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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
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

UK EXPERIENCE OF CONSORTIA ENGINEERING FOR NUCLEAR POWER STATIONS

Critical Again – Lessons for New UK Nuclear Power Projects

The UK government has indicated its support for new nuclear power stations to be built to replace the many in this country now past or nearing the end of their economic and safe life. Continuing uncertainty in future oil and gas supplies and prices together with commitment to environment emissions targets are likely to sustain this policy. The new stations in the UK are expected to be based on the pressurized-water reactor (PWR) type of reactor as now most preferred by the electrical generation utility companies in the US and Europe, especially France, for new power stations.

The government's wish is that the utility companies will promote and operate these new stations, preferably at least two utilities in competition. Reactor suppliers have recently announced agreements with other engineering and construction companies to design and construct these projects. Consortia of UK 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 partly 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 today 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 programmes of gas-cooled projects, as lessons from that formative period 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 which has the engineering and managerial capacity and authority to integrate and control the design and supply of the whole project. This simple lesson is the same as stated from many capital projects, particularly the process industries. It is agreed in all industrial countries. It is not well sustained by UK companies. Investors may now demand that it is applied. So may the safety regulators.

CONTENTS

UK EXPERIENCE OF CONSORTIA ENGINEERING FOR NUCLEAR POWER STATIONS

1. FIRST FORMATION OF UK NUCLEAR CONSORTIA

In 1955 the UK government encouraged the country's power station turbine-alternator manufacturers to get together with boiler maker companies to form 'consortia' to undertake the development, supply, construction and commissioning support of Britain's first generation of civil nuclear power stations, the 'Magnox' projects.[1] The Magnox power station programme was based upon the government policy of using natural uranium fuel so as to be internationally independent in energy supplies and to produce plutonium for weapon material.[2]

Formation of consortia was recommended to the government by the state Atomic Energy Authority (UKAEA) as necessary 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 UKAEA's natural uranium-fuelled gas-cooled 'PIPPA' reactor design recently put into operation at Calder Hall up to a size which would be commercially attractive to electricity generating organizations. Once formed the consortia were given access to the UKAEA's nuclear information. The UKAEA was the advisor to the customers and was then the UK's nuclear design safety authority.[4] The UKAEA was also the fuel manufacturer and re-processor of the fuel and responsible for its militarily important by-product plutonium.

The UK Central Electricity Authority (CEA) and its successor the Central Electricity Generating Board (CEGB) became the major customer.[5] The consortia supplied eight twin-reactor Magnox stations to the CEGB, and one to the South of Scotland Electricity Board (SSEB). The projects are listed in Table B. There was world-wide interest in the potential of this new source of power. Serious interest was expressed by several countries. Single-reactor Magnox stations were supplied to the Italian power company Enel and to the Japan Atomic Power Co (JAPCo).

Staff of the CEGB had little participation in the designs for the first tenders, perhaps because their nuclear engineering and project management organizations were still being established. They became increasingly influential. After the first projects they encouraged continued development for each successive Magnox project. 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.[6]

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 boiler makers.[7] 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.[8] NPPC had the largest number of member companies, spreading the financial risks amongst the widest range of engineering resources.

Two of the first four consortia included civil engineering contractor members, and two employed contractors without their being consortium members. A pair of civil engineering contractors planned to be members of the fifth consortium, but withdrew from its membership and were instead employed by that consortium. AEI employed a civil engineering consultant 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.[9] 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 their consortium, operating through its Atomic Energy Division.[10] Simon Carves shared 40% of research, engineering and supporting costs up to tendering to a customer, but were GEC’s nominated sub-contractor for the boiler systems and the civil engineering.

3. CONSORTIA RESOURCES

Each consortium established its own new headquarters for its nuclear power work, starting with small engineering, nuclear physics and management teams. 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 UKAEA offices concerned, and the fifth in London.

The first staff for the consortia were seconded from their member companies. Many more engineers and physicists, metallurgists, mathematicians and commercial staff were then recruited from other engineering industries, the UKAEA, research organizations, academia and the armed services.[11] 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 one project and for tendering for more projects.

Babcock & Wilcox, John Laing, Parsons, Reyrolle, Strachan & Henshaw, Taylor Woodrow and Whessoe had experience of major work for Calder Hall, but each as a contractor to the UKAEA. Most of their staff with that experience returned to their companies and few were seconded to their consortia. Parolle, a joint Parsons and Reyrolle company they owned to coordinate collaborative work for conventional 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 any 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

Each consortium established 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 each consortium and by the UKAEA was coordinated by specialist working party meetings led by the UKAEA and attended by CEGB.

5. MAGNOX FUEL

Natural uranium rods in a Magnox sheath were stipulated by the UKAEA to be the basis of the design of the fuel elements for the reactors. Detailed design of the elements for their reactor was the responsibility of each consortium, hence a variety of different designs. For each design a working party was formed by the UKAEA and the relevant consortium, requiring the UKAEA staff involved to take care with the contradictory demands of collaboration and confidentiality.

The UKAEA had responsibility for the fuel manufacture and also for its subsequent reprocessing and waste disposal, and so worked closely with each consortium to agree every detail of each fuel element design.

6. FIRST PROJECTS

The four original consortia developed their reactor designs competitively. Their first tenders were required to offer a design for a complete twin-reactor power station which could be chosen for construction at either Bradwell or Berkeley, in England, or at Hunterston in Scotland. Their station plans and much detailed design to suit a site followed selection of a consortium to build their project.

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 each Calder Hall reactor. These reactor designs were in effect distinct prototypes which the consortia expected to compete for selection as a standard for further contracts.

Some data and the outlines of these four reactor designs became public when chosen for the first sites. This design information was known when the fifth consortium bid for their first project. This fifth consortium bid in competition with the established four and for a designated site, Trawsfynydd.

The four original consortia offered their reactor designs for the first export project, Latina, 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 UKAEA 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 to conform to US engineering standards.

The fifth consortium's reactor design showed similarities to Bradwell, but up-rated. The Sizewell A reactor design was based on the Hinkley Point A design. None of the other reactor designs were repeated.

7. MAGNOX ENGINEERING ACHIEVEMENTS

Greater power per reactor from each Magnox project was achieved by a series of 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 some published papers listed in Appendix C. They demanded step changes in technology in many of the contributing industries, for instance welding, which were then used in other industries.[12]

Different fuel designs led to different designs for fuel handling systems for loading the reactors and for removing the spent fuel. 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-fuelling. 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 much 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 which contained the entire reactor circuits of reactor core, boilers and gas circulator systems.

The consortia’s designs of the reactors, station systems and structures were subject to detailed review by the UKAEA as well as by the customers, and insurers and consulting engineers employed by them. Initially the UKAEA were advisers to all parties and were also the national safety authority until formation of the Nuclear Installations Inspectorate in 1965.

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 unit designs preferred by their individual member companies when 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.[13]

Perhaps because of location in their member companies and their experience of conventional power station work some design and construction staff in those 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 reinforced the need to recognise the interdependence of design roles. To guide all parties the diagram reproduced in Appendix D was used in one consortium to show their interdependence in nuclear, conventional, control and supporting system design. It also showed how many apparently unrelated design decisions are linked so that a small change in one part of the design can have unexpected consequences elsewhere.

UK practice for conventional power station projects had been that the customer, usually through consulting engineers, was responsible for station layout and services, buildings and plant layout, cabling, piping, instrumentation, services and coordinating design, construction and testing. With turnkey contracts the consortia engineering teams had to add expertise in all these requirements for a complete power station and to maintain sustained coordinated attention to the detail through to testing and commissioning.[14] 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

Within each of the first four consortia working relationships were reported to have been friendly, probably partly because of previous work together for Calder Hall or other projects and partly because of the great motivation in individuals evident in this new industry. At higher levels relationships between 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 other direct business with the power utilities.[15] 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 their competitors. By contrast, one observer commented that APC was "not committed to the furtherance of its member companies", taken to mean that the APC management operated in the interests of APC as a company and its management. These risks of divergence and uncertainties in relationships are characteristic of many joint ventures, alliancing and cooperative contracting.[16] The consortia needed engineering expertise and managerial skill to resolve disputes with member companies.[17] Disputes were resolved generally in agreement with the consortium managements' decisions. The problems were anticipated in others 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 from those member companies were then placed 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 employees of the consortium rather than the member company that actually paid their salaries. Later most transferred to being consortium employees, particularly when some consortia amalgamated. At that stage the few leading staff who declined to transfer returned to their member companies.

The AEI-John Thompson and NPPC consortia amalgamated in 1960, to form TNPG, when it seemed likely that the CEGB and other customers would be ordering fewer Magnox projects than first expected. In 1962 GEC and APC formed UPC to manage their projects, but including none of the GEC/Simon Carves engineering team. 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 supporting development, 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 customers paid the costs of changes to the consortia's designs 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 perceptions of need and practicability for these projects. No bond was ever called. To do so would have depended upon distinguishing the effects of new nuclear information from other causes of delay or extra cost.

In the two export contracts the consortia were responsible for specifying but not supplying secondary plant, piping, cabling and construction.

Financing a turnkey contract was a strain for some members of the consortia.[18] Payment to them from the customer was indirect through their consortium, and 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.

No problems in the operation of the terms of these contracts are reported on the reviews of the Magnox programme. The contracts appear to have been used as the basis for cooperation rather than conflict. There were some lengthy and detailed claims for additional payment, but without showing that different terms of contract would have been better for customers or consortia.

11. PROCUREMENT

The consortia entered into contracts with their member companies to employ them as sub-contractors, but differences in consortium structure affected how far these contracts governed their relationships with the companies which were thus their sub-contractors but also owned them.[19]

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 unsatisfactory and replaced by Japanese steel.

The supply and disposal of the nuclear fuel was the subject of a contract between each customer and the UKAEA.[20]

Most other supply was from UK, but not always through member companies. The second tier suppliers were usually selected by the normal processes of competitive tenders from sub-contractors familiar to each member company.

Many quality and accuracy requirements for reactor components were higher than those common amongst their suppliers. Some sub-contractors found great difficulty in reaching the standards required in mechanical construction work for the reactors, for instance nuclear 'clean conditions' requirements. These needed detailed instruction, supervision and inspection by the consortium to achieve specifications.

12. CONSTRUCTION

Each consortium established its construction management teams, as with their design teams based upon a few staff from member companies and many recruits 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."[21] He was partly right. Allowing for their being prototypes, 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.[22] 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 and other industries. The sites 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 in situ 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 new 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 reactor systems were assembled for the first time in the reactor buildings without trial assembly, checking by their design teams or testing before leaving their factories. A widespread difficulty on the first projects was gross under-estimation of the complexity of cable 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 to anticipate potential problems of the sequence and timing of work, use of space, inconsistent labour relations and lack of common services.[23] 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.

Safety in construction of the UK nuclear projects was stated to be better than on other construction sites.[24]

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.

13. COMMISSIONING

The customers were the organizations licensed to operate the 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. 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.

The customers' 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. Joint customer-consortium commissioning teams were set up for the later projects to provide transfer of experience to operational staff.

Some consortia appointed a Commissioning 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.

14. PROJECT MANAGEMENT

The senior managers of each consortium were in effect the project and contract managers of their first Magnox projects. Tendering and obtaining a second contract precipitated greater attention and accountability for each project, in the consortia and down through member companies.[25]

As 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. 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 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.

One consortium's organization was based on practice in manufacturing companies with 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.[26] 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.

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.

One minor lesson found also in other new industries was that each pioneering organization used inconsistent or ambiguous terminology which if continued unchecked could have been hazardous. Boilers were variously also known as 'heat exchangers' or 'steam raising units', and more recently 'steam generators'. The fuel 'elements' for the reactors were also variously referred to as 'cans', 'pins', 'slugs' or 'cartridges', and the PIPPA language lingered in the Magnox projects in the inconsistent use of the terms 'Burst can detection' and 'cartridge leak detection' systems. Potentially more hazardous, in Fermi's pile of graphite bricks in Chicago in 1942 which demonstrated that a carbon moderator would create a natural uranium chain reaction the top layer of bricks was called the 'pile cap'. In the Magnox programme the term 'pile cap' was sometimes used to mean the top of the concrete shield floor above the reactor vessel. 'Charge floor level' was the much safer term for that, to avoid any confusion during commissioning or maintenance which might have permitted access to the pile itself once fuel was loaded. Industry-wide agreement to establish standard terminology was needed.

15. RESULTS OF THE MAGNOX PROGRAMME

The amalgamated TNPG consortium delivered a total of six Magnox projects. BNDC delivered three. The GEC/Simon Carves consortium delivered two, partly within UPC, but ceased to tender after Tokai Mura following GEC's policy of withdrawal from heavy engineering. APC delivered one Magnox project. The projects suffered delays in design, construction and commissioning, and new nuclear data from the UKAEA and engineering problems required many design changes, but none so extensive as to cause any of the projects to be abandoned.

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 closed when their maintenance ceased to be economical. Latina was closed with other nuclear projects in Italy after the Chernobyl explosion. Tokai Mura was closed after exceeding its economic life and it had achieved its prototype role in Japan.

Successive reviews have criticized UK governments, the UKAEA 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' which met the UK's base load demand for power.[27]

16. THE SECOND PROGRAMME – THE AGR PROJECTS

The structure of now three consortia continued after the Magnox programme for the successor programme but with mixed fortunes for the consortia and for their member companies in responding to the decisions by the CEGB and UKAEA on choice of type of reactor and the competition for contracts.[28]

Throughout the Magnox programme the government, UKAEA, 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 UKAEA, 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 UKAEA 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 1965 the CEGB with UKAEA 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.[29] 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 UKAEA's prototype, the APC consortium tendered an AGR design at a price then judged by the UKAEA and CEGB to be competitive with the other consortia's tenders for AGR, BWR or PWR-based designs.[30] 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-fuelling 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.[31]

17. RESULTS OF THE AGR PROGRAMME

TNPG briefly considered working with APC on their design but "soon found that many of the assumptions made and the corners cut" in the proposal were untenable.[32] 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 higher 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".[33] 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 at the insistence of a different customer the repeat followed too soon to take much advantage of sequential loading of suppliers' manufacturing capacity and re-use of construction skills and equipment. As a result of the resulting delay in the reactor work, the completed turbine-alternators and power systems were mothballed 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. The BNDC and TNPG teams were then formed into the National Nuclear Corporation (NNC).[34] 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.[35] 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 refuelling was not achieved. Seven twin-reactor stations in the UK completed the AGR programme. The final two AGR stations, Torness and Heysham 2, were regarded as the most successful, particularly in completion to budget and schedule. Because of high capital cost AGR reactor designs were too expensive to attract export orders.

Torness and Heysham 2 were largely repeat designs but with changes to meet revised safety standards and to suit each site. NNC was responsible for their engineering and construction, but the Electricity Boards (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.[36] 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.[37] 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 and more dependent on design by their member companies. 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.[38] 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. 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.

18. NOW

One difference in the UK now compared to the Magnox and AGR programmes is that adopting a proved type of reactor should minimize research and development time, costs and risks, but it should be noted that many of the lessons from the UK’s previous nuclear programmes were not due to problems arising from nuclear advances and innovations. The managerial lessons were as much the organizational and leadership problems of bringing companies together to design and supply complete projects. PWR technology and its users’ experience can now provide the nuclear heart for new power stations, but a lesson from the Magnox and AGR programmes which is commonly concluded from reviewing other large capital projects world-wide is that to be economic and safe to operate each new project should be planned and controlled by an organization which has the engineering and managerial capacity and authority to integrate and control the design of the whole project.[39] That this lesson is not easily applied even by experienced customers and contractors is demonstrated by a long list of problems of responsibilities and communications between the leading parties recently reported from a current European PWR project.[40]

The utility companies are expected to promote these new projects for the UK. As no UK organization today has designed or managed a nuclear power station project since Sizewell B was completed in 1995, the engineering and managerial strength required will have to be hired or recreated.[41] A utility’s organizational choices in employing contractors and consultants are those of any customer for a capital project - as summarised in Appendix E. Ideally in their contracts the risks of a project should be borne by whoever can best minimise and resolve it.[42] On large projects the major risks affect all parties, but differently. The 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.[43]

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. US and French reactor suppliers have each recently 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 Magnox programme may therefore be directly relevant to them and to the utilities their prospective customers.

One particular lesson from the UK nuclear and many other consortia is that the utilities who are their prospective customers 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 amongst the Magnox consortia and their member companies. The term 'consortium' may mean that a consortium's central role is only coordination. Or it may mean direction and control. A customer employing a joint set of contractors should therefore be concerned that not only are the risks underwritten by all the parent companies of the members of the cooperative agreement, but also that the companies establish a central organization with the resources and authority to decide what is best for managing the engineering and managerial risks of delivering their project right through to achieving its promised performance. Cooperative projects are only part of the interests of each of their members. 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 power and accountabilities.

The Magnox programme was subject to a nuclear regulator which was then also the first developer of the reactor system. Nuclear safety is now 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 indicated its political but not financial 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.[44] It is the utilities and their suppliers who will need to obtain the regulator's approval of their projects.

This report draws on experience of consortium responsibilities for design, construction and commissioning. It takes for granted much that went well. Many of the lessons for all parties are the same as stated from all capital projects, particularly 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 are therefore substantially understood and agreed. Regulatory authorities and investors in new nuclear projects 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 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.

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Gowing M & Arnold L, 1974, *Independence and Deterrence, Britain and Atomic Energy – Vol 2: Policy Execution*, Macmillan.

[2] The UK had then 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] Structure of the British nuclear industry, *Nuclear Engineering*, 1963, vol 8, pp 96-99.

[4] Until the creation of the Nuclear Installations Inspectorate (NII) in 1965.

[5] In 1957 the government owned and financed but operationally independent CEGB replaced the less authoritative CEA (Central Electricity Authority) as the electricity generating, distribution and sales organization for England and Wales. Following privatization the remaining former CEGB and SSEB power stations are now owned by utility companies.

[6] House of Lords, 1968, The Nuclear Reactor Programme, debate, *Hansard*, v 291, 8 May.

[7] Gowing & Arnold state that the UKAEA had rated John Thompson highly as the exception to an evaluation of British boiler maker companies as “only sophisticated blacksmiths”.

[8] The word ‘conventional’ is used in the electricity industry to denote non-nuclear power plant.

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

[10] Jones R & Marriott O, 1970, *Anatomy of a Merger, A history of GEC, AEI and English Electric*, Jonathan Cape.

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

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

[13] For instance in what might appear to be the simple coordination of space and economy in station layout required agreement between thermodynamic, control, construction, 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.

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

[15] Hill P F, 1966, Power reactors – Market analysis*, Nuclear Engineering*, vol 291, 290-293.

[16] Wearne S H & Wright D, 1998, Organizational risks of joint ventures, consortia and alliance partnerships, *Int. Jl. of Project & Business Risk Management*, Spring, v 2, n 1.

[17] 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.

[18] Some of the first tenders may have been priced expecting that part of the costs incurred up to that time would be borne by repeat orders.

[19] The change in the APC structure from two civil engineering contractors being consortium members to being only 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.

[20] British Nuclear Fuels Ltd (BNFL) was created in 1971 from the UKAEA’s nuclear fuel manufacturing and reprocessing operations.

[21] Lord Citrine, quoted by Taylor.

[22] *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.

[23] At one site the reactor pressure vessel contractor’s work was seriously delayed by practices from other troubled 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.

[24] It was a common belief that the attention to nuclear risks engendered a greater general safety consciousness.

[25] In the Magnox era the concepts of project management were only beginning to be defined 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 techniques.

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

[27] Burn D, 1978, *Nuclear Power and the Energy Crisis: Politics and the Atomic Industry,* Macmillan, for the Trade Policy Research Centre.
Taylor S, 2007, *Privatisation and Financial Collapse in the Nuclear Industry*, Routledge.

[28] During this time TNPG were also turnkey contractor for an oil-fired power station for the SSEB.

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

[30] CEGB, 1965, *Dungeness B AGR Nuclear Power Station*, report, July 1965, Central Electricity Generating Board.
Board J & George B, 1986, The Sizewell 'B' PWR - and the relative merits of the AGR, *Chartered Mechanical Engineer*, 31-35.

[31] See the House of Lords 1968 debate and Burns.

[32] *The NNC Story.*

[33] *The NNC Story.*

[34] Three of the UK's largest turbo-alternator and electrical engineering companies which had formed three of the four original competing consortia were by then all part of GEC.

[35] Engineering staff from the UKAEA who had been employed on prototype designs had transferred to TNPG.

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

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

[38] *Sizewell B Public Inquiry*, 1987, report, H M Stationery Office - known as the Layfield report, after its chairman, Sir Frank Layfield.

[39] Morris P W G & Hough G H, 1987, *The Anatomy of Major Projects,* John Wiley & Sons.
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[40] 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, pp 142-153.

[41] Major Projects Association, 2006, *A New Generation of UK Nuclear Power Plants – are we ready ?* seminar at the Institution of Civil Engineers, London.

[42] World Nuclear Association, undated, *Structuring Nuclear Projects for Success*.

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

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

CORRECTIONS AND COMMENTS

Corrections and comments on this report are welcome and should be sent to wearne@manchester.ac.uk

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