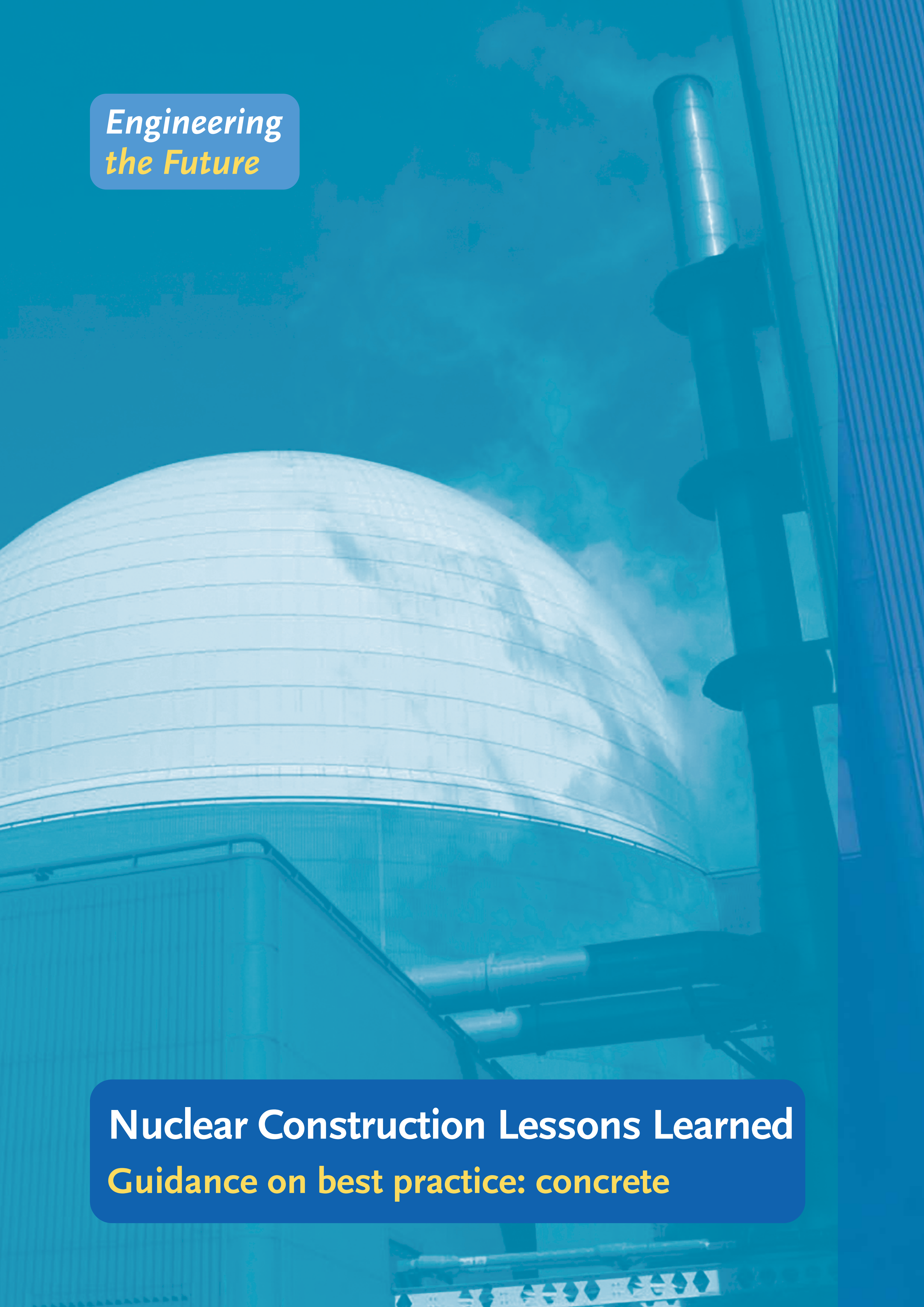

Engineering
the Future

Nuclear Construction Lessons Learned

Guidance on best practice: concrete

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ISBN: 1-903496-81-0

February 2012
Published by
The Royal Academy of Engineering
3 Carlton House Terrace
London SW1Y 5DG

Tel: 020 7766 0600 Fax: 020 7930 1549
www.raeng.org.uk
Registered Charity Number: 293074

A copy of this report is available online at:
www.raeng.org.uk/ncllconcrete
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www.engineeringthefuture.co.uk/government/

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Foreword

Achievement of the UK government's challenging carbon reduction targets is directly related to the successful delivery of a fleet of new nuclear power stations. In support of this, *Engineering the Future*, following a request from the Department of Energy and Climate Change and the Office for Nuclear Development, set up a steering group to examine the lessons that could be learned from recent civil nuclear power plant construction projects. The project steering group was formed by representatives from relevant engineering institutions and bodies and considered both the lessons that could be learned and how they should be incorporated into the proposed UK new build programme. In October 2010 the project steering group delivered a report to Charles Hendry MP, Minister of State for Energy & Climate Change, on the construction lessons learned from six international nuclear new build projects.

The purpose was to help UK industry in fully understand the issues that had led to delays, rework and redesign past nuclear build projects in order to incorporate that learning into new build projects and thus reduce delays and increase investor confidence.

The *Nuclear Lessons Learned*[1] study examined experiences from six recent nuclear construction projects and established five general lessons:

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

Once these general lessons were established, an industry stakeholder group meeting in November 2010 suggested to the steering group that a focus on specific areas of nuclear construction would be of particular use to industry. It was decided that the first three of these 'deep dives' would cover nuclear safety culture, welding and concrete. Working groups led by the most relevant professional engineering institutions took these topics forward, producing best practice guidance documents for each. Industry was widely consulted on the draft guidance documents, which were finalised following a workshop held on 19 September 2011.

The *Nuclear Safety Culture*[2] best practice document presents an overarching view of safety culture in the context of a new nuclear build programme. The recommendations of *Nuclear Safety Culture* specific report apply to all aspects of nuclear construction. This report looks at best practice in relation to concrete at all the stages of construction.

The aim of these best practice guides is to provide accessible information to help those involved in nuclear construction projects to adopt behaviours conducive to successful project delivery. Although they are not intended to be standards, codes of practice or contract conditions, the members of the *Engineering the Future* alliance believes that following the recommendations will be beneficial to companies in terms of delivering new nuclear projects to cost and programme.

A consistent approach is important, given the degree of sub-contracting prevalent in the UK market, as the success of the project relies on all those involved throughout the supply chain.

The guidance documents are aimed at all those within the supply chain wishing to better understand the demanding requirements of nuclear construction. The documents are particularly relevant to those whose roles encompass the design, specification, tendering and bidding for work within nuclear construction projects, as well as those responsible for delivery. The recommendations should prove selectively useful for those developing business strategies through to those working on site.

Through these documents, *Engineering the Future* seeks to facilitate learning from previous construction projects to help create a strong and successful new nuclear build programme in the UK.

During the nuclear new build programme further lessons will surface, it will be important to ensure that an effective mechanism is in place to capture and disseminate this learning. This process will further contribute to the effective delivery of a fleet of new nuclear power stations.

1. Introduction

Constructing high quality concrete structures in the nuclear sector is a key requirement owing to the high integrity demands on concrete performance. For example:

- Many concrete elements are required to undertake a shielding and secondary containment role in addition to structural duty.
- Concrete may need high structural strength and ductility requirements to resist seismic, thermal and other normal operating demands, plus fault and extreme environmental loading.
- The longevity of nuclear facilities requires continued strength, containment and shielding function often for many years beyond an operational life of 60 years or more.
- Many of the concrete structures become effectively inaccessible once the plant becomes operational.

In view of the above four points, concrete on a nuclear facility, including its design and installation, can become an integral part of the nuclear safety case necessary to justify plant operation throughout its life. The recommendations of the companion report on *Nuclear Safety Culture*[2] therefore complement this report.

As part of the *Nuclear Lessons Learned*[1] study, this report focuses on the specific issues arising from current and previous nuclear construction projects. It does not attempt to be a complete guide to best practice in all aspects of concrete construction. It does however apply, where relevant, to all types of concrete, whether mass, reinforced or pre-stressed, and whether cast in situ or precast.

In conventional reinforced concrete construction, significant emphasis is placed on the assessment of concrete quality following placement through inspection, cube strength tests and cover meter surveys. This approach operates on the traditional basis that if quality is not achieved, the contractor may be asked to 'break it out and start again'. However, the massive sections that are typical of the nuclear industry make this approach impractical for much of new build nuclear construction. More crucially, beyond the impracticality of such measures, failing to meet the concrete quality requirements will inevitably cause programme delay, dissatisfaction in client and contractor teams and critically, a loss of both regulator and investor confidence.

Therefore, for nuclear construction, the emphasis must be moved from post-placement verification of quality, to pre-placement quality of design, specification and training to minimise the potential for defects. Details such as cover and reinforcement position must be verified before placing concrete and all items must be secured to ensure that nothing occurs during the pour to change this[7]. The following sections provide an overview of some of the issues that must be addressed in these key stages.

Recommendation 1

Need for pre-placement quality assurance – given the key role of concrete in nuclear structures and the difficulty of modifying it later in the construction or operational phases, licensees should move the focus from the traditional post placement verification of quality to pre-placement quality of design, specification and training.

2. Pre-construction activities

The root cause of a significant number of the defects, problems and errors that occur during construction can be traced back to failures in planning and preparation rather than purely from failures in execution[3]. Therefore a strong focus on the pre-construction phases will significantly enhance the likelihood of successful delivery.

One of the first construction activities for a new nuclear power station that will take place on a licensed site is the pouring of the large base raft. This is typically between 40m and 55m in diameter and 4m or 5m thick, with a volume of 5,000 to 10,000 cubic metres.

With such a major activity taking place at the very start of the delivery programme, there is both high pressure to deliver to programme and a sharp focus on the results of the activity. Without proper preparation, this focus and pressure may not always lead to informed decision making.

While the large base raft concrete pour is an early activity after the granting of a site licence, a significant part of the preparation for this is likely to have taken place before a nuclear site licence is issued. The companies involved in this early stage of construction must instil confidence in the ONR that preparatory steps have been taken to deliver the high standards expected under a site licence.

Procurement

Today, UK supply chains are often ‘deeper’ compared both to other territories and to previous major power station construction programmes. As such, this may mean that the licensee may not have a direct contractual relationship with the company ultimately undertaking the concrete pour. It is important that the procurement process selects competent contractors across the whole delivery supply chain.

Competency assessment should include a review of quality assurance (QA) systems, workforce and supervisory training and assessment as well as relevant experience. Recognising the depth of supply chains, licensees must be aware of how prime contractors intend to undertake assessment and selection of their own specialist supply chains. There is limited value in a licensee appointing a prime contractor for managing the civil construction based on a quality assessment, if that prime contractor in turn selects specialist suppliers based on purely a lowest cost basis. The licensee may find it useful to limit subcontractors to those who have prequalified, to reserve the right not to accept a proposed subcontractor or to limit the number of permitted levels of subcontract.

All levels of the delivery supply chain must understand and adhere to easily visible and robust quality arrangements, which must be auditable by the licensee and regulators. In turn, both the licensee and the regulators must ensure that their requirements are widely understood at all levels. There is no point, however, in issuing a large volume of tender requirements unless the tender period allows sufficient time for these to be passed down the chain and fully digested. While the contract must include appropriate quality requirements, it is important that the licensee cultivates team working and a quality culture; if it becomes necessary to continually impose contractual requirements, the battle has been lost.

Throughout any contracting process, the licensee must retain ultimate responsibility for the quality of work performed, whether by its staff or by contractors, as well as for maintaining the safety of the licensed facility[4]. Effective oversight by the licensee must ensure that the quality of products and services from its contractors and any subcontractors is commensurate with their safety significance. The licensee's oversight must ensure compliance with applicable codes, standards and regulatory requirements. In order to do this, the licensee must retain sufficient core capabilities to:

- be an 'intelligent customer' in its contracting process and oversight
- have a robust management system to ensure the required quality
- be the 'controlling mind' for all activities
- maintain and take ownership at the appropriate time of its safety case
- be the 'design authority' for the facility.

Planning and scheduling

The INPO report *Principles for Excellence in Nuclear Project Construction*[5] lists 'realistic and understood' schedules as one of its nine Principles for Excellence. This best practice guide fully endorses that view.

One of the most disruptive activities to a controlled and good quality construction project is an unexpected design change. While there will be pressure to move ahead with construction, it is important that each stage of the design is completed in time to permit proper planning of construction.

Any credible construction programme will include a detailed schedule prepared and agreed for the concreting activity itself. However, in addition, the schedule should include planning activities for the pour itself comprising contingency plans in the event of hiatus in materials supply or plant breakdown. Furthermore, in addition to the scheduling of activities associated with the concrete pour and the subsequent curing and testing, proper planning and the communication of the plan through the schedule should include specific reference to and allow adequate time for the key pre-construction activities. These include:

- design and specification, including mix design activities
- contract procurement, for all aspects of the delivery supply chain
- definition, installation and testing of the batching plant
- concrete trials and preparation, including allowances for trial panels and sections, additional trials if required and post trial reporting
- material procurement, including reinforcement, encast items, temporary works and bulk materials
- fixing of reinforcement, encast items and shuttering
- pre-placement inspection
- planning of placement, including pumps or other means of delivery to the point of placing

Through undertaking and communicating these preparatory activities, all suppliers should be able to understand the importance and interdependence of the key stages and know what good work looks like for all key elements of the concrete works. Early contractor engagement brings the added benefit of enabling main contractors to draw on the expertise, skill and innovation of small and medium sized enterprises (SMEs) within the supply chain, and ensure that the project's quality requirements are fully understood by all levels in the supply chain.

Communication within the delivery team is essential, and the use of electronic databases can make it much easier for all parties to receive details as soon as they are issued. Some design details, however, will be deemed 'sensitive nuclear information' and such databases must be planned early in the project in order to meet the security requirements.

Recommendation 2

Licensee oversight –the licensee must manage the core capabilities of the integrated design and construction programmes to ensure that the arrangements for oversight of work carried out by the supply chain guarantee quality work that meets the licensee's ultimate responsibility for quality and safety.

Recommendation 3

Early contractor engagement – early contractor engagement should be undertaken to ensure comprehensive integration of the design with the construction approach for complex areas.

Recommendation 4

Integrated design and construction programmes – design and construction programmes must be realistic and fully integrated across all disciplines with appropriate allowance for approvals and contingency. In particular; mechanical, services and process plant design should be sufficiently well advanced as to allow design of encast items penetrations and equipment. Co-location of the design and construction teams is desirable.

Involvement of contractor in design

As illustrated in Figure 1, close cooperation between designer and contractor at an early stage is required to ensure design is optimised for construction quality in addition to efficiency. There can be a conflict of interest here, as engagement can only occur after the contractor has been appointed, yet a well defined design is necessary to place a traditional contract. There is a risk that the contract may be placed with insufficient definition and could therefore lose control of costs and quality. One solution may be a staged contract, where the initial phase allows contractor involvement in design but the construction contract is not finalised. To permit genuine negotiation, there must be an option to reject the phase two price, but a level of trust on both sides is essential if this approach is to succeed. It is common practice in

Japan for a client to develop the design with a trusted supplier and only agree a contract one third into the project. Key factors to be considered at the time of design are listed in Table 1.

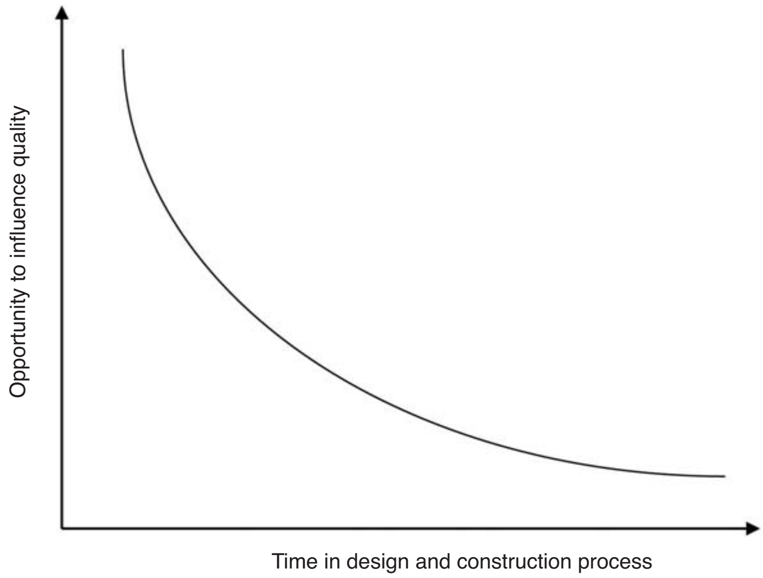

Figure 1 – The right time to influence quality

Area	Issue	Proposed Solution(s)	Comment
Designer appointment	Experience of designer (and critically team) in nuclear or heavy industrial structures. Competitive tender heavily biased on price is likely to affect quality.	Long term framework relationships. Appointment based on quality and experience rather than lowest cost. Attention to be paid to the key design team members and clear design responsibility.	Improved design based on extensive LFE provided there are adequate knowledge management systems in place. Quality and cost benefits from proper investment in design skills.
Designer / Contractor integration	Design does not match contractor's chosen method or sequence of construction / designers assumed sequence not communicated to contractor.	Early contractor involvement in the following: • construction sequence • detailing • mix design • construction joints	Coordinated design that draws on skills of both the contractor and the designer.
	Design tolerances unnecessarily tight or not achievable.	Designer awareness of what can be achieved and of the commercial consequences of over-specification.	Reduction in rejected work; cost and time saving; respect for the specification.
Reinforcement congestion	Inability to fix reinforcement. Insufficient room to place concrete leading to voids. Insufficient room for concrete poker leading to poor compaction / voids.	Review whether full tension laps are always required, particularly in congested areas.	Reduced laps lengths have the potential to ease steel fixing constraints and congestion.
		Consider use of couplers instead of lapped bars. Couplers with a significantly larger diameter may require increased cover to the bars.	Can ease congestion but increase costs and loss of flexibility. Often lapped bars allow greater flexibility to avoid congestion.

Area	Issue	Proposed Solution(s)	Comment
		Consider use of 10mm size aggregate in concrete mix design.	Aids flow around bars. Can cause issues with heat owing to higher cement content.
		Consider use of self compacting concrete.	Aids areas where difficult to vibrate effectively but may not solve areas of high rebar congestion and may cause heat problems.
		Ensure bars align in parallel mats in roll-out systems to prevent bar spacing being reduced.	Improved access for concrete flow and poker.
		3D modelling / detailing of congested areas.	To ensure bars can be fixed and clashes avoided.
		Other issues for consideration – detail to assist • use of longer bars • ground level prefabrication of cages • welded bars	Longer bars reduce congestion and save material, but can be difficult and/or hazardous to fix. Better inspection, time saving. Less risk of movement
Encast Items	Increased congestion to critical areas. Often difficult to hold in position within large pours. Late information can result in delays or incorrect plates cast into concrete.	Consider a more flexible design with fewer designs of larger anchored plates to support multiple fixings at greater tolerances.	Increased flexibility in design that can address late changes. Fewer plates to hold in position.
		Design of support steel to encast items within the main design rather than rely on a contractor designed approach undertaken in isolation.	Holistic review of all rebar required to identify clashes / congestion.
		Co-ordinate embedment anchor spacing with rebar spacing.	Only effective if embedments are before rebar.
Access for rebar fixing	Poor access for rebar fixing to bottom mat.	Leave appropriate access to fix and inspect bottom mat with coupled bars to close.	Safer fixing, more confidence that work is built as designed.
	Shear reinforcement difficult to fix between mats.	Shear rail type systems allow much improved ease of fixing.	Safer fixing, more confidence that work is built as designed.

Table 1: Key factors to be considered at the time of design

Specification

The specification of concrete is a key part of the design, and should be mandatory and therefore enforceable. A specification which imposes requirements that are impossible to meet or unnecessary for the correct implementation of the design will only result in conflict and delay.

The specification must be clear to the whole supply chain at the tender stage. Any requirements that differ from normal commercial practice should be highlighted. If a contractor fails to appreciate the requirements and submits a price which is too low, the contract could fail as the contractor's focus may only be on avoiding a loss.

Some contracts are tendered against performance specifications. These give the contractor flexibility to deliver the work in the most effective manner. A disadvantage is that, at tender stage, contractors with greater knowledge of the measures that must be employed to achieve a satisfactory outcome may submit uncompetitive bids. If, as result, the contract is awarded to those without the experience, unsatisfactory work would be difficult and often impractical to replace. Performance based specifications can, however, drive innovation and efficiencies. The licensee and designers should consider this issue on a case by case basis.

Recommendation 5

Specification – the specification should be comprehensive, achievable and well understood across the supply chain. This will ensure that it can be enforced as mandatory.

Personnel training and assessment

Training is a key issue for which licensees should take responsibility. The step change in the volume of nuclear construction work means that there is a specific need for training; the required skills and cultures do exist but not in the number of people required. It is relevant to repeat Recommendation 4 from the *Nuclear Safety Culture* report[2]:

"A systematic approach to training should be taken to provide confidence that all personnel are trained and competent. Commonly recognised qualifications and standards should be used where these have been established."

Staff training from design through to construction, supervision and testing is a critical area in ensuring concrete placed is of high quality. Key to this training is an understanding of why concrete quality is important to nuclear facilities, which will encourage compliance and a pride in the work at all levels.

All staff should have some form of skills passport based on a real test of ability (similar to welding certification). The Client Contractor National Safety Group (CCNSG) safety passport is currently used by some licensees, but this does not address quality related skills. The Construction Skills Certification Scheme (CSCS) provides certification at several levels - with red, blue or gold cards - for relevant trades such as steelfixer and concrete placer. A green card - for a general construction operative – is not evidence of the skills required for this work.

Training should focus on the importance of high quality concrete in the nuclear industry as the material needs to meet shielding and containment requirements, supports extreme (including seismic) loading and the longevity of facilities. There must be a focus on high quality as there is limited opportunity for repair and maintenance.

Basic training should ensure that designers, technicians and inspectors understand issues such as: concrete hydration, the water content's effect on strength, curing plus heat of hydration and early thermal cracking.

This will allow improved design, detailing and supervision as well as informed debate on design and construction processes. Emphasis should be placed on the importance of the lead technician role for complex RC and structural steel detailing work, with commensurate rewards, both financial and in terms of job satisfaction. This is essential as the market expands with the potential for off-shore detailing.

Practical site experience on a nuclear or heavy industrial project will ensure that designers and technicians have an understanding of the contractor's constraints and challenges, such as the practical problems of steel fixers.

Site operatives should be given practical training and 'toolbox talks' in the techniques of concrete placement and should have an understanding of the importance of their role. This is likely to be more effective than financial incentives. This should extend to site batching plant operatives, who have a key role but may have a limited knowledge of the consequences of their decisions.

The importance of having a trained, skilled workforce cannot be overstated. Although UK construction employs three million people – 8% of the workforce – there is a perception that construction work is unskilled. It is therefore essential that those working in this sector are trained, educated and recognised for the skills they have at all levels of the various organisations. For the largest pours, which can be the most crucial, it is often necessary to supplement the normal concrete gangs. This must be arranged so that any less skilled operatives are supervised, particularly if the pour extends into the hours of darkness.

In 2010 an Occupational Standards Working Group was set up by the Institute of Concrete Technology and Proskills in 2010 to address a perceived decline in concrete construction quality across the country. The quote from this group, below, highlights the problem that, while there are a lot of very experienced people within the concrete industry, many do not have a formal qualification related to their work.

"Concrete is one of the most widely used construction materials but also one of the most misunderstood and misused. It is therefore time to define working with concrete as a specialism that requires significant knowledge, experience and competence. You will, I am sure, be able to relate to many examples in your professional career to date where insufficient knowledge and experience has led to considerable project delays and extra cost being the price for getting it wrong."

The Concrete Society/ICT has now developed a National Occupational Standard for concrete professionals, which has led to the introduction of the Qualifications Credit Framework (QCF). A portfolio of accredited bespoke qualifications is now offered to recognise the skills and competence required across the industry and is delivered through various methods to suit both employees and employers alike.

It is worthy of note that concrete operatives in some European countries such as Sweden have to serve a three-year apprenticeship, just as a brick layer or joiner would in the UK.

Recommendation 6

Need for understanding across the team – concrete has an important role to play in ensuring nuclear safety. Everyone involved in the concrete process must understand the importance of producing high quality durable concrete and the procedures and specifications for concrete works.

Recommendation 7

Designers need practical experience – design and technician staff should gain practical site experience of constructing heavily reinforced concrete structures to understand the contractor's challenges and constraints. Such experience should be an integral part of a formal training programme for all design and detailing staff.

Recommendation 8

Importance of Technician role – the role of the lead technician should be recognised as key to the successful delivery of the construction design, as part of a core team of experienced staff specifically identified, trained and supported appropriately.

Quality assurance

Licensees have a responsibility to ensure that they employ designers and contractors who are committed to quality. This can be difficult to assess. One approach is to require tenderers to price QA as a separate item or to guarantee the level of QA resource. When fully established, however, QA becomes an integral part of the design and construction process, requiring only audits to confirm that the process is indeed working. This can result in the paradox that organisations with an established quality culture may appear to have fewer people working on QA. While a proactive assurance culture is much better than a reactive control culture, a level of independent audit, inspection and supervision will still be necessary, and this may be a more measurable resource. Since the 2000 edition of ISO 9001, the standard has focused on 'continuous improvement' rather than 'preventing nonconformity at all stages from design through to servicing' as in the previous editions. This may be more appropriate for a routine process than for a construction process, although it does become relevant for a series of replica stations.

Recommendation 9

Integrated and visible quality assurance process – to achieve the required long-term durability properties the licensee should ensure that there is an integrated approach to quality management, achieved by creating an attitude of teamwork among all parties involved.

Quality assurance

The licensee has ultimate responsibility for supervision, but in practice will exercise this using a degree of delegation. Both the contractor and the concrete supplier (if different) have a responsibility to ensure that their product is correct and must provide supervision to assure themselves of this. They must not rely on any independent supervision.

Similarly, irrespective of any third party accreditation, work procedures and method statements that may be in place, the licensee cannot assume that the work will be done in accordance with the specification, unless there is independent supervision or an audit. Traditionally, this was the role of the Clerk of Works (CoW). This title may not be used any more, but the role remains essential to ensure that processes designed to ensure quality are working properly. While the CoW or equivalent will 'sign off' the work, this must not take away responsibility from the contractor. While the number of inspectors may vary between sites, few inspectors could suggest either that the contractor has adopted the appropriate culture and is self policing the work, or (the quality of work will show which) that the licensee does not have proper control.

3. Construction practice

Concrete trials and preparation

Modern standards, specifications and procedures alone will not ensure high quality concrete and a structure that will satisfy whole-life performance requirements. The best way to specify and achieve durability has been the subject of many debates over recent years. Much of the previous work on concrete durability has been focused on constituent materials, such as cement, aggregate and reinforcement with little emphasis on the workmanship element necessary to achieve durability of the assembled structure.

Concrete constituent material is predominantly determined by the designer and specified using the standards now available; both BS and EN. Standards alone cannot be relied on to reflect best practice as they only provide a framework with minimum standards into which the designer must insert the project requirements. Therefore after design and specification considerations are crucial to develop high performance, nuclear grade concrete.

There is much technical knowledge now available but it has not always been put into practice. While batching facilities will be set up on the site, they will probably be managed by established concrete suppliers and, in any case, will be staffed mainly by people from the existing UK concrete industry. This is set up for high volume but low quality concrete where commercial considerations are always paramount. Typically, concrete suppliers are third-party accredited only for normal industrial quality levels, but should be required to meet more rigorous nuclear requirements. The fact that concrete material costs, such as admixtures, are very small (almost insignificant, when viewed against the total cost of a project) is rarely taken into account. This results in lifetime costs usually being given little consideration as reduced initial cost is the driver on which industry practice has been built.

Mix design development

Mixes must be designed not only to meet compressive strength requirements, as is usually the case, but also for consistency in production, placement and finishing properties. It is important that only approved mixes are used. Any changes should be approved in advance by nominated representatives of both customer and supplier.

The concrete batching plant should be erected and commissioned well in advance of commencement of all concrete operations to allow a reasonable period of time for plant trials and all specified testing requirements to be completed prior to mix design approval being given.

It is important that a fully integrated approach is taken at this stage for the benefit of all parties including concrete supplier, contractor and client.

Initial design stage and plant/lab trials should include the following considerations:

- Mix requirements within specification scope: the strength and durability of the mix (and therefore minimum and maximum cement content and water to cement ratio) as well as consistence and retention is important.
- Robust design: segregation limits must be explored, focusing on high levels of cement replacements, which come under pressure.
- Material selection: the choice of cement and cement replacements, aggregates and admixtures is crucial, as well as their compatibility and availability and the storage of aggregates on site.
- Handling & placing: mixing efficiency, such as admix distribution and speed, pumpability, focusing on the type of pump, line length and line logistics and thermal dynamics including heat generation balanced against the programme timescale, are vital. Concrete movement, such as shrinkage and creep, the degree of compaction and surface finish, the rate and amount of bleed, plus sand runs are also points that should be considered.
- Further considerations prior to commencement of concreting operation include ensuring that the batching plant has adequate cold weather facilities and precautions in place and carrying out a mock-up trial to assess pumpability/ distance and placement methods prior to the first major structural pour. Site test panels to set the standard of compaction and specified surface finish types should also be carried out.

Recommendation 10

Concrete mix design – All concrete mixes should be designed for all relevant properties, tested and approved. Any changes to the approved set of mixes should be formally controlled.

Fixing reinforcement and encasts, shuttering and clean-out

In relation to fixing reinforcement and encasts, shuttering and clean-out, the following points should be considered:

- 3D modelling assessments of reinforcement in congested areas should be carried out to ensure potential problems are highlighted pre-pour.
- Consider the use of self compacting concrete (SCC) in extreme cases. The use of SCC has a positive impact on durability by ensuring a minimum quality of placed concrete, by means of full compaction. Also after the elimination of the compaction process aids the introduction of automation into concrete construction.
- With multiple layers and congested areas, consider the use of temporary vertical alignment bars in order to keep lines of sight open and pathway for pokers during the pour.
- Minimise tie wire off-cuts to reduce debris.

- Temporarily displacing bars for any reason, such as access, encast items, concreting, should be discouraged.
- Spacer blocks are a potential source of weakness and should be specified carefully. Blocks should be tapered in cross section and their layout should be part of the temporary works planning; they should be detailed with consideration to the advancing face of the concrete. Plastic spacers are not recommended. Custom concrete blocks should match the strength and durability of the pour.
- Rigorous inspection of the bottom mat and soffit formwork should become a hold point and be reflected both in the specification and in the Inspection and Test Plan. Hanging straps and loose bars should be eliminated.
- Pre-pour inspection checks should include: cover spacer blocks, debris, cover zone foreign objects and pre-pour cleaning out. Setting out checks on all encast items and embedments should be signed off. A minimum 24 hours notice should be given to ensure that the appropriate level of checking can be carried out prior to permission to pour. Inspections should only be carried out in daylight hours with sufficient time allowed for a thorough inspection. Pours should be progressively cleaned to prevent large accumulations of debris that are difficult to see and remove once all reinforcement and shutters have been fixed. The use of endoscopes or similar in areas where visibility is impaired should be considered.
- Reinforcement must be solidly fixed to ensure that the measured cover is maintained. Post-pour cover meter surveys may provide a useful incentive to get things right, but the disruption that results from breaking often creates a damaging conflict of interest between quality and programme.

As an additional consideration to assist inspection, the use of coloured (such as white) soffit/slab formwork should be considered. This may make things like loose tie wire and general debris stand out and therefore aid inspection and cleanliness. There would be a cost implication but this additional cost may be insignificant when viewed against the total cost of a project. Use could be restricted to cell soffits or soffits with dense reinforcement. A comparison trial with the proposed different surfaces/types could be carried out to assess the effectiveness of the approach.

Pre-placement preparation

The success of a concrete pour largely depends on the preparations made before any concrete is placed. Few construction operations are as difficult to reverse if problems occur. Designers must be aware of placement methods and design with placement in mind, but the placement method should be the contractor's choice, subject to licensee approval. The following points should be included in the specification for implementation, as appropriate, in method statements:

- Concrete mix designs should cover pumpability and consistence.
- Pump capacity selection should include realistic friction loss calculations, taking into account the concrete mix to be used over the real pumped length.

- Colour-coded depth gauging on poker vibrators should be considered to ensure full penetration to the bottom layers of deep lift pours.
- Arrangements should be in place for the monitoring and control of temperature and differentials in large pours.
- Consider limits on pour size and duration. It appears to be a matter of pride in recent construction works to place very large volumes in a single pour, which may not be beneficial.
- Method statements should include detailed planning of the pour with contingencies for a back up concrete supplier or concrete pump breakdown.
- Materials and equipment for curing should be ready on standby before the pour starts.
- Adequate concrete level checks and controls should be planned to ensure the product is within tolerance.

The operatives placing and compacting the concrete must be adequately trained and the specification should require this. If evidence of formal training is not available, site briefings should be held to ensure awareness of the method statement and potential issues such as fatigue.

The roll-out steel reinforcement system may have advantages. Site labour requirements are lower, installation times are improved, operatives have fewer back complaints and large areas of rebar can be installed in limited weather windows, which suit the changeable UK weather. A further benefit is that traditional steel fixing skills are becoming increasingly scarce. However, there are hazards associated with this system that need to be considered and should be fully assessed before use via constructability exercises. as a result of the congestion and high density of rebar found in nuclear structures, blockage of concrete flow by the flat steels joining the bars in the mat can occur. Problems are also often caused when displacing bars, because the bands have to be cut.

Recommendation 11

Concrete placement – good preparation will ensure that concrete can be place efficiently and correctly. Any problems should be resolved before the pour, nor during or after it.

Testing

It should be remembered that concrete is probably the only major construction component that is manufactured on site as opposed to in controlled factory conditions. Concrete placement has traditionally been regarded as an unskilled job but the scale of the nuclear new built programme provides an opportunity to increase the pool of skilled workers in this area. While it is the responsibility of the concrete supplier (who may be the main contractor) to control the product, independent checking is essential as an effective practical control.

Industry wide, the cube test is still used as the cornerstone of both concrete supplier and contractor quality control systems. However this is based on a 28 day test after the concrete has been placed and is only a tool to demonstrate that the required quality has been achieved. It must be the independent site testing laboratory's prime function to ensure compliance of the concrete with the specification is established before the concrete is placed. This should be done through stringent quality control of all stages of concrete production. Therefore emphasis should not be concentrated on testing the final product but more importantly towards testing in the earlier stages for control purposes and on ensuring appropriate action is taken when necessary.

There is a need to establish a dedicated independent technical site team to incorporate the following key elements:

- Experienced technical staff should survey all site batching operations.
- Database summary trends should be produced per plant and per mix grade.
- Independent laboratory compliance data must be shared with the concrete suppler, contractor and client for complete continual performance feedback reviews, which is needed for total production control for both fresh and hardened concrete.
- All concrete material quality activities should be tracked and permanently recorded.
- A continuous surveillance/improvement culture must be maintained.
- Material quality, specification and end product requirements should be reviewed and compliance achieved.
- Site teams must be supported by technical managers from ready mix suppliers, contractors and clients to enable effective feedback into all organisations.

The effectiveness of supervision, inspection and quality control cannot be overemphasised. A 'box ticking' approach to quality control should not be adopted or allowed. While making good and snagging are recognised as expensive and time consuming operations, the required 'stop the line' culture when something is wrong cannot be achieved without these elements being present. It is widely accepted that safety comes first, with quality closely linked, but the pressure to meet the programme and targets needs to be matched by pressure to meet quality requirements.

Curing

Throughout the concrete industry, the purpose of early age curing is not fully understood across the whole workforce and as a result is frequently ineffective. Contractors should be especially aware of the need for adequate curing when using high level cement replacement (GGBFS and PFA) mixes that are more sensitive to early curing.

While contractors generally have well written and thorough curing procedures, it is often found that they are not being implemented on site. The operatives, supervisors and engineers on site do not understand why they have to follow curing procedures because the role of water in the chemical reaction has not been adequately explained to them and there is a traditional understanding that concrete should 'dry out'. It is therefore important that curing procedures are not only specified but that the purpose of curing and the consequences of poor curing are made clear to all. Adequate supervision is necessary, particularly since curing is carried out at the end of the pour and may be the last task of the day.

Response to non-conforming product

Acceptance of any non-conformance reduces the robustness of the structure and may also reduce the incentive to avoid further non-conformances. Processing of non-conformances can place a significant load on the design team and may impact on the programme for issue of design information. Poor control of non-conformances will attract the attention of the regulator. For examples, see discussion of individual projects in the parent *Nuclear Lessons Learned* report[1]

There are two principal approaches to QA: 'limited trust' and 'high trust'. The 'limited trust' model, which requires more time and effort to manage, tends towards confrontation and is at risk if the supervision fails. The 'high trust' model relies on common goals; it can be significantly more efficient and provides defence in depth, but it is vulnerable to abuse if the common goals are not shared.

Reports from projects (see parent report[1]) identify issues such as too much trust placed on interested parties in QC resolution, non-conformance not being openly or promptly addressed and issues managed on a basis of blame instead of improvement. They also say that there is a need for third party inspection, increased control of contractors and the need to strengthen QA and QC teams.

These issues are all symptomatic of what happens when the 'high trust' model is used but goals are not shared and the nuclear safety culture is not in place across the supply chain.

It may be that the 'high trust' model is impractical in a new partnership; it may take time to develop the trust.

Each project must decide where it can justify pitching its strategy. 'High trust', if it works, can deliver better quality faster, but if it fails, the downside may be greater. The customer and lead contractor should make honest and transparent assessments of the project maturity and level of trust that can be relied upon. The degree to which the common goal is shared by the whole supply chain should then influence the way corrective actions are specified and implemented.

Recommendation 12

Treatment of non-conformance – licensees should give consideration to how non-conformances will be addressed and should make this clear to all parties. They must then follow that process if non-conformances arise.

4. Post construction

Capturing and sharing lessons learned

The nuclear industry as whole will stand or fall on the performance of every participant. This applies to construction delays and overspends as well as INES events on operational stations. The industry must be convinced of the need for transparency and information sharing. This has been illustrated for operational plant by the success of INPO and WANO and the same attitude should apply to construction.

Information to benefit the operational lifetime of the station

The recording of every construction detail and incident is crucial to the long term safety case of a station and to support future enhancements and decommissioning. As a plant ages, defects will appear and the remediation of these will depend on knowledge of how the structure was originally built. Details that may have seemed insignificant at the time may assume great importance. There is no substitute for contemporary records and subsequently, it may be impossible to retrieve information that was readily available during construction. Adequate pour records are a useful element in investigating future defects and in one case were used to correlate high carbonation of concrete to placement late on Christmas Eve.

Many defects in civil engineering structures originate from a root cause associated with their design and/or method of construction. Although these may only become apparent after a period of operation, they typically exhibit a high rate of common cause failure and of fortuitous detection. It is crucial that potential major long-term latent defects are avoided or identified and corrected before the construction stage, as they may affect nuclear safety and be difficult, as well as expensive, to identify and correct during plant operation. The aim prior to and during construction should be to use lessons learned during all stages of existing and previous projects to reduce risk and develop a 'right first time' culture in all organisations involved.

The IAEA has identified[6] that as relevant good practice, the plant operator should address ageing management even at the pre-operational stages and this should include information regarding the potential implications of variations and concessions and non-conformances detected and corrected prior to plant operation. The plant supplier, design organisations, constructors and manufacturers may not be available for support at future stages of the plant life-cycle, and thus the transfer of knowledge and experience is important from the conceptual stage onwards.

A sound foundation for proactive ageing management of the plant entails continuous learning from experience and improvement over the entire lifetime of the plant; its design, construction, commissioning, operation and decommissioning, including all associated activities such as engineering, procurement, fabrication, transportation, installation, testing and maintenance. Licensees should ensure that support to ageing management is built into the construction process. They should ensure, for example, that enough test cubes are made to permit long-term testing over the life of the plant as well as quality control during construction.

Connecting ageing management with minimisation of non-conformance through use of shared lessons learned reflects the IAEA Fundamental Safety Principle[7] that nuclear operating organisations establish a programme for the collection and analysis of operating experience. This is important in supporting a safety culture that governs the attitudes and behaviour in relation to the safety of all organisations and individuals concerned. Such a safety culture must be integrated in the management system and include measures to encourage a questioning and learning attitude, as well to discourage complacency with regard to safety[6].

Information to feed back into construction

Follow-on replica stations should benefit from the lessons learned from the design, construction and early operation of a first-of-class design in any country and so have the potential to be less costly and quicker to build with significantly fewer non-conformances. This will only happen if these lessons are communicated. This report picks up many lessons, but feedback must be continued in order to help to reduce the recurrence of past design, construction, commissioning and operational problems.

Mechanisms should be developed to share experience in a systematic and timely manner among relevant organisations undertaking new nuclear build and use should be made of existing information exchange arrangements where appropriate. Reputational concerns should be addressed by sharing solutions rather than problems. Suppliers, designers, constructors and operators will benefit from sharing lessons learned and will thus continually improve leadership, organisational capability, safety decision making and safety performance.

Recommendation 13

Feedback processes – processes should be put in place across all developers to allow for the collection, analysis and implementation of lessons learned and experience feedback.

Recommendation 14

Knowledge transfer over plant lifetime – the licensee should ensure that mechanisms are in place for the transfer of knowledge and experience at each stage of the project and the management of ageing from the conceptual stage onwards.

5. Conclusions

The quality of the concrete in a nuclear power plant is crucial. As the first element to be constructed, it sets the benchmark for the project. Unlike many components, the concrete can never be replaced and must perform to specification for the life of the station. Concrete quality should therefore be assured through proactive measures so that the need to reject unsuitable concrete never arises.

The whole supply chain should understand that nuclear structures are different. While suppliers may be fully accredited to the quality standards required for general construction work, they will need to take additional measures for nuclear work.

Careful planning will facilitate good quality concrete placement. This applies to design of the reinforcement and encast items, mix design, formwork design, pour sequencing and curing.

Placing concrete requires a trained workforce. All operatives should have appropriate certification of their competence to perform the task allocated to them.

Finally, the most effective cultural environment to ensure good quality concrete requires a positive alignment of objectives across all parties. Individual employees from all contractors and sub-contractors must genuinely believe that quality is in their interests and aim for zero defects. This culture will take time to develop, and licensees should put a robust supervisory regime in place.

Abbreviations and acronyms

BS	British Standard
CNSG	Client Contractor National Safety Group
CSCS	Construction Skills Certification Scheme
EN	European Standard
GGBFS	Ground Granulated Blast Furnace Slag
IAEA	International Atomic Energy Agency
ICT	Institute of Concrete Technology
INES	International Nuclear Event Scale
INPO	Institute of Nuclear Power Operations
LFE	Learning from Experience
OECD-NEA	Organisation for Economic Cooperation & Development - Nuclear Energy Agency
ONR	Office for Nuclear Regulation
QA	Quality Assurance
QC	Quality Control
QCF	Qualifications Credit Framework
SCC	Self Compacting Concrete
SMEs	Small and medium sized enterprises
SQEP	Suitably Qualified and Experienced Person
WANO	World Association of Nuclear Operators
W/C	Water/Cement [Ratio]

Acknowledgements

Best Practice:

Chris Bolton (Institution of Structural Engineers) (Chair)

Nick Jones (URS Scott Wilson)

Quentin Leiper (Carillion plc)

Les Smith (Office for Nuclear Regulation)

Neil Tait (Sellafield Ltd)

Keith Waller (Department of Energy & Climate Change)

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