvements can be made in going from first-of-a-kind to a follow-on station.

The Project Team should have a clear identity and be located in one place in addition to the site. This concentration of skills, short direct lines for communication and decision making, and the elimination of traditionally difficult interfaces was a major contributor to the success of the SXB project. ***Active interface management and rigorous quality assurance are essential throughout the design process and must seamlessly integrate with the manufacturing and construction management and QA processes.***

3D modelling is an essential tool, for example, to route piping and cabling; identify access requirements and locate embedments and size holes in walls so they could be in place well ahead of piping and cabling installation. It is important that these models are accessible to all from designers through to maintenance engineers and radiation protection advisors and that the status of the model is controlled and clear to users at all times. Computer models have almost completely replaced physical scale models. It is essential that such models are capable of reproducing and processing the complexity of the design detail. All services must be included. Such complex computer models are not so readily understood or easy to visualise as physical models by the non-engineering staff. There may still be a place for physical models.

A project data base should be established coupled with a robust information system to provide access to a common set of information from the start. The quality assurance programme and associated procedures should be established to covering the design as well as manufacture and construction. This assurance of quality and traceability throughout the design, manufacture and construction process is an essential element in meeting the stringent safety and licensing requirements. The need for nuclear security may preclude the use of web-based information systems.

Project management arrangements must reflect the allocation of risk between client and constructors. A unified organisational structure works well for such a complex and interactive project; the right person must be selected as project director; and the management systems, QA, planning, cost control; and information systems must be of high quality. It is essential that the quality requirements for nuclear facilities are fully appreciated by all the organisations and individuals in the supply chain. An effective industrial relations approach must be adopted. The project director must have the full backing of the client organization and be given the necessary authority to act. Many decisions are taken daily and must be delegated to the appropriate team members. The director can only do this with confidence if he/she has the authority to do so without reference to a committee. ***It is important that the director is appointed early and is committed to remain until the completion of the project.*** This helps to build loyalty within the project team, the contractors and the site workforce generally and fosters collaboration.

The project should maintain a risk register that can be directly related to the contingency provision.

The contract strategy must reflect the risk being carried by the parties. The contracts must clearly define the scope and responsibilities of contractors, and most importantly, the work must be placed with quality contractors. Competitive tendering works well for the procurement of many goods and services but is not a panacea. For some of the more complex and technically challenging tasks which require a range of special skills an arrangement is required which provides for incentives for specialist contractors to collaborate and innovate.

Contractors should be involved with the project management and design teams in the production of integrated programs and detailed schedules. Comprehensive pre-planning and detailed scheduling with designers and support from main contractors, using three dimensional models, prior to start of construction will save time during construction, reduce rework, help avoid disputes between contractors and identify labour and related logistic requirements on site. By contractually requiring main contractors to collaborate as a Joint Planning Team to produce integrated schedules it is less likely that there will be interface problems and disputes on the site. If there are problems on site there is an established process for reference back to the design teams.

Vendors and prime contractors need to establish a subcontractor network for companies with proven skills; awareness of nuclear quality and understanding of nuclear safety culture must be taught to companies that have no previous experience; management of work conducted by subcontractors is a challenge of its own.

The modular construction of mechanical/electrical systems is well established and the use of civil/mechanical/electrical modules has been demonstrated to save construction time and improve quality, by having module fabrication and testing carried out off-site in more carefully controlled conditions. This also allows work on many different parts of the plant to be carried out in parallel.

In circumstances where the modular approach requires novel construction or manufacturing techniques to be used, there may be a requirement to do

additional work with the regulatory authorities in order to demonstrate full compliance with accepted regulatory standards.

Construction

Contract management must instil a disciplined approach. Contractors should be incentivised to meet agreed milestones. The focus on meeting program milestones should be relentless with daily, weekly and monthly meetings at all levels up to and including director level to ensure problems are identified and addressed early and program dates are met. ***This must be done without comprise to safety and quality.***

Interfaces require active management with a rigorous QA program to ensure that when a hand-over occurs between one contractor and another the job is complete, correct in all respects and ready for that hand over. This will help to ensure that errors do not accumulate and when commissioning takes place the activity is about setting to work and checking performance against expectation rather than discovering and rectifying construction and installation errors.

Commissioning and Operation

The transfer of responsibility and knowledge from construction teams to commissioning teams and on to the station operations staff can be facilitated by appointing commissioning and station operations teams early and actively encouraging collaboration. Making equipment suppliers and installers responsible for setting to work and having commissioning staff as members of their team ensures that the right expertise is made available in a timely way, experience is gained and knowledge transferred. Similarly station staff should be participants of the commissioning process. However, contractually the integration of operating staff early in the process may present challenges given the timescale of construction, and there will be a need for approved simulation facilities and trainers consistent with plant that may have contrasting operational characteristics to the current fleet.

Ensuring that foreign material is prevented from entering the Primary Circuit and taking measures, prior to nuclear power generation, to reduce the circuit material oxides that could circulate through the core, will reduce radiation fields and operator dose that arise from subsequent operation of the plant. There have been considerable developments in the understanding of the control of radiation fields since the commissioning of Sizewell B and 'good practice' has been incorporated into Operator Guidelines and Quality Assurance requirements. A lack of cleanliness during commissioning of either circuit can result in problems several decades into operation.

Provision of Skills and Knowledge Management

There is a nuclear expertise and skills shortage among potential UK based subcontractors. Knowledge and skills in particularly short supply include project management, site supervision and designers and managers with knowledge and experience of nuclear related codes and standards and of regulation and safety culture

All forms of technical publication should be embraced and, in particular, ensure that concerted learning associated with the construction experience is serialised in an archived conference or journal to facilitate easy sourcing

in the future. It must be noted, however, that records may need editing to remove data which is sensitive for commercial or nuclear security reasons, while ensuring that the learning remains available. Such information might be used, for example, to educate apprentices, graduates and post-experience students from industry or internal management development in businesses. However, a risk does exist that the Professional Engineering Institutions that have documented much of the technical achievements in past UK nuclear projects, will not experience the same flexibility in documenting future new-build projects coordinated by overseas vendors.

Vendors need to establish a subcontractor network from companies with proven skills; awareness of nuclear quality and understanding of nuclear safety culture must be taught to companies that have no previous nuclear experience; management of work conducted by subcontractors is a challenge of its own. The evaluation of a manufacturer's ability at the shop floor is important and difficult to achieve via audit alone.

Glossary

ABWR	Advanced Boiling Water Reactor
AEA	Atomic Energy Authority
AGR	Advanced Gas-cooled Reactor
ALARP	As Low As Reasonably Practicable
ANP	Areva NP
ASN	Authorité de Sûreté Nucléaire
BIS	Department of Business, Innovation and Skills
BNN	Babcock Noell Nuclear GmbH
BWR	Boiling Water Reactor
CEGB	Central Electricity Generating Board
CP	Construction Plan
CRDM	Control Rod Drive Mechanisms
DiP	Decision in Principle
EIA	Environmental Impact Assessment
EPG	Energomontaz-Polnoc Gdynia
EPR	European Pressurised Reactor
EPRI	Electric Power Research Institute
FEL	Front End Loading
GDA	Generic Design Assessment
HSE	Health and Safety Executive
IAEA	International Atomic Energy Agency
ICRP	International Commission for Radiological Protection
INPO	Institute of Nuclear Power Operations
IRS	Incident Reporting System
ISCO	Integrated System for Centralised Operation
IVC	Inspection and Validation Centre
LASP	Licensing Activities Summary Programme
LWR	Light Water Reactor
NAECI	National Agreement for Engineering Construction Industry
NDA	Nuclear Decommissioning Authority
NE	Nuclear Electric
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission (USA)
NIA	Nuclear Industry Association
NII	Nuclear Installations Inspectorate
NNC	National Nuclear Corporation
OECD	Organisation for Economic Cooperation and Development
PCSR	Pre Construction Safety Report
PPG	PWR Project Group
PPS	Primary Protection System
PSA	Probabilistic Safety Assessment
PWR	Pressurised Water Reactor
QA	Quality Assurance
SER	Significant Event Report
SNPTC	State Nuclear Power Technology Corporation
SNUPPS	Standard Nuclear Power Plants
SOER	Significant Operating Experience Report
STUK	Radiation and Nuclear Safety Authority (Finland)
SXB	Sizewell B
THORP	Thermal Oxide Reprocessing Plant
TMI	Three Mile Island
TVO	Teollisuuden Voima Oyj
UKAEA	United Kingdom Atomic Energy Authority
WANO	World Association of Nuclear Operators

Appendix A: List of Interviewees

Keith Ardron	EDF
Stuart Campbell	COSTAIN, Project Manager
Robert Davies	AREVA
Chris Bolton	Sellafield Ltd., no audio record made
Bill Bryce	Director of Babcock during the construction of Sizewell B now Director of Doosan Babcock Energy [no audio record made].
Nigel Buttery	Safety Manager for construction project team and Licensing Manager for Sizewell B now retired working part time for British Energy/EDF
Dr Paul Dorfman	Warwick Business School, University of Warwick
Dr Colin Elcoate	no audio record made, Clyde Union Pumps
George Felgate	WANO, Managing Director
Brian George	Director of PWR British Energy during Sizewell B Public Inquiry and Construction now retired
Dame Sue Ion	
Clive Loosemore	COSTAIN, Project Director
Mike Napier Director	COSTAIN, Strategy and Business Development
David Powell	Westinghouse UK
Mark Richardson	Rolls Royce
Peter Wakefield	WANO, Deputy Director
Richard Waite	Commissioning Manager for Sizewell B now Managing Director CH2M Hill

Appendix B: Steering Group

John Earp (Chair)	Associate Director – Strategy Aker Solutions (also representing the Nuclear Institute and the Institution of Mechanical Engineers)
Andrew Crudgington (Sec.)	Senior Policy Manager Institution of Civil Engineers
David Baird	Vice President Jacobs
Chris Bolton	Principal Engineer Institution of Structural Engineers
Paul Davies	Head of Policy Institution of Engineering and Technology
Andrew Furlong	Director of Policy and Communications Institution of Chemical Engineers
Quentin Leiper	Group Chief Engineer Carillion
Mike Napier	Strategy and Business Development Director Costain
Ashok Patel	Principal Consultant Magnox North
Richard Ploszek	Senior Policy Advisor Royal Academy of Engineering
Keith Waller	Senior Advisor Office for Nuclear Development

Annex C: Authors Details and Disclaimer

Authors' Details

Dr Richard Garnsey: Joined the CEGB's research laboratories (CERL) in 1968. He supported the PWR Director at the Sizewell B Public Inquiry and joined the PWR Project Group as R&D manager and then headed the Safety and Technology Branch that was responsible for the production of the Sizewell B Pre Operational Safety Case. He moved to NNC as head of their Engineering Design Centre and later headed their Defence and Environmental Engineering Department. He transferred to the Marconi Marine (now BAE Systems Submarine Solutions) Shipyard at Barrow in Furness and was the Nuclear Facilities Design Authority during the latter part of the Vanguard nuclear submarine programme and the early part of the Astute build project. He has worked for the NDA on R&D and Knowledge Management and is currently employed by Lancaster University. He is a past president of the British Nuclear Energy Society.

Professor Malcolm Joyce: Joined the Company Research Laboratory at BNFL plc in 1994 as Research Associate. He was appointed Lecturer in the Engineering Department at Lancaster University in 1998, progressing to Professor of Nuclear Engineering in 2007 and Head of Engineering at Lancaster in 2008. He has research interests spanning nuclear instrumentation, safeguards, decommissioning and nuclear medicine, and has published over 90 journal papers on these subjects. He is Director of Studies for the Nuclear Engineering MEng and the Decommissioning and Environmental Clean-up MSc at Lancaster, and is currently chair of the Nuclear Academic-Industrial Subcommittee (NAILS) of the Nuclear Institute.

Dr Ian Nickson: Joined the Research and Technology business group at BNFL plc in 1998 for two years as part of his PhD under the supervision of Professor Colin Boxall. Following this, he spent 6 years working for a SME developing energy storage devices before joining The John Tyndall Institute for Nuclear Research. He was appointed as a Research Associate in The Lloyd's Register Educational Trust Centre for Nuclear Engineering at Lancaster University in 2010.

Disclaimer

This report was prepared by the Department of Engineering at Lancaster University, UK. It was commissioned by the Institution of Civil Engineers, on behalf of Engineering the Future, and the Office for Nuclear Development of Her Majesty's Government. No commercial sponsorship has been received of any kind to support this study. It has been coordinated by a cross-sector steering group (the membership of which is listed in Annex B). All contributors to the report gave their time gratis and were fully introduced to the aim and objectives of the exercise prior to their agreement to contribute. Wherever possible, the final draft of the report has been made available for review by contributors to ensure accuracy and consistency.

Appendix D: Ethics form

Participation Identification Number:

CONSENT FORM

Project title: Nuclear Lessons Learned

Name of Researcher:

Please initial box

1. I confirm that I have read and understand the information sheet dated April 2010 for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reasons. ☐

3. I understand that any information given by me may be used in future reports, articles or presentations by the research team. ☐

4. I understand that my name will not appear in any reports, articles or presentations without my consent. ☐

5. I agree to take part in the above study. ☐

____________________	__________	____________
Name of Participant	Date	Signature
____________________	__________	____________
Researcher	Date	Signature

When completed, please return in the envelope provided (if applicable). One copy will be given to the participant and the original to be kept in the file of the research team at: the Department of Engineering, Lancaster University

Appendix E: Project information sheet

INFORMATION SHEET

Project title: Nuclear Lessons Learned

1. Research Summary
In this project, researchers in the Engineering Department at Lancaster University are collating the significant lessons learned in recent civil nuclear building projects. This is a short project (six months) culminating in a report to our sponsors that we hope will form the basis of a journal publication of value to all in the sector. We will meet with stakeholders from the international new build community and supply chain, and will interview many retired experts from, for example, the Sizewell B project. The key researchers on this project are:

- Professor Malcolm Joyce, currently Head of Engineering at Lancaster and formerly of BNFL plc.
- Dr Richard Garnsey, who was previously in senior positions on the Sizewell B project and on a number of other projects in the defence and decommissioning sectors.
- Dr Ian Nickson, currently a post-doctoral researcher on the project and formerly of the University of Central Lancashire and BNFL Springfields.

We are very interested to fold in your experience into this study and we anticipate that this could be of benefit to participants such as yourself since it will hopefully stimulate further discussion and involvement of expertise from ourselves and the project's sponsors in your activities if desired. The process is entirely transparent and prior to any publication of course all interviewees will be provided with a copy of the associated publication for clearance etc. The focus of the lessons we seek evidence on tends to be towards the Engineering Project Management and Technical issues aspects of the projects, i.e. not financial.

2. Research body and sponsors
The project is sponsored by the Institution of Civil Engineers (ICE) and the Office for Nuclear Development (OND).

3. Purpose of the study
The purpose of the project is to seek and collate evidence of good practice in nuclear build activities that may be at risk of being lost and areas where, with hindsight, it is clear the nuclear build sector could have taken a better route to resolving a challenge and appealing to an opportunity.

4. What is expected of participants in the research
We would like to interview participants concerning their experience and reflections on recent nuclear build projects. We usually record these interviews and then transcribe these audio records and study them for the benefit of the research as a whole. The audio records are achieved in a secure PC database in the Department of Engineering at Lancaster.

5. Anonymity and confidentiality
We will only draw reference to the identity of participants where their full permission has been granted, including the permission for contributions by participants to be quoted in context in the outputs from the project. Where desired, full anonymity of the participant will be assured. The main outputs from the project will be:

1. An interim report
2. A final report
3. Updates for the project's steering group meetings
4. An academic journal paper for the Energy journal of the Institution of Civil Engineers

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