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UK EXPERIENCE OF CONSORTIA ENGINEERING FOR NUCLEAR POWER STATIONS

Critical Again – Lessons for New UK Nuclear Power Projects

REPORT

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ACRONYMS AND DEFINITIONS

AEA	United Kingdom Atomic Energy Authority
AEI	Associated Electrical Industries Company
AGR	Advanced Gas Cooled Reactor
APC	Atomic Power Constructions Company
B&W	Babcock & Wilcox Ltd
BNDC	British Nuclear Design and Construction
BNFL	British Nuclear Fuels Ltd
BWR	Boiling Water Reactor
CANDU	Canadian Heavy Water Reactor
CDFR	Commercial Demonstration Fast Reactor
CEA	Central Electricity Authority for England and Wales
CEGB	Central Electricity Generating Board for England and Wales
EDF	Electricité de France
EE	English Electric Company
Enel	Enel – Italian energy company
GEC	General Electric Company of England
HTR	High Temperature Reactor
HWSGR	Heavy Water Steam Generating Gas Cooled Reactor
JAPCo	Japan Atomic Power Company
JT	John Thompson Company
Magnox	Natural Uranium fuel clad in a Magnesium alloy
NDC	Nuclear Design and Construction
NII	Nuclear Installations Inspectorate
NNC	National Nuclear Corporation
NPPC	Nuclear Power Plant Company
PFR	Prototype Fast Reactor
PIPPA	Pressurised Pile for Producing Power and Plutonium
PWR	Pressurized Water Reactor
SGHWR	Steam Generating Heavy Water Reactor
SSEB	South of Scotland Electricity Board
TNPG	The Nuclear Power Group
TWC	Taylor Woodrow Construction Ltd
UKAEA	United Kingdom Atomic Energy Authority
UPC	United Power Company

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Critical Again – Lessons for New UK Nuclear Power Projects

International electrical power generation utility companies are now planning to build new nuclear power stations in the UK to replace the many nearing the end of their economic and safe life. The UK government has indicated its support for these new projects. Continuing uncertainty in future oil and gas supplies and prices together with commitment to environment emissions targets are likely to sustain this support.

The new stations in the UK are expected to be based on the pressurized-water (PWR) and boiling water (BWR) types of reactor as now most preferred by the electrical generation utility companies and safety authorities world-wide. The UK government expects that together with the international suppliers of the reactor systems the utilities will employ British engineering and construction companies to design and construct these new nuclear power stations. Consortia of UK-based turbine-alternator engineering and boiler maker companies were formed in 1955 to undertake the design, construction and project management of the country's first programme of gas-cooled reactor power station projects. Those consortia, later amalgamated, went on to undertake the programme of advanced gas-cooled reactor projects, until the change of national policy to use a PWR design for the Sizewell B project completed in 1995. Since then no UK organization has designed or managed a complete nuclear power project.

These notes review the experience of individuals employed in the engineering and project management of the UK's projects up to Sizewell B, as lessons from those forty years of projects may be relevant to re-establishing a nuclear power programme in this country. The dominant lesson is that to be economic and safe to operate each new project should be planned and controlled by an organization that has the engineering and managerial capacity and authority to integrate and control the design and supply of the whole project. This has been learnt from capital projects in many industries world-wide. The investors in new nuclear projects may now demand that it is applied.

CONTENTS

UK EXPERIENCE OF CONSORTIA ENGINEERING FOR NUCLEAR POWER STATIONS

1. FORMATION OF UK NUCLEAR CONSORTIA

In 1955 the UK government announced that it would invest in a programme of civil nuclear power stations to use natural uranium 'Magnox' fuel so as to be internationally independent in energy supplies and to produce plutonium for weapon material.[1] The prototype was the gas-cooled 'PIPPA' design of reactor recently put into operation at Calder Hall by the UK's Atomic Energy Authority (AEA), the national nuclear research and development organisation.[2]

The government then encouraged the UK-based power station turbine-alternator manufacturing companies to get together with boiler maker companies to form 'consortia' to undertake the development, construction and commissioning support of the new Magnox projects. Formation of consortia was recommended to the government by the AEA to establish contractor organizations strong enough technically and financially to undertake 'turnkey' contracts for the engineering and construction of complete power stations and to sell these overseas.[3] For the UK turbine-alternator and boiler making companies this was the opportunity to have a share of the new nuclear power market. Four consortia were formed in 1955, and a fifth in 1957. Those consortia and their member companies are listed in Appendix A.

The consortia were invited to compete in undertaking research, development and design to take the Calder Hall reactor design up to a size which would be commercially attractive to electricity generating organizations. The consortia were given access to the AEA's nuclear information. The AEA was the nuclear advisor to all parties, and until 1965 was also the UK's nuclear design safety authority.[4] The AEA was the fuel manufacturer and re-processor of the fuel and responsible for its militarily important by-product plutonium.

The customers for the projects were two newly re-organised UK power generation utilities, the Central Electricity Generating Board (CEGB) and the smaller South of Scotland Electricity Board (SSEB).[5] The consortia delivered eight twin-reactor Magnox stations to the CEGB and one to the SSEB. The projects are listed in Table B. Following world-wide interest in the potential of this new source of power single-reactor Magnox stations were supplied to the Italian power company Enel and to the Japan Atomic Power Co (JAPCo).

2. CONSORTIA MEMBERS

The turbine-alternator companies took the lead in inviting the boiler makers and other companies to join them in forming consortia. AEI was reported to have wanted to be the dominant partner in their consortium and therefore invited John Thompson, one of the smaller but respected boiler makers.[6] By comparison, English Electric invited Babcock & Wilcox as the most experienced, technically equipped and internationally connected of the UK boiler makers. NPPC was based on companies known to each other from Calder Hall and some 'conventional' projects.[7] NPPC had the largest number of member companies, spreading the financial risks amongst the widest range of resources.

Two of the first four consortia included civil engineering contractors as members. Two consortia employed contractors without their being consortium members. Two civil engineering contractors planned to be members of the APC consortium, but withdrew from its membership and were instead employed by that consortium. AEI-John Thompson employed civil engineering consulting engineers who had been responsible for design of Calder Hall structures.

The five consortia varied in the range of other companies included and in their internal structures of contracting, financial commitment and control.[8] The AEI-John Thompson and the English Electric/Babcock & Wilcox/Taylor Woodrow cases were true “consortia” in that they were partnerships with liabilities shared between their member companies. NPPC and APC were companies wholly owned by their member companies, with their liabilities guaranteed by their member companies. So were their successors TNPG and UPC. GEC was the sole contracting member in what was called their consortium. In this Simon Carves shared 40% of research, engineering and supporting costs up to tendering to a customer, but when a utility agreed a contract for the delivery of a project Simon Carves was GEC’s nominated sub-contractor for the supply of boiler systems and the civil engineering.

3. CONSORTIA RESOURCES

Every consortium established its own headquarters team for its nuclear power work. The English Electric-led and the GEC-led consortia established their teams near or at their existing factories. The other three consortia established their teams at new locations, two near to the AEA offices concerned, and the fifth in London.

The first members of the teams were engineers and nuclear physicists, the engineers mostly seconded from their member companies. Many more engineers and physicists, metallurgists, mathematicians and commercial staff were then recruited from other engineering industries, academia, the AEA and the armed services.[9] The recruitment of staff was typically in at least three waves; first the team perceived as required to initiate reactor design, research and development, then additional engineering and commercial expertise to prepare the first tenders, and then further growth for engineering, construction and managing more projects.

Of the companies that joined in the consortia, Babcock & Wilcox, John Laing, Parsons, Reyrolle, Strachan & Henshaw, Taylor Woodrow and Whessoe had experience of major work for Calder Hall, but as separate contractors to the AEA. Most of their staff with that experience returned to their companies and few were seconded to any of the new consortia. Parolle, a joint Parsons and Reyrolle company they owned to coordinate collaborative work for conventional power station projects, was an exception. Parolle had been employed in a project coordinating role at Calder Hall and was employed similarly by their consortium NPPC to provide general management and also inspection services. Simon Carves had previous experience of consortia working for a steelworks project in India (ISCON), and one person with some knowledge from that work was seconded to their consortium. English Electric and possibly other companies had experience of turnkey contracting, but no individual with such experience is known to have been seconded to a consortium for that reason.

Technical training for the consortia’s first leading staff was provided at the Atomic Energy Research Establishment, Harwell, and at the Calder Hall repeat project under construction at Chapelcross.

4. RESEARCH AND DEVELOPMENT

The consortia established their own separate nuclear engineering research and development laboratories at their manufacturing member companies’ factories. In the EE/B&W/TWC and GEC/Simon Carves consortia these laboratories were therefore close to their engineering offices. In addition to those at their member companies’ factories, the AEI-John Thompson and the NPPC consortia also built nuclear engineering research and development laboratories alongside their new headquarters, increasing them in scope as reactor, fuel and boiler design needs became known.

Reactor technology research and development work for the Magnox programme by the consortia and by the AEA was coordinated by specialist working party meetings led by the AEA and attended by CEGB.

5. MAGNOX FUEL

Natural uranium in Magnox cans was stipulated by the AEA to be the basis of the design of the fuel elements for the first programme of nuclear power stations. Detailed design of the elements for their reactor was the responsibility of each consortium, hence a variety of different designs. The AEA had responsibility for the fuel manufacture and also for its subsequent reprocessing and waste disposal.

For each design a working party was formed by the AEA and the relevant consortium, requiring the AEA staff involved to take care with the contradictory demands of collaboration and confidentiality.

6. FIRST PROJECTS

The four original consortia developed their reactor designs competitively. Their first tenders to the CEGB and SSEB were required to offer a design for a complete twin-reactor power station which could be chosen for construction at either Berkeley or Bradwell, in England, or at Hunterston in Scotland. Their station plans and detailed design to suit a site followed selection of a consortium to build their project. The CEGB and SSEB had little influence on the designs for the first tenders, perhaps because their nuclear engineering and project management organizations were still being established. They became increasingly influential.

Capital cost per MWe of power generating capacity was the criterion stated for judging the tenders. The selection of three of the consortia's designs for Berkeley, Bradwell and Hunterston were announced in 1956, and after some changes a fourth in 1957 for construction at Hinkley Point. Their designs typically offered treble the power output per reactor compared with one Calder Hall reactor. These reactor designs were in effect distinct prototypes. Every consortium expected it would be invited to develop its design for selection as the standard for further stations.

Some data and the outlines of these four reactor designs became public when chosen for the first sites. Information on these designs was thus known to the fifth consortium when it bid for their first project. This fifth consortium bid in competition with the established four, for a designated site, Trawsfynydd. The fifth consortium's reactor design showed similarities to Bradwell, but up-rated.

The four original consortia offered their reactor designs to utilities in other countries. The first export was the Latina project, Italy. The chosen design was based on the design for Bradwell, achieving greater power output and earthquake re-design within the same size of vessel. The contract was negotiated after the AEA had recommended the TNPG design. The consortia competed for the second export project, Tokai Mura in Japan. This contract was awarded to GEC/Simon Carves for a design which differed markedly from their Hunterston A design in order to meet the major earthquake risks and conform with US engineering standards.

After the first projects the AEA and CEGB encouraged the development of reactor designs for each successive Magnox project. In the series of UK Magnox projects that followed the Sizewell A reactor design was based on the Hinkley Point A design. None of the other

reactor designs were repeated. The resulting advances in power output per reactor together with a reduction in UK anxiety about international risks to oil and gas supplies resulted in fewer projects than first expected.

7. MAGNOX ENGINEERING ACHIEVEMENTS

Greater power per reactor in the series of Magnox projects was achieved by advances by the consortia and their member companies in the design and construction of the reactor pressure vessels, fuel elements, graphite moderators, gas circulation systems, boiler tubing, boiler pressure vessels, fuel handling equipment, instrumentation and control systems. These achievements are indicated in the published papers listed in Appendix C. They demanded step changes in technology in many of the contributing industries, for instance welding, which were then of value in other industries.[10]

The design, development, manufacture and testing of remote-controlled fuel handling equipment was new to all but one company and was greatly extended from the Calder Hall experience by designing for on-load re-fueling. The design of the boilers was very different to those for coal-burning power stations. The design of the turbine-alternator plant and other conventional systems also demanded changes from established designs, particularly as the maximum steam temperature generated using Magnox fuel was lower than in the contemporary conventional power stations.

Most of the Magnox reactor pressure vessels were steel, as in the Calder Hall reactors, but larger and spherical. The use of steel up to the then maximum weldable 3” thickness set a limit on coolant gas pressure and hence heat transfer in the reactor cores and boilers. Early in the programme some of the civil engineering companies started to develop prestressed reinforced concrete pressure vessels which would allow a significant increase in coolant gas pressures and therefore the output attainable from a reactor. As a result the last two Magnox projects used prestressed reinforced concrete pressure vessels.

The consortia’s designs of the reactors, station systems and structures were subject to detailed review by the AEA as well as by the utilities, and insurers and consulting engineers employed by them.

8. ENGINEERING ORGANIZATION

The consortia varied in the extent that the development and detailed design of the nuclear and the conventional plant, systems and structures was centralized or was the responsibility of the established engineering departments in their member companies, other companies and consultants.

In two cases the consortia’s central engineering teams were initially set up to coordinate rather than lead design decisions. Those consortia found that the designs preferred by their individual member companies for their parts of a project if put together would not produce a project which would be economic and safe in commissioning and operation. Their member companies learned from this that the interdependence of the design of nuclear, conventional, control and supporting systems required the consortia’s central engineering teams to have the authority to initiate and control design, not just coordinate hardware, but working closely with the design, plant installation and commissioning staff in the individual mechanical, electrical, vessel fabrication and boiler maker companies.[11]

Perhaps because of different location and their experience of conventional power station work some design and construction staff in member companies disregarded expert advice available from consortium staff, for instance on potential problems of component vibration in

high pressure coolant gas flow and on materials and fabrication restrictions in nuclear conditions. Resolution of these problems showed that all had to recognise the interdependence in design decisions. To guide all parties the diagram reproduced in Appendix D was used in one consortium to show the interdependence of nuclear, conventional, control and supporting system design. It indicated how many apparently unrelated design decisions are linked so that a small change in one part of the design can affect much elsewhere.

When procuring conventional power station projects the utility, usually through consulting engineers, was responsible for specifying the station layout, buildings, cabling, piping, instrumentation and services and coordinating design, construction and testing. For the Magnox projects the consortia as turnkey contractors had to gain expertise in all these requirements for a complete power station and to maintain sustained coordinated attention to the detail through to testing and commissioning.[12] Late attention to conventional requirements caused as many design problems as did new nuclear information.

The consortia also undertook studies of other reactor systems and smaller projects for prototype and experimental reactors. These were usually the work of small teams separate from the Magnox projects.

9. CONSORTIA OPERATIONS

Working relationships were reported to have been friendly within all the first four consortia, probably partly because most of the leading individuals had been together at training run by the AEA and partly because of the great motivation evident in this new industry. During their first projects managerial relationships between the consortia central teams and their some member companies did not initially all go smoothly. Being required to guarantee a consortium's liabilities jointly led some member companies to expect that in return they would be guaranteed a corresponding share in the work for a project. These companies tended to see sharing liabilities in a consortium as a necessity for obtaining manufacturing work for their factories but not as important as their direct business with the power utilities for conventional power projects.[13]

Creation of a consortium as a creature of its member companies to bring them work also created the expectation in the companies that each would get the work they wished and none would go to competitors not in their consortium. By contrast, one observer commented that the APC consortium was "not committed to the furtherance of its member companies", taken to mean that its management operated in the interests of APC as a company and its management. The consortia needed engineering authority and managerial skill to anticipate and resolve disputes with member companies.[14] The disputes that occurred were generally resolved in agreement with the consortium managements' decisions. The problems were anticipated in other cases because their member companies' senior managers had previously worked together and cooperation between them was supported by regular steering meetings of top executives.

As noted earlier, creation of a consortium as a creature of its member companies to bring them work created expectation in some member companies that the design of a project would be based on the design of their plant each preferred. Staff seconded to a consortium's team from those member companies were then in an ambiguous role in negotiating with their parent company, especially when the consortium's system design imposed unwelcome demands or restrictions on that company's own individually preferred designs. This problem of roles was initially resolved by specific clarification that seconded staff were essentially consortium staff. As one observed, individuals seconded to a consortium soon went native, that is behaved as a project team rather than as employees of

the member company that actually paid their salaries. Later most transferred to being consortium employees, particularly when consortia amalgamated.

The AEI-John Thompson and NPPC consortia amalgamated in 1960, to form TNPG, when it seemed likely that the advances achieved in power per reactor would lead to the CEGB and SSEB ordering fewer Magnox projects than first expected.

In 1962 GEC and APC were brought together as UPC to manage their projects. In this the UPC organisation included none of the GEC/Simon Carves engineering team, and this amalgamation was abandoned in 1964 at the time that GEC withdrew from tendering for further nuclear projects.

In 1965, reorganization within English Electric led to the EE/B&W/TWC consortium forming a joint subsidiary, NDC, later BNDC.

10. CONTRACTS

For all the UK Magnox projects the consortia entered in effect into comprehensive 'turnkey' contracts with their customer, the CEGB or SSEB, with responsibility for design and its supporting development work, procurement, construction, pre-commissioning testing and commissioning support of a complete power station up to handover for the customer. A major exception in liabilities was that the utilities paid the costs of changes to a consortium's design caused by new nuclear information. The contracts were not finally agreed until well into the construction work.

After the first projects the CEGB required contract performance bonds, but probably following their corporate policy for all contracts rather than from perceptions of their need and practicability for these projects. No bond was ever called. To do so successfully could have depended upon distinguishing the effects of new nuclear information from other causes of delay or extra cost.

Payment from the utilities was indirect through their consortium. Each company had to bear its own cost risks if they encountered engineering or other problems and share the liability for the consortium's problems of a contract. Costs were said to have been a problem because many priced their first tenders expecting that part of the costs incurred up to that time would be borne by repeat orders. Financing their work in a turnkey contract was a strain for some members of the consortia when payment from a utility awaited agreement on liability for design changes.[15] There were some lengthy and detailed claims for additional payment, but without showing that different terms of contract would have been better for the utilities or the consortia.

11. PROCUREMENT

The differences in the ownership and liabilities in the consortium structures affected how far their internal relationships were contractual.[16] In practice the member companies behaved as sub-contractors in contract with their consortia teams, as illustrated in Figure 1.

Most of the second tier suppliers were selected by the member companies following their normal processes of competitive tenders from sub-contractors known to them.

UK and Canadian companies supplied the pile graphite bricks for the UK stations, French for Tokai Mura.

The steel for the Tokai Mura reactor pressure vessel, originally supplied from the UK, was found defective and replaced by Japanese steel.

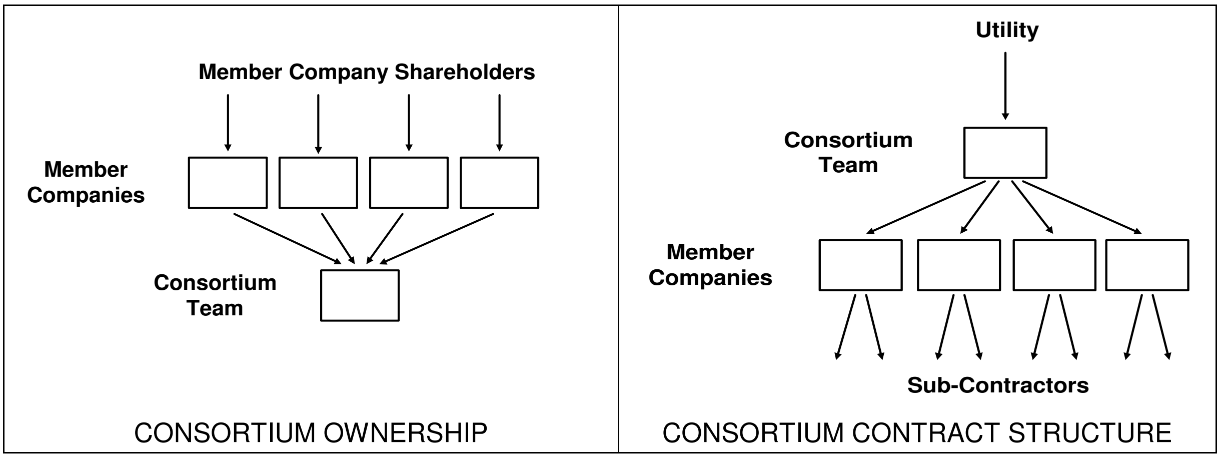

Figure 1. Ownership and contractual relationships in a consortium

The supply and disposal of the nuclear fuel was the subject of contracts between the utilities and the AEA.[17]

Most other supply was from UK, but not always through member companies. In the two export contracts the consortia were responsible for specifying but not supplying secondary plant, piping, cabling and construction. Many quality and accuracy requirements for reactor components were higher than those familiar to their suppliers. Some sub-contractors found great difficulty in achieving the standards required in mechanical construction work for the reactors, for instance nuclear 'clean conditions' requirements. These needed detailed instruction, supervision and inspection by consortium staff to achieve specifications.

12. CONSTRUCTION

Each consortium established its construction management team, as with their design teams based upon a few staff from member companies and many recruited from elsewhere. Consortia site offices provided some common services, but member companies established their own site organizations to direct and supervise their own site teams and sub-contractors.

The Chairman of the CEA is reported to have said in 1955 that "The problems of building nuclear power stations will not differ materially from those met in the construction of conventionally fired stations."[18] He was partly right. The speed of construction of the UK Magnox projects was similar to UK conventional power station projects at a time of poor productivity and labour relations difficulties also being faced by chemicals, steel and other industry projects.[19] The consortia's sites near areas suffering from the decline of heavy engineering and disputes in industrial relations may have attracted these problems. So may the lack of training in project and construction management of engineers and supervisors recruited from manufacturing. The sites further away from industrial areas proceeded without delay from labour disputes but were slow to complete by international standards.

The projects in Italy and Japan were constructed more rapidly, apart from a major materials delay, but they drew on UK experience of the first Magnox projects and enjoyed favourable local sub-contracting and labour conditions.

The engineering problems of building the nuclear power stations which differed very greatly from the construction of conventional stations were the construction of the reactor pressure

vessels, assembly of the graphite cores, installing and testing nuclear instrumentation and maintaining nuclear clean conditions throughout the construction of the reactor vessels and gas circuits. Construction of the steel pressure vessels for the reactors first required the erection of heavy cranes and tracks for these close to the equally critical excavation for the reactor buildings. Much of the boiler engineering was new in form or size. Some of this work was more akin to heavy chemicals plant construction than conventional power station work, but larger and using some different materials.

Because of time pressures most of the new designs of fuel handling machines, control rod mechanisms, emergency shut-down devices, core restraints and other specialised systems were delivered to site without factory testing and needed space in the reactor buildings for rectifying assembly problems, checking by their design teams and operator training. A widespread difficulty on the first projects was under-estimation of the complexity of control and service systems installation in the reactor buildings, a problem due to designers' limited experience of power stations rather than nuclear requirements.

The managerial problems of building the nuclear power stations which differed materially from the construction of conventionally fired stations were in the risks of the above and the role of the consortium as the customer for the contractors, a role on conventional power station projects taken by the CEGB and its predecessors. Respect given to individual consortium and member company staff with Calder Hall or Chapelcross experience gave them initially a special authority, but some of them found it difficult to understand managerial roles in the greater commercial complexity of a consortium, particularly that member companies were formally sub-contractors to a consortium which they owned.

One result of member companies' establishing their own site organizations to direct and supervise their own site teams and sub-contractors was three levels of direction and supervision – customer, consortium and contractor – with initially some lack of detailed planning agreed by the three levels. Meetings to plan the work first required team building between customer, consortium and companies. More than coordination was required. On one site it took time to accept that the member companies' own site organizations should be directed by the consortium's site manager in order to anticipate potential problems of the sequence and timing of work, use of space, inconsistent labour relations and lack of common services.[20] Other sites enjoyed good cooperation between companies with different cultures and labour agreements, for instance a boiler maker company assisted a pressure vessel contractor with severe industrial relations problems.

Some coastal sites made it possible to bring in large fabricated components by sea, but in one case local advice on the bearing strength of a connecting road was wrong.

Safety in construction of the UK nuclear projects was stated to be better than on other construction sites.[21]

13. COMMISSIONING

The utilities were the organizations licensed to operate nuclear projects. Consortium staff were responsible for drafting the testing, commissioning and operating manuals and schedules for a project, for agreement with the customer, consultants and regulators. The utilities' staff took over control of a project when tests showed it was sufficiently complete to commence loading fuel, but with extensive technical support from consortium staff, member companies and equipment suppliers until operation at full power and completion of contractual tests.

Temporary teams had to be recruited for planning the commissioning of the first projects, as the consortia and member company staff lacked operating and maintenance experience of power station systems and of their companies' products in use. Some consortia appointed a dedicated manager to plan for pre-commissioning testing from the start of construction, as is now recommended as best practice. No problems were reported from projects where the role was filled later, as the customer's commissioning management and operating staff took the lead. Joint customer-consortium commissioning teams were set up for the later projects to provide transfer of experience to operational staff.

14. PROJECT MANAGEMENT

The managers of each consortium were in effect the project managers of their first Magnox projects. The development of the reactor systems tended to have first attention when the consortia were formed. The project teams and their planning and progress reviewing did not initially cover the detailed needs of procurement, installation, testing and handover of the conventional and nuclear plant and systems. Tendering and obtaining a second contract precipitated more specific attention to managing each project.[22] More coordination and managerial roles were created with growth in the scale of the engineering, tendering and commercial work, providing unexpected career opportunities for some staff. Definition of responsibilities in commitments with member companies was particularly needed in the transition from collaboration in development and design to contractual relationships in tendering and in managing contracts.

Many of the staff recruited to the consortia were relatively young and were highly motivated in joining this new industry. Team spirit needed little or no planned team building, though at first security practice limited briefing them on design policy and risks. High morale and confidence were maintained through the first projects and the amalgamation of some of the consortia, but project management demanded increasing attention to the commitment and performance of member companies when facing unexpected costs and risks and no repeat orders in prospect.

The structure of one consortium's team was based on practice in manufacturing companies accustomed to little innovation from project to project in which a department experienced in preparing tenders largely from previous designs hands over a project on receipt of a contract to another department experienced in providing manufacturing instructions. Following this practice part way through the design of novel reactor plant still dependent on development work needed transfer of staff with each project to avoid discontinuity and loss of understanding of design criteria. As observed of other industries, the engineering of high risk one-off projects needs continuity through to handover to operations.[23]

For the Latina project NPPC established a small management and engineering coordination expatriate team at their customer's project office in Italy, supported by many visits by the UK-based project manager, senior managers and many technical specialists. For the more distant Tokai Mura project GEC established its own subsidiary company in Japan with a senior management and engineering expatriate team, also supported by many visits from UK-based staff. At the commissioning stage the chief member of the UK engineering staff and a small technical liaison team moved to the Tokai Mura site, providing a direct link with the customer's team and calling up specialist and senior management support from the UK when needed.

15. PERFORMANCE OF THE MAGNOX PROGRAMME

The amalgamated TNPG consortium delivered a total of six Magnox projects. BNDC delivered three. GEC/Simon Carves delivered two, partly while functioning within the UPC

organisation, but ceased to tender after Tokai Mura following GEC's withdrawal from heavy engineering.[24] APC delivered one Magnox project.

All the Magnox projects suffered delays in design, construction and commissioning, and new nuclear data from the AEA and engineering problems required many design changes, but none so extensive as to cause any of the projects to be abandoned. Speedier completion might have been expected in this series of successive projects, through learning from the repetition of designs, 'First of a Kind' managerial learning and the establishment of routines. Contrary to this, completion times were generally longer through the Magnox programme. The authors of the one study speculate whether increasingly more safety requirements could explain why these completion times did not improve.[25] So could the lack of repeated designs. Another cause could be the emphasis on confidentiality of information characteristic of the start of the nuclear industry that could have limited analysis of how well the work was being managed. More influential on the motivation of all concerned may have been a gradual lessening of the initial pioneering sense and a decreasing 'Hawthorne' effect of top management interest after a team's first project, together with the growth in size of the teams after their first project resulting in the dilution of experience and changes of roles.

Operation of some of the reactors in service was eventually at lower power than intended to avoid corrosion to mild steel components in the gas circulation systems, but with this all of them achieved at least their 20-year design life, and some up to 40 years. An indicator of high reliability is that one reactor produced power for 653 days without interruption. The UK electricity supply came to depend upon the Magnox power stations, particularly through the upheavals of the run-down of the UK coal industry and continued international uncertainties of oil supplies. The reactors were eventually closed when their maintenance ceased to be economical. Tokai Mura was closed after exceeding its economic life and it had achieved its prototype role in Japan. Latina was closed with the other operational nuclear power station in Italy after the Chernobyl explosion.

Successive reviews have criticized UK governments, the AEA and the CEGB for encouraging continuing development of the Magnox type of reactor project by project rather than standardize on the most economical design. They have also been criticized for persisting with types of reactor which attracted only two export orders. Amidst those criticisms the reviewers and historians give credit to the consortia in investing in new technology and undertaking the role of turnkey contractors to produce what have been described as the 'workhorses' that met the UK's base load demand for power.[26]

16. THE SECOND PROGRAMME – THE AGR PROJECTS

Throughout the Magnox programme the government, AEA, CEGB and the consortia had been investigating a range of successor types of reactor. TNPG led a European consortium to design a high temperature gas cooled breeder reactor. Prototypes of several different reactor designs were built by the AEA, notably including a fast breeder reactor which would utilize plutonium, higher temperature gas-cooled designs and a heavy water steam-generating design, and all parties gave increasing attention to types of reactor chosen in other countries, particularly various pressurized water-cooled reactor (PWR) designs adopted by the US and France, boiling water designs (BWR) in the US and the Canadian heavy water reactor design (CANDU).

A prototype 'Advanced Gas-Cooled' (AGR) completed by the AEA in 1963 used lightly enriched uranium fuel by then available in the UK. It offered higher thermal efficiency than the Magnox stations and promised to utilize the UK's experience of gas-cooled systems, graphite technology and pre-stressed concrete pressure vessels. In April 1964 the government published a White Paper announcing the UK's second programme for investing

in nuclear power projects and opening the UK market to liquid-cooled as well as gas-cooled enriched fuel reactor systems.[27] Following this, in 1965 the CEGB with AEA support invited the three consortia to tender to design and construct the first project for a programme of AGR stations and also the alternatives of BWR or PWR designs with US partners.[28] The invitation was based on following the same organizational structure as the Magnox programme with the consortia expected to compete for turnkey contracts to design and supply complete stations.

Extrapolating greatly from the AEA's prototype, the APC consortium tendered an AGR design at a price then judged by the AEA and CEGB to be competitive with the other consortia's tenders for AGR, BWR or PWR-based designs.[29] The APC offer was based on changes from the fuel element design specified. The other two consortia had complied with the fuel design specified. All three offered on-load re-fueling as an advantage over BWR and PWR reactors. Applauded by the government and many observers, APC was awarded the first contract. The other two consortia's loss of that contract was the subject of much discussion of fairness.[30]

17. PERFORMANCE OF THE AGR PROGRAMME

TNPG briefly considered working with APC on their AGR design but "soon found that many of the assumptions made and the corners cut" in the proposal were untenable. Following discussion with the CEGB, TNPG instead reworked their own first design and negotiated their first AGR contract. BNDC similarly reworked their first design to meet CEGB requirements and in turn obtained their first AGR contract.

Meanwhile APC had found that their design was seriously under-engineered, not only because of the change of fuel element design but also in much of the reactor thermal and pressure vessel systems. Eventually the project turned out to be a financial disaster for the CEGB and the APC member companies. APC went into administration in 1969. Execution of its AGR project was taken over by a team drawn from BNDC, GEC and the CEGB.

TNPG also found that their experience of gas-cooled systems, graphite technology and pre-stressed concrete pressure vessels from the Magnox era was severely stretched in designing for much higher AGR gas temperatures and gas pressure. BNDC found the same when proceeding with their AGR design. They and their member companies had to invest in extensive development work, particularly for the fuel strings, gas circulator systems, boilers, the prestressed concrete vessels and their thermal insulation. Achieving the insulation of the pressure vessels "at times seemed to be intractable". These projects were subject to many reactor design changes, problems of graphite machining and construction sequencing. Compounding the intrinsic engineering advances needed for the AGR designs were many innovations in pursuit of competitive advantage. Limited space in the reactor buildings aimed at reducing capital cost caused acute problems and therefore unexpected costs in installing equipment and services.

TNPG were asked to supply a repeat-design second AGR project, but for the SSEB and at their insistence too soon to take much advantage of sequential loading of suppliers' manufacturing capacity and the re-use of construction resources. As a result of the resulting delay in the reactor work, the completed turbine-alternators and power systems were moth-balled for months and plant and system testing and pre-commissioning had to be repeated.

In 1972 the UK government and the CEGB agreed that competition between consortia had outlived its usefulness in developing British reactor designs. The BNDC and TNPG teams were then formed into the National Nuclear Corporation (NNC). NNC became responsible for completion of the AGR projects then under way. NNC also continued the consortia's

studies of prospective other types of power reactors.[31] In forming NNC most of the BNDC and TNPG engineering and management staff were brought together at one location, but some returned to their parent companies and others in what had been a young industry had by then reached retirement age. Their nuclear engineering laboratories were similarly rationalized.

The AGR stations eventually succeeded the Magnox stations in meeting the UK base load demands for power, though the potential operational advantage of on-load refueling was not achieved. Seven twin-reactor stations in the UK completed the AGR programme. Because of high capital cost AGR reactor designs did not attract export orders. The final two UK AGR stations, Torness and Heysham 2, were regarded as the most successful, particularly in completion to budget and schedule, and in 2016 Heysham 2 Reactor B achieved a world record of 895 days of continuous operation.[32]

The Torness and Heysham 2 stations were largely repeat designs, but with changes only to meet revised safety standards and to suit each site. NNC was responsible for their engineering and construction, but the SSEB and CEGB entered into separate contracts with the suppliers of the main components and the construction contractors. The terms of their contracts made each contractor liable for significant costs to the others of errors or failures to perform.[33] In effect this was similar to their previously joint liabilities, but this change marked the end of the consortia as turnkey contractors.

The question studied by various enquiries and authors is why the APC consortium failed.[34] APC was similar to NPPC, TNPG and BNDC in being owned by the companies who expected to be its principal sub-contractors, so structure does not appear to explain differences in success, but TNPG and BNDC each brought greater engineering and management experience to the AGR programme, starting from having competed in engineering development work to offer their first Magnox designs and had then managed the risks of engineering several projects through to commissioning. APC had experience of only one Magnox project and their design had followed the others and not demanded taking so many engineering risks. APC was set up with a smaller engineering team. It was stated to be mainly a management organization. As Burn comments, APC appears to have failed for lack of the “knowledge, capacity and skill” to manage the engineering decisions which determine the performance, safety, reliability, flexibility, capital and operating costs of any industrial project.

From early in the Magnox programme all interested UK parties had continued to debate the potential advantages of the US and Canadian alternatives of light water and heavy water moderated power reactors. In 1980 the CEGB invited NNC to prepare a design of a PWR station based upon Westinghouse reactor technology and Bechtel’s PWR experience, to meet UK safety requirements and to be constructed as Sizewell B in Suffolk. The CEGB announced that for a first station of a reactor type new to the UK the accountabilities of the CEGB for safety, procurement policy and cost were such that the Board itself should undertake the leadership of the project.[35] Most of the NNC staff then working on the project continued to do so under contracts from the CEGB. The Sizewell B project was completed in 1995 two months ahead of the target date proposed in the business case. The UK electricity supply Industry was privatised and NNC sold during the project, but the project organisation was sustained through these changes in ownership.

18. NOW

The capital cost per MWe of power generating capacity was the criterion stated for judging the tenders from the consortia for the Magnox and AGR programmes, as was UK government policy for conventional power plant. Satisfying the increasing demand for power

was then the primary objective. International utility companies and international investors are now the promoters of the new nuclear projects for the UK. Under commercial pressures speed of return on capital employed becomes the primary objective, requiring drive in project execution in place of the cost dominated 'natural pace' of project planning and approval processes.[36]

At its start the UK's Magnox programme was subject to a nuclear safety regulator which was then also the primary developer of the reactor system. Since 1965 safety has been regulated independently in the UK and the government is no longer the owner of the electricity generation industry or a prime driver with an interest in the plutonium by-product. The government has given its political but not commercial support for new nuclear power stations to be built to replace the many in this country now past or nearing their economic and safe life.[37] It is the utilities and their suppliers who need to obtain the safety authority's approval of their projects.

Many of the lessons from the UK's previous nuclear programmes were not due to nuclear advances and innovations. They were as much the organizational and leadership challenges of bringing companies together to design and deliver a complete project. PWR and BWR technology and its users' experience can now provide the nuclear heart for new power stations, but a lesson to be learnt from the previous programmes and from other industries is that to be economic and safe to operate each new project should be planned and controlled by an organization that has the engineering and managerial capacity and authority to integrate and control the design and delivery of the whole project.[38] This lesson is not readily applied even by experienced nuclear investors and contractors, as demonstrated by the problems of responsibilities and communications between the leading parties reported from a recent European PWR project.[39]

As no UK organization today has designed or managed a nuclear power station project since Sizewell B, the engineering and managerial strength required has to be hired or recreated. The consensus of international experience is that the risks of investing in a project should be borne by whoever can best minimise and resolve them.[40] The structure of contracts between them should therefore be designed to provide the framework for building the teamwork between utility, consultants, contractors and other suppliers needed to cooperate to anticipate and manage each risk through to completion of their project.[41] There are now no large turbine-alternator and boiler manufacturing companies in the UK and only a few companies in the world have the engineering and commercial strength to supply the main components of nuclear power stations. French, US, Chinese and Japanese nuclear organisations have announced agreements to work with sets of UK engineering and construction companies to design and construct new nuclear power projects in this country. If they offer to undertake projects jointly the managerial lessons from the consortia formed for the UK's previous programmes may therefore be relevant to them and to the utilities.

20. CONCLUSIONS

This report draws on experience of consortium responsibilities for design, construction and commissioning. Much went well. Many of the lessons for all parties are the same as stated from all capital projects, particularly projects in the process industry. The particular risks of an industry affect the content of decisions, but not their nature.

These common lessons have been stated in reports and papers, as well as individuals who have contributed to this report. They appear to be understood and agreed. The investors in new nuclear projects and also the regulatory authorities are now likely to insist that they are seen to be applied in the engineering and safety decisions through to commissioning and operations.

ACKNOWLEDGEMENTS

Thanks are due to the senior staff of the consortia who compiled the private unpublished monograph *The NNC Story* and to the individuals listed in Appendix F who have contributed information and comments from their experience of the engineering and management of the Magnox and AGR projects. The opinions indicated in this report are the responsibility of the authors.

CORRECTIONS AND COMMENTS

Corrections and comments on this report are welcome and should be sent to
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THIS REPORT

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APPENDIX A – UK CIVIL NUCLEAR POWER CONSORTIA 1955-1972

The consortia established in 1955 were:

CONSORTIUM	POWER PLANT	BOILERS	REACTOR MECHANICAL PLANT	REACTOR PRESSURE VESSELS	CIVIL ENGINEERING CONSTRUCTION
AEI - JOHN THOMPSON [i]	Associated Electrical Industries	John Thompson	John Thompson Ordnance	John Thompson	Balfour Beatty and John Laing employed but were not consortium members
EE/B&W/TWC[ii]	English Electric	Babcock & Wilcox	English Electric	Babcock & Wilcox	Taylor Woodrow Construction
GEC / SIMON CARVES [iii]	GEC	Simon Carves	GEC	Motherwell Bridge employed but was not a consortium member	John Mowlem (Scotland) employed but was not a consortium member
NUCLEAR POWER PLANT CO (NPPC)	C A Parsons and A Reyrolle	Clark Chapman and Head Wrightson	Strachan & Henshaw[iv]	Whessoe	Sir Robert McAlpine and Alexander Findlay

plus in 1957:

ATOMIC POWER CONSTRUCTIONS (APC) [v]	Richardsons Westgarth and Crompton Parkinson	International Combustion	Fairey Engineering	Babcock & Wilcox employed but not a consortium member	Trollope & Colls and Holland, Hannen & Cubitts.[vi]

Sources: *Nuclear Engineering*, 1963, pp 96-99, The structure of the British nuclear industry, and *The NNC Story*

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i The AEI-John Thompson and the Nuclear Power Plant Co. consortia amalgamated in 1960 to form the Nuclear Power Group (TNPG).

ii Reformed as Nuclear Design & Construction (NDC) in 1965. Incorporated as British Nuclear Design & Construction (BNDC) in 1969.

iii The GEC / Simon Carves Atomic Energy Division joined the Atomic Power Constructions in 1962 to form the United Power Company (UPC). UPC was dissolved in 1964. GEC remained responsible for the completion of Hunterston A and Tokai Mura, but sold their turbine-alternator business to Parsons.

iv Strachan & Henshaw also designed and supplied fuel charging machines for other consortia's reactors.

v APC, BNDC and TNPG went on to undertake the UK's programme of Advanced Gas-Cooled reactor (AGR) power stations, but APC went into administration in 1969.
Staff from BNDC and TNPG finally formed the core of the National Nuclear Corporation (NCC) organization last employed on the Sizewell B pressurized water reactor (PWR) project. NNC was purchased by Amec in 2007.

vi These two civil engineering contractors had formed 'Nuclear Civil Constructors' when planning to be founder members of APC, but they and Elliott Automation withdrew from being consortium members of APC before it was awarded a contract.

APPENDIX B - THE UK MAGNOX AND AGR POWER STATION PROJECTS

The UK consortia undertook the engineering, construction and commissioning support of the following projects:

PROJECT	REACTOR net MWe	TYPE	CUSTOMER	CONSORTIUM	YEAR*	CLOSED	COMMENTS
Berkeley (Gloucestershire)	2 x 138	Magnox	CEGB	AEI - John Thompson	1962	1989	
Bradwell (Essex)	2 x 150	Magnox	CEGB	NPPC	1962	2002	
Hunterston A (Ayrshire)	2 x 160	Magnox	SSEB	GEC / Simon Carves	1964	1990	Managed by UPC 1962-1964
Latina (Italy)	1 x 200	Magnox	Enel	NPPC	1963	1986	
Hinkley Point A (Somerset)	2 x 225	Magnox	CEGB	EE/B&W/TWC	1965	2000	
Trawsfynydd (Gwynedd)	2 x 235	Magnox	CEGB	APC	1965	1993	
Tokai Mura (Japan)	1 x 166	Magnox	JAPCo	GEC / Simon Carves	1966	1988	Managed by UPC 1962-1964
Dungeness A (Kent)	2 x 250	Magnox	CEGB	TNPG	1965	2006	
Sizewell A (Suffolk)	2 x 210	Magnox	CEGB	NDC	1966	2006	
Oldbury (Gloucestershire)	2 x 217	Magnox	CEGB	TNPG	1967	2012	
Wylfa (Anglesey)	2 x 495	Magnox	CEGB	BNDC	1971	2015	
Dungeness B	2 x 545	AGR	CEGB	APC → NDC	1985		Managed by GEC from1969
Hinkley Point B	620 & 600	AGR	CEGB	TNPG	1976		
Hunterston B	610 & 605	AGR	SSEB	TNPG	1976		
Hartlepool (Durham)	2 x 595	AGR	CEGB	NDC	1984		
Heysham 1 (Lancashire)	2 x 615	AGR	CEGB	BNDC	1985		
Torness (East Lothian)	2 x 625	AGR	SSEB	NNC	1988		
Heysham 2	2 x 615	AGR	CEGB	NNC	1988		

* Year of completion of the first reactor of each pair.

Berkeley to Sizewell A had steel reactor pressure vessels. Oldbury and all after had prestressed concrete reactor pressure vessels.

The capacity of each Calder Hall reactor was 50 MWe (first reactor completed in 1956, closed in 2003).

Some of the Magnox reactors were operated below the MWe stated above

Sources: http://www.british-energy.com/pagetemplate.php?pid=425; http://www.nda.gov.uk/sites/; http://www.world-nuclear.org/info/inf84.html.

APPENDIX C – BIBLIOGRAPHY

MAGNOX PROJECTS ENGINEERING

Atkinson R V, Bird R H *et al*, 1968, Refueling of gas-cooled reactors, symposium, 12 December 1968, *Proceedings of the Institution of Mechanical Engineers,* v 183, part 3 G, papers covering:
Berkeley - Connor F P & Thomas T, pp 45-55
Bradwell, Dungeness 'A', and Oldbury - Fortey J & Vowlest A F, pp 116-123
Hinkley Point 'A' - Atkinson R V & Lawson D S, pp 131-159
Sizewell and Wylfa - Rawson P J & Shipman T, pp 99-108
Tokai Mura - Bird R H & Saunders A S, pp 56-61
Trawsfyndd - Harding H W, pp 37-44

Bailey R W & Hicks R, 1960, Behaviour of perforated plates under plane stress, *Journal of Mechanical Engineering Science*, v2, n2, pp 143-161

Bailey R W & Hicks R, 1960, Localized loads applied to a spherical pressure vessel through a cylindrical insert, *Journal of Mechanical Engineering Science*, v 2, n 4, pp 302-311

Baker A L L, Moncrieff M L A et al, 1962, The design, construction testing of a prestressed concrete reactor pressure vessel model, *Proceedings of the Institution of Civil Engineers,* v23, n3, paper 6557

Bird, R.H, 1957, Coolant gas circuit and steam raising plant, *Atomics*, 8(7), July, 245-250

Brown A & Weston J M, 1966, Steam turbine plant for Wylfa nuclear power station, *Nuclear Power Plant*, conference, Paris, Société des Ingénieurs Civils de France and the Institution of Mechanical Engineers, Institution of Mechanical Engineers, pp 12-26

Chambon P, 1966, Boiler plant at Wylfa nuclear power station, *Nuclear Power Plant*, conference, Paris, Société des Ingenieurs Civils de France and the Institution of Mechanical Engineers, Institution of Mechanical Engineers, pp 1-11

Gill S S, 1970, *The Stress Analysis of Pressure Vessels and Pressure Vessel Components,* Pergamon Press

Gill S S, 1982, Pressure vessels - analysis for design, *International Journal of Mechanical Sciences,* 24, special issue

Harwood A E, Scott P & Stonehouse B H, 1959, The design of electro-mechanical auxiliaries directly associated with power producing reactors, *Proceedings of the Institution of Electrical Engineers,* 106, pt A

Hicks R, 1958, Theoretical analysis of the stresses induced in a spherical pressure vessel due to the constraining effect of a cylindrical skirt, *Proceedings of the Institution of Mechanical Engineers,* v 172, pp 707-726

Hicks R, 1959, Asymmetrically ring reinforced circular hole in a uniformly end-loaded flat plate with reference to pressure vessel design, *Proceedings of the Institution of Mechanical Engineers*, v 173, pp 329-342

High pressure gas as a heat transport medium, symposium, 9-10 March 1967, *Proceedings of the Institution of Mechanical Engineers*, 1966-67, v 181, part 3 I

Holmes R L, Southwood J R M & Whitehouse P R, Boilers for nuclear plant, in Steam Plant for the 1970s, convention, 23-25 April 1969, *Proceedings of the Institution of Mechanical Engineers*, v 183, part 3O, pp 64-70

Institution of Civil Engineers, 1967, *Prestressed Concrete Pressure Vessels*, conference, London

Irving J, Carmichael G D T & Hornby I W, 1974, A full-scale model test of hot spots in the prestressed concrete pressure vessels of Oldbury nuclear power station, *Proceedings of the Institution of Civil Engineers,* 2, 57, pp 331-351, and pp 795-798

Jones T E M & Twigg B K, 1962, Fabrication of heat-exchanger shells for Bradwell nuclear power station, *British Welding Journal*, v 9, pp 199

Moncrieff M L A, 1958, British Patent 800,388, *Improvements in or Relating to Nuclear Reactors: Elastically-hinged joints in concrete vessel*

Muto K, Bailey R W & Mitchell K J, 1963, Special requirements for the design of nuclear power stations to withstand earthquakes, *Proceedings of the Institution of Mechanical Engineers*, v 177, n 7

Noone M J & Bishop R F, 1961, Pressure vessels for gas-cooled graphite-moderated reactors, *Proceedings of the Institution of Mechanical Engineers*, v 175, pp 471-495

Stonehouse B H & Spurgin A J, 1961, The control of nuclear power stations, *Electrical Review*, v 169, n 24, 15 December, pp 945-949

Udall, Marilyn S. (ed.), 1968, *Prestressed Concrete Pressure Vessels,* conference, Institution of Civil Engineers:

Barber D, McLelland G S & Seaton A R, *Corrosion protection of the Wylfa vessel cooling system*, pp 725-733

Langan D, *Correlation between theory and experiment - Wylfa vessel*, pp 435-446

Vaughan, R D, 1957, Optimization of the NPPC design [Bradwell], *Nuclear Engineering*, 2(13), April, 141-151

Vaughan, R.D, J.R.M. Southwood *et al*, 1964, Berkeley and Bradwell nuclear power stations, symposium, 27 June 1963, *Proceedings of the Institution of Mechanical Engineers*, special volume

Waters T C & Barrett N T, 1963, Prestressed concrete pressure vessels for nuclear reactors; *J. Brit. Nuclear Energy Soc*, July 1963; and discussion April 1964

West H & Shaw A L, 1958, *Trends in the Design of Large British Nuclear Power Stations*, World Power Conference.

AGR PROJECTS ENGINEERING

The Construction, Commissioning and Operation of Advanced Gas-Cooled Reactors, 1977, conference, May, Institution of Mechanical Engineers

International Atomic Energy Agency, 1980, *Advanced Gas-Cooled Reactors*, conference, Lausanne, September

Jenkins G E C, 1992, AGR - fulfilling the potential, *Proceedings of the Institution of Mechanical Engineers*, pp 21-31

Jones W K C, Rider G & Taylor D E, 1986, Modification increases AGR boiler output, *Chartered Mechanical Engineer*, pp 58-62

Johnston G, 1989, Heysham 2 and Torness AGRs raise power in record time, *Nuclear Engineering International*, v 34, pp 59-61

Logie J H & Royston D E, 1995, Hunterston B advanced gas-cooled reactor - development of electrical auxiliary system with station life, *Nuclear Energy*, v 34, n 6,pp 361-368

Moore R V & Thorn J D, 1963, *Advanced Gas-Cooled Reactors - An Assessment*, British Nuclear Energy Symposium on AGR, March, pp 3-17

Simpson H, 1990, A comparison of predicted and measured temperatures in the insulated areas of four advanced gas cooled reactors, *Thermohydraulics of Nuclear Reactors*, conference, Institution of Mechanical Engineers, pp 68-75

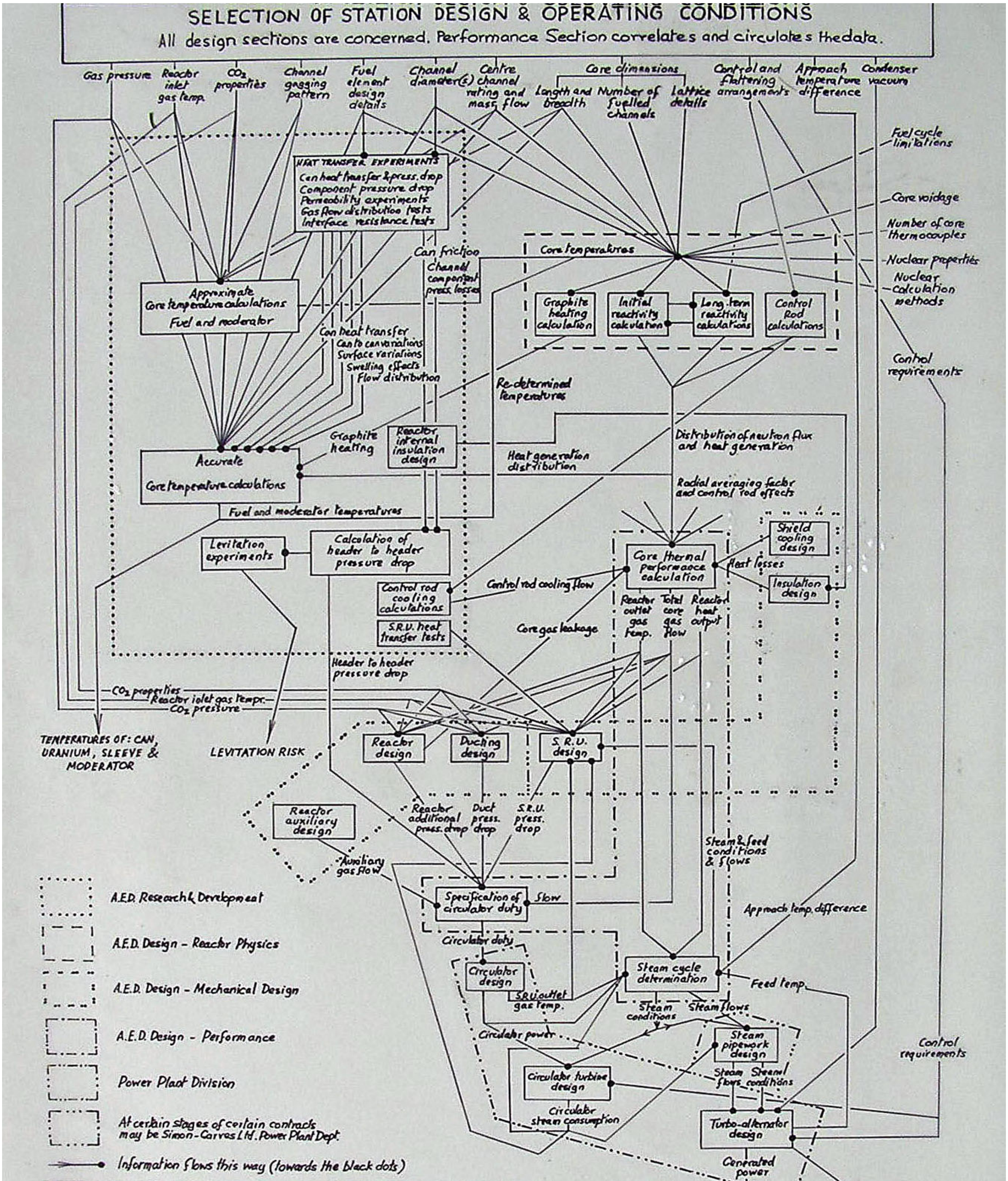
Smith D R, 1979, AGR design for Heysham 2 and Torness, *Nuclear Energy*, v 18, n 4, pp 251-259 , and v 19, n 2, pp 104-104

Vaughan R D & Smith D R, 1966, Exploitation of the AGR for Hinkley Point B, *Nuclear Power Plant*, conference, Paris, Société des Ingenieurs Civils de France and the Institution of Mechanical Engineers, Institution of Mechanical Engineers, pp 27-43

Westerman M, 1988, Commissioning: programmes, problems and procedures at Heysham B and Torness reactors, *Nuclear Power Station Project Management*, conference, British Nuclear Energy Society, Blackpool, 20-22 July 1988

APPENDIX D – NUCLEAR POWER STATION DESIGN DEPENDENCIES

The diagram overleaf was drawn in 1960 to guide a project team in understanding the interdependence of decisions in the design of a nuclear power station.



WORK & FLOW OF INFORMATION FOR STEADY STATE PERFORMANCE ESTIMATE OF A NUCLEAR POWER STATION WITH TURBINE DRIVEN CIRCULATORS

NOTE: The outcome of any stage of calculation or design may call for a feed-back to the selection of design and operating conditions.

R.H.B. SEPTEMBER 1960

APPENDIX E – WHY CONSORTIA ?

The Choice in 1955

The records found from 1955 do not state why the AEA recommended the formation of consortia to design and build the Magnox projects for the first nuclear power programme. The government's Sanders Committee appointed in 1964 to review the organisation of the UK nuclear industry could not trace the reasons for that recommendation.[42]

The Sanders Committee was a group of senior civil servants, advised by the AEA and CEGB. The Committee papers state that their objective was "to examine the effect of tendering methods on the capital cost of nuclear power stations". The Committee was probabaly appointed because of the public argument about fairness in 1963 in the choice of consortium for the Wylfa nuclear project. There is no indication in the Committee papers that they obtained the views of the nuclear consortia, or lessons from other industries. The papers show that the Committee concentrated on organisational questions on the role of the consortia in relation to the AEA.

The Committee papers state that trends in the coal and chemical industries towards turnkey contracts for new projects were thought to have influenced the decision to encourage the engineering companies to form consortia for the UK's first nuclear power projects. All parties appear to have assumed that turnkey contracts were the natural contract structure when employing consortia. A turnkey contract had been successful for the Fawley Refinery project, then the largest industrial project completed in the UK, but the chemical and coal industries did not in fact usually use turnkey contracts.[43] Nor were they used for 'conventional' coal-fired UK power station projects.[g]

The Sanders Committee papers indicate that they discussed whether the CEGB should abandon turnkey contracts. One Committee paper reported the view that abandoning turnkey contracts for further nuclear power projects would be contrary to US practice. Turnkey contracts were the basis of new nuclear power stations in the USA only from 1962 to 1966. The US reactor engineering companies ceased offering turnkey contracts because of the cost risks.[44]

The Committee papers include comments that there were then too many consortia then competing for the relatively few projects, but not the question why a fifth consortium had been allowed to enter the market after the first four. The papers record the view that grouping of companies in the consortia around the heavy electrical manufacturers wrong in principle as electrical plant only 20% of project capital cost. The Committee papers indicate that they did not go on to discuss this.

No report by the Committee has been found and their conclusions were probably not published. It is possible that the priority for the government and the two utilities following *The Second Nuclear Programme* White Paper in April 1964 was action to proceed with the new nuclear power stations, rather than questions of contract structure.

Potential Use of Consortia as Contractors

The potential advantage to the utilities was that a consortium would be responsible for delivering a project complete, up to handover to the utility as the licensed operator to manage the loading of fuel and testing through to commissioning the plant. A disadvantage was that the utility was one contract removed from contact with the major suppliers of the mechanical and electrical power plant and the construction contractors.[45] In the Magnox programme it was the consortia not the utilities that gained the first-hand experience and learned the need for a central engineering and project management authority, and with this how to coordinate detailed discussions of design, operating and maintenance detail between the suppliers and the future users of the systems, plant and services.

A common lesson from the UK nuclear and other consortia operations is that the utilities expect a joint organization of contractors to act as a quasi-customer in leading its set of member companies to deliver the whole project not just each company its own part. Different understandings of the meaning of the term 'consortium' were one cause of problems in achieving this between the Magnox consortia

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[g] A later exception in the UK was a turnkey contract in 1970 between the SSEB and NPPC for an oil-fired power station

and their member companies. Without an agreed definition some stakeholders may assume that 'consortium' means that its role is only to provide coordination whereas their customer expects it to take the cost risks of project delivery.

A customer employing a joint set of contractors to deliver a project should therefore be concerned that not only are the contract liabilities underwritten by all the parent companies of the members of the cooperative agreement, but also that those companies establish a central organization with the resources and authority to decide what is best for managing the engineering and managerial risks of delivering the project through to achieving its promised performance. Cooperative projects are only part of the interests of companies that form consortia, alliancing and other joint ventures. Their other interests may cause divergence and uncertainties in their internal relationships as they proceed with a project. The greater the risk that a common interest may not be sustained through a project the higher the level of internal pre-nuptial agreement needed on authority and accountabilities.[h]

[h] This section draws on an article 'Contractor collaboration for new nuclear power stations' published in *Nuclear Future*, 2013, v 6, n 1, 18-22, and a paper Bird R H & Wearne, S H, 2016, *Contract structure for new nuclear projects,* Project Management and Sustainability Resources Group, University of Manchester..

APPENDIX F – CONTRIBUTORS TO THESE NOTES

D W T Angwin

BSc, CEng, FIMechE, CCIMgt

War service, Royal Navy. 10 years with GEC, including secondment to AEA during building of Calder Hall. Chief Engineer Construction, Hunterston A, and Resident Manager, GEC/Simon-Carves Atomic Energy Group. 10 years with Guest Keen & Nettelfold Group as a director of several companies. Chairman, British Metalworking Plant Makers Association. Since 1974 independent business management consultant in a variety of temporary executive roles including "company doctor" on four successful turnarounds and other assignments involving the management of change and exploitation of opportunity.

R H Bird

BScTech(Hons), CEng, FIMechE, AMCT

In 1955 transferred from Simon-Carves Boiler Department to the GEC/Simon-Carves Atomic Energy Group to work on the design and execution of the Hunterston A and Tokai Mura power stations. Appointed Chief Performance Engineer in 1958. Two years on the Tokai Mura site as Chief Engineer and saw the project to its conclusion. Subsequently joined the Reyrolle-Parsons Group of companies (later Northern Engineering Industries) and played a leading role in 'conventional' power station projects for London Transport, British Steel and the National Thermal Power Corporation of India. Now retired and living on the edge of the Lake District.

Peter Cameron

MBE, FREng, BSc(Tech), FIMechE

Seconded from Metro-Vickers (AEI) at the formation of the AEI-John Thompson consortium in 1955. Responsible for turbo-generators and associated equipment. Later member of BWR proposal team and the Design Manager, Inverkip Project. Manager, Conventional Engineering, NNC, 1980. Elected a Fellow of the Royal Academy of Engineering. General Manager of Gas Reactor Construction, NNC. Project General Manager and Chief Engineer, Heysham 2 and Torness, NNC.

R A Flint

CEng, FIEE, FIERE

In 1955 joined English Electric Atomic Power Division; on design and build of large analogue computer for reactor kinetics and control studies; leader fuel handling machinery control equipment design; 1964 Deputy Head Control and Instrumentation Department; 1966 Chief Electrical Engineer NDC; 1971 Engineering Manager, Dungeness 'B' (secondment from BNDC); 1975, on formation of NNC, Special Assistant to Chairman and Managing Director; 1976 General Manager Nuclear Power Company (Whetstone); 1980 General Manager PWR; 1982 Lead Witness on Capital Costs, Sizewell 'B' Inquiry; 1986 Business Manager; 1987 General Manager Special Projects; May 1990 Deputy Operations Director for Defence and Process Engineering Divisions; September 1990 Operations Director for Defence and Process Engineering Divisions. Retired in 1991. Author of published papers on large analogue computers, application of digital computers to reactor control and instrumentation, and nuclear power plant control systems.

S A Ghalib

CBE, FREng, BSc(Eng)

Sel Ghalib was the General Manager responsible for the formation of the AEI-John Thompson consortium in 1955. On the merger with the Nuclear Power Plant Co in 1962 he became the Commercial Manager and Deputy General Manager of The Nuclear Power Group. From 1966 to 1973 General Manager of The Nuclear Power Group. Managing Director, National Nuclear Corporation 1973 until retirement in 1975.

Stanley Gregory

B.Sc.(Tech), MIMechE

Structural Design and Development Engineer, GEC/Simon Carves Atomic Energy Group, 1955. Development Engineer with Head Wrightson; Assistant to the Group Technical Director of Winget Gloucester Group (became part of Babcock and Wilcox Group); Technical Director of Winget Ltd; Managing Director of Winget Refrigeration, Blaw Knox Steelworks and Blaw Knox Transmission Lines; President of Babcock Contractors Ltd, Pittsburgh; Managing Director of Seaforth Engineering Ltd (subsidiary of Taylor Woodrow); Managing Director of GEC Mechanical Handling Ltd.

Raymond Hicks
BSc, MSc, PhD, CEng, MICE, MIME
Head of Structural Development, GEC/Simon-Carves Atomic Energy Group, 1955. Led a team of specialist graduates to analyse stress distributions in reactor vessels, supporting skirts, grillages, etc. Worked closely with Japanese engineers on problems of earthquake design. Joined Head Wrightson in 1960 as Development Manager, and the Winget Gloucester Group in 1962 as Group Technical Director. As a result of this group being taken over by Babcock moved to Tyneside to be Managing Director of Huwood. In 1979 became Managing Director of Babcock Mining Services. Retired 1985.

George Inglis
CBE, FREng, BSc, CEng, FIMechE
In 1952 seconded by Parsons to the PIPPA design team at Harwell. Senior Design Engineer on Calder Hall. Joined the Nuclear Power Plant Co at its formation in 1955 as Chief Mechanical Engineer. In 1961 joined the AEA Production Group as Chief Engineer (Fuel). Appointed Director, Fuel Division, British Nuclear Fuels Ltd, and main Board Member. In 1984 appointed Managing Director, URENCO. Retired 1992.

Harry Kline
MBE, MC, ERC, RE (AER), CEng, FIEE
Royal Engineers and Royal Electrical & Mechanical Engineers from 1939. Unilever and W S Atkins. Deputy Commercial Manager, Atomic Power Constructors, 1957-1962. United Power Company, 1962-1964 and GEC, 1964-1978. Project Manager, Tokai Mura, 1962-1966. Project Director, 1969. Managing Director, GEC Transportation Projects, 1969-1978. Consultant Nichols Kline International.

Derek Limbert
Eur Ing, CEng, BSc, FICE
Joined Taylor Woodrow at Hinkley Point A in 1961.Various levels of site civil section management at Wylfa, Dounreay PFR and Hartlepool. Design and development work on Dungeness B in the 1960s Reactor Manager at Heysham 1 and Overall Project Manager at Heysham 2. Subsequently involved with Sellafield and Trident construction work as contracts manager. Managing Director of TW Civil Engineering 1990-1999.

Peter A. Lindley
BSc(Eng), ACGI
Chief Engineer of the GEC/Simon-Carves Atomic Energy Group at its formation in 1955. Led the design team which prepared the initial proposal (tender) designs for Hunterston and Tokai Mura for the GEC-Simon Carves group. Later joined Westinghouse Electric Corp. in their Nuclear Fuel Division and was responsible for the management of some of their development programs for PWR fuel. Has also worked on uranium extraction technologies for both Westinghouse and Gulf Oil Corp.

Stephen Mitchell
BSc(Eng)
Initially with Shell Tankers (UK) Ltd, then moving to GEC Large Steam Turbine Division based at Rugby. Worked on various aspects of the Power Plant Technology, Construction and Commissioning associated with the AGR Program at Hartlepool and Heysham. Joined BP Group of Companies in 1978 and after initial involvement in their power generation projects moved into management of their major project portfolio in South East Asia and the USA. On retiring from BP in 2008 and returning to the UK. engaged by BP initially as a Subject Matter Expert for their Managing Projects and Engineering Management courses held at the University of Manchester and then as a Project Management Consultant for their Alternative Energy Business.

Malcolm Moncrieff
BSc(Eng), PhD, CEng, FICE, FIStructE
Following involvement with the design of the research reactor in Chalk River Ontario and a shielding research facility at Harwell joined GEC/Simon-Carves Group in 1955 on the civil and structural design of Hunterston A and Tokai Mura reactors. During this time involved with the early development and model test of prestressed concrete pressure vessels. Simon-Carves representative in Japan 1960-1963. Subsequently Research Fellow at Imperial College managing research project testing a AEA-designed spherical prestressed concrete pressure vessel. Then ten years with Kiers looking after a design-and-construct department. Joined Pell Frischmann. Director of three of their companies,

responsible for a lot of overseas work, mainly in the Middle East. Retired in 2002. Later an Expert Witness for a number of cases, several of them collapses.

Norman Sellers

MSc, CEng, MIET, MInstP.

Joined the AEA Fast Reactor team at Dounreay in 1957, and then to NPPC and commissioned the reactor control system at Latina. Appointed Head of Electrical Research, Central Electricity Generating Board, North West Region in 1962, returning to Nuclear Operations at Wylfa and as Deputy Power Station Manager at Hartlepool in 1974. Seconded to the Sizewell B Project Team in 1998 and after two years in Atlanta with the Institute of Nuclear Operations (INPO) was appointed Operations Evaluation Manager until retirement in 1992.

Derek Smith

OBE, MA, FREng, FIMechE, MIEE.

In 1955 joined AEI-John Thompson consortium as a founder member, soon made responsible for the design the reactor design of Berkeley Magnox nuclear power station. Following the merger to form TNPG in 1959 served that consortium and its successors in various senior management roles. Appointed Chief Engineer of the Sizewell B Joint Project Team in 1981, continuing in that role throughout the successful Public Inquiry. Appointed Engineering Director of the National Nuclear Corporation in 1983 and elected a Fellow of the Royal Academy of Engineering in the same year. Author of numerous invited technical papers on nuclear reactor design and safety. Retired 1991 and joined several retired colleagues to write *The NNC Story.*

Bernard Stonehouse

BSc(Eng), CEng, FIET

Joined GEC/Simon Carves Atomic Energy Group in 1955 to design the electrical plant associated with the nuclear plant. Chief Electrical Engineer of the Group 1959-1963. Returned to GEC 1964.

Malcolm Tilley

BSc, BA, CEng, FIMMM, MIMechE.

Joined GEC Atomic Energy Division in 1959. Assistant Engineer at Hunterston. Reactor Plant Engineer at Tokai Mura, British General Electric Co, Japan, 1965-1967. Joined ICI Dyestuffs Division as Technical Officer. Ritchies Blasting Agents, Plant Manager, Widnes. In 1969, joined Anglo American Corporation on the Zambian Copperbelt, in engineering and managerial appointments, the major appointment being General Manager, Maamba Colliery. In 1989 returned to the UK as Senior Port Engineer, Forth Ports in Edinburgh. Progressed to Chief Engineer for the company, now Forth Ports plc. Retired in 1996.

Roger Vaughan

OBE, FREng, BMechE, FIMechE

Chief Engineer of the Nuclear Power Plant Co at its formation in 1955 and appointed Director in 1959. Held same position in The Nuclear Power Group following the merger of NPPC and AEI/JT in 1962. He was single-minded in promoting gas-cooled reactors beginning with the Oldbury Magnox concept for overseas and then the AGR. These reactors were succeeded by the helium-cooled HTR with ceramic fuel and the CO_2 cooled fast breeder reactor conceived as an international project in Brussels. With the amalgamation of TNPG and BNDC to form NNC in 1975 headed a new Technology Division responsible for physics and performance as well as research and development for all company projects. Took over the Fast Reactor Division which was to secure the early operation of PFR and the CDFR concept to surpass the French Super-Phenix. The fast reactor was seen to be costly and uncompetitive until there is at least a fourfold increase in uranium price. This led to many collaborative schemes with other countries which have yet to bear fruit.

Stephen Wearne

BSc(Eng), DIC, PhD, CEng, FIMechE, FICE, HonFAPM.

Site mechanical construction engineer at Bradwell, NPPC, 1957. Moved to the GEC/Simon-Carves Atomic Energy Group as reactor engineering coordinator for Hunterston A and then Project Engineer for Tokai Mura. Previously employed in the design, construction and coordination of hydro-electric projects in the UK and South America. Professor (Emeritus) of Technological Management, University of Bradford, 1974-1984. Senior Research Fellow, Management of Projects Group, University of Manchester, UK. Author and co-author of books and papers on project organization, engineering contracts, joint ventures and the management of urgent unexpected projects.

Alan Young

BSc(Hons)(Eng), MBA

Civil engineer British Railways 1957. Planning engineer AEA 1959 for projects at Risley, Capenhurst, Windscale, Chapelcross and Hunterston A. Moved to GEC in 1962 as planning engineer at Hunterston A and site manager for Tokai Mura in 1964-1965. Joined SSEB in 1966 as senior engineer for Hunterston B and deputy project manager for Torness. Operations director, John Brown Engineering, 1982-1989, responsible for 63 power stations world-wide. Commercial director, Scottish Hydro-Electric 1989-1994. Managing director Scottish Overseas Health Support 1994-1997. Non-executive director AEA 1999-2007, Member Competition Commission 1998-2008 and director Webster Young Limited (energy and business consultancy) 1965

REFERENCES

[1] HM Government, *A Programme of Nuclear Power*, 1955, White Paper, London: HMSO, Cmd 938. Nuclear power was then welcomed world-wide as the answer to the demand for of energy – see for instance: Price, T, 1990, *Political Electricity*, Oxford University Press, and articles in *The Economist,* 23 July 1955, 11 March 1956, and 1 December 1956,

[2] Gowing M & Arnold L, 1974, *Independence and Deterrence, Britain and Atomic Energy – Vol 2: Policy Execution*, Macmillan
At the time of the 1955 White Paper the UK had no facilities for producing enriched uranium. The plutonium produced by the reactors was also potentially valuable for a future programme of fast breeder power stations

[3] Appendix E reviews the evidence for recommending the employment of contractor consortia

[4] The AEA was the UK's nuclear safety authority until the creation of the Nuclear Installations Inspectorate (NII) in 1965

[5] Baker R J S, 1962, *The Management of Capital Projects – Studies in the Coal, Transport and Electricity Supply Industries*, G Bell & Sons for the London School of Economics & Political Science

[6] Gowing & Arnold state that the AEA had rated John Thompson highly as the exception to an evaluation of British boiler maker companies as "only sophisticated blacksmiths"

[7] The word 'conventional' is used in the electricity supply industry to denote non-nuclear power plant

[8] Fletcher P T *et al*., 1995, *The NNC Story*, unpublished

[9] See *The NNC Story* and also a personal memoir by Hicks R, 2007, *An Odyssey: From Ebbw Vale to Tyneside*, Tyneside Free Press

[10] Margerison T, 1956, The new nuclear power stations, *New Scientist*, December 27, 10-12

[11] For instance in what might appear to be the simple coordination of space and economy in station layout required agreement between thermodynamic, control, construction, inspection, commissioning and maintenance ideals early in project design - Hunt J A & Wearne S H (1966), Logical design of power reactor layout, *Nuclear Structural Engineering*, 1966, v 3, no l, 83-94

[12] Fletcher P T, 1975, Interpreting the concept – A project role, *Proceedings of the Institution of Mechanical Engineers,* vol 189, 351-366

[13] Hill P F, 1966, Power reactors – Market analysis*, Nuclear Engineering*, v 291, 290-293

[14] A consortium's central expertise was crucial for instance (i) in design when a member company's strong preferences conflicted with the central team's conclusions on what was best for a project, (ii) in tendering when setting risk provisions, (iii) in procurement when an outside company's offer was preferred to that from a member company

[15] See the papers of the government committee *Nuclear Power Policy in the United Kingdom*, 1961-1962, committee, TNA PRO EG 1/355, and Webster T, 1961, The profit and loss of nuclear power, *British Power Engineering*, December, 57-59

[16] The change in the APC structure from two civil engineering contractors being consortium members to being sub-contractors may have led to doubt about terms of contract after a letter-of-intent which became the case *Trollope & Colls and Holland Hannen and Cubitts Ltd v Atomic Power Constructions Ltd*, QBD, 26 October 1962

[17] British Nuclear Fuels Ltd (BNFL) was created in 1971 from the AEA's nuclear fuel manufacturing and reprocessing operations

[18] Lord Citrine, quoted by Taylor

[19] *Report of the Committee of Inquiry into Delays in the Commissioning CEGB Power Stations,* 'the Wilson report', 1969, HMSO
Large Industrial Sites, report, 1970, National Economic Development Office, and subsequent reports of industry working parties

[20] At one site the reactor pressure vessel contractor's work was seriously delayed by industrial relations problems in other industries. The consortium's site manager took over managing the contract and obtained government, corporate and trades union support to actions which restored productive industrial relations

[21] No evidence has been found to support or confound the belief at the time that the attention to nuclear risks engendered a greater general safety consciousness

[22] In the Magnox era the concept of project management was only beginning to be recognised in the chemicals and aerospace industries. Critical path scheduling was used in the Magnox consortia. Other techniques such as design reviews, risk analysis and configuration management were probably in effect applied by individuals but not as recognised management discipline.

[23] Wearne S H, 1993, *Principles of Engineering Organization*, 2nd ed, Thomas Telford Ltd

[24] GEC withdrew from further nuclear power projects but as a result of merger with English Electric and take-over of AEI became the dominant company in the consortia. See Jones R & Marriott O, 1970, *Anatomy of a Merger, A history of GEC, AEI and English Electric*, Jonathan Cape

[25] Butler, G. and Abram, T, 2014, FOAK-NOAK in Nuclear – Model or Reality, *Nuclear Future – Journal of the Nuclear Institute*, 10 (3), 38-41

[26] Burn D, 1978, *Nuclear Power and the Energy Crisis: Politics and the Atomic Industry,* Macmillan, for the Trade Policy Research Centre
Hill, C. N, 2013, *An Atomic Empire - A Technical History of the Rise and Fall of the British Atomic Energy Programme*, Charterhouse

Taylor S, 2007, *Privatisation and Financial Collapse in the Nuclear Industry*, Routledge
Williams, R, 1980, *The Nuclear Power Decisions*, Croom Helm

[27] Ministry of Power (April 1964) *The Second Nuclear Programme* [White Paper] London: HMSO (Cmnd. 2335)

[28] Jones P M S, 1987, *Nuclear Power: Policy and Prospects*, John Wiley and Sons

[29] CEGB, 1965, *Dungeness B AGR Nuclear Power Station*, report, July 1965, Central Electricity Generating Board

[30] See the House of Lords 1968 debate and Burns

[31] Engineering staff from the AEA who had been employed on prototype designs had transferred to TNPG

[32] *World Nuclear News Weekly*, 2-8 August 2016

[33] Every contractor was liable through their customer for reimbursing these costs. Payment was made in at least one case

[34] Particularly Burn, quoting the House of Commons Select Committee, Science & Technology, 1972-1973

[35] Garnsey, R, Nickson, I. & Joyce, M, 2011, Lessons learnt from recent nuclear build projects, *Proceedings of the Institution of Civil Engineers – Energy*, 164 (2), 57-70
Marshall, R. *et al*, 1998, *The British PWR*, special issue, Nuclear Engineering Publications
Royal Academy of Engineering, 2010, *Engineering Future – Nuclear Lessons Learned*, report

[36] Speed in delivering the first Calder hall reactors depended upon concentrating design in one office and discipline in completing detail first time on time

[37] As exemplified by the formation of the UK government's Office for Nuclear Development (OND) to act to enable investment in nuclear new build, following the Department for Business, Enterprise & Regulatory Reform 2008 white paper *Meeting the Energy Challenge*

[38] Flyvbjerg B, Berzelius N & Rothengatter W, 2003, *Megaprojects and Risk: An Anatomy of Ambition*, Cambridge University Press
Merrow, E.W, 2011, *Industrial Megaprojects – Concepts, Strategies and Practices for Success*, John Wiley & Sons
Winch, G.M, 2012, review of Merrow book, in *Construction Management and Economics*, 30(8), 705-708 and earlier in Morris P W G & Hough G H, 1987, *The Anatomy of Major Projects,* John Wiley & Sons

[39] Ruuska I, Artto K, Aaltonen K & Lehtonen P, 2009, Dimensions of distance in a project network: Exploring Olkiluoto 3 nuclear power plant project, *International Journal of Project Management*, v 27, issue 2, 142-153

[40] World Nuclear Association, undated, *Structuring Nuclear Projects for Success*
Kidd S, 2008, Nuclear projects: How should they be structured? *Nuclear Engineering International*, 28, October

[41] Ruuska I, Ahola T *et al*., 2009, *A new governance approach for large projects: Lessons from Olkiluoto 3 and Flamanville 3 nuclear power projects*, International Research Network on Organizing by Projects (IRNOP), IX Conference, Berlin

[42] National Archive document no. AB 38/453 - Copies of memos and papers for the Sanders Committee

[43] Gray L P & Abrams M, 1954, *Construction of Esso refinery, Fawley*, British Institute of Management

[44] Burness H S, Montgomery W D & Quirk J P, 1980, The turnkey era in nuclear power, *Land Economics* v 56, n 2, May, 188-202

[45] The potential disadvantages to the utilities of turnkey contracting with consortia for the Magnox projects were discussed in *The Economist* as early as 23 July 1955