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Activities of the OECD Nuclear Energy Agency in the Area of Concrete Containment Ageing

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ABSTRACT

The OECD Nuclear Energy Agency has 27 Member countries. Its working group on structural integrity has recently widened its scope to include the ageing of concrete structures. In the four years of the existence of a group on the ageing of concrete structures, there have been workshops organised on the loss of tendon prestress in containments, the development priorities for NDE of concrete nuclear structures, and the Finite Element analysis of degraded concrete structures. In addition to the proceedings of these meetings, a status report on ageing of concrete structures on NPPs has been issued, and a summary of the conclusions from the workshops is being prepared.

INTRODUCTION

The OECD Nuclear Energy Agency has 27 Member countries. Under the auspices of the Nuclear Safety Division are two senior committees dealing with regulatory aspects (CNRA) and technological aspects (CSNI). Under these two committees there are five Principal Working Groups on various technical areas. Activities relevant to concrete (mainly containment) structural integrity are carried out under the Principal Working Group 3 (PWG-3) on Integrity of Components and Structures. The main activities are the preparation of status reports or state of the art reports, the organisation of benchmarks, and the organisation of workshops and specialist meetings.

PWG3 has recently widened its scope to include the ageing of concrete structures. In the four years of the existence of a sub group on the ageing of concrete structures, there have been workshops organised on the loss of tendon prestress in containments, the development priorities for NDE of concrete nuclear structures, and the Finite Element analysis of degraded concrete structures. In addition to the proceedings of these meetings, a status report on ageing of concrete structures on NPPs has been issued, and a summary of the conclusion from the workshops is being prepared. This paper has been prepared by the chairman and the secretary of the group.

The group works in co-operation with other relevant international organisations such as WANO, IAEA, RILEM and FIB as appropriate.

STATUS REPORT

In 1994, the Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI), decided to set up a task group to study what were the needs for international activities in the areas of concrete structural integrity, and specifically the ageing aspects. A letter requesting information and comments from Organisation for Economic Co-operation and Development (OECD) Member Countries not represented on the task group was distributed. Results obtained from the letter, input from task group members, and information presented in the open literature were used to prepare a report (ref. 1) which described both the present status of the topic and made proposals for future work. Since then, an expanded group has continued the work.

Safety-related concrete structures (primarily containments) for several reactor concepts were briefly described in the report as well as their materials of construction. Primary mechanisms that can produce adverse ageing of the concrete structures were described (e.g., chemical attack and corrosion of steel reinforcement). The overall performance of nuclear power plant concrete structures was described and age-related degradation incidences that had occurred were noted (e.g., corrosion of steel in water intake structures and corrosion of metal liners).

As over 80 of the OECD Member Country nuclear plants have been in operation for over 20 years, many countries are developing systematic ageing management programmes. Although the majority of these programmes are addressing components such as the reactor pressure vessel and steam generator, several national programmes have sophisticated activities that address the concrete structures (e.g., Canada, France, Japan, Switzerland, United Kingdom, and the United States).

International ageing management activities have primarily been addressed under the auspices of the International Atomic Energy Agency (IAEA) and the Commission of European Communities (CEC). The IAEA has completed a co-ordinated research programme that identified ageing management activities for concrete containment buildings. CEC activities primarily have addressed an assessment of the long-term durability of reinforced and prestressed concrete structures and buildings, and steel containments in nuclear power plants. This was done through visual inspections, material sampling, and testing at selected plants ranging up to 29 years in age. Corrosion of steel reinforcement and the steel containment pressure boundary were the primary degradation mechanisms observed.

In reviewing national and international activities addressing ageing management of safety related nuclear power plant reinforced concrete structures and liners, several conclusions were derived.

- Performance—Performance of the structures has been good. Where problems have been identified, they initiated during construction (e.g., poor material quality control and premature stripping of formwork). As these structures age, degradation due to ageing may threaten their fitness for continued service.
- Material Data—Numerous data are available on the physical and chemical nature of concrete under various service conditions (e.g., freeze/thaw cycling and elevated temperature). However, insufficient data exist where more than one of these ageing factors is operating at the same time.

- In-Service Inspection Methods—When properly used and applied, in-service inspection techniques are effective in detecting ageing and provide vital input for assessing the structural condition (e.g., relevant parameters or indications of ageing processes). Techniques for in-service inspection of thick sections and inaccessible areas require development.
- In-Service Monitoring — Instrumentation systems to routinely monitor performance provide valuable data for assessing the structural condition and detecting ageing phenomena. However, these systems should be used in conjunction with periodic condition assessments.
- Condition Assessment—General guidance exists for conducting condition assessments. However, criteria do not exist for interpreting the data provided (i.e., a definitive answer on when ageing has advanced to the point of degradation that requires implementation of a remedial measures activity).
- Repair Methods— Repair methods for general civil engineering reinforced concrete structures are well established and effective when correctly implemented. The long-term effectiveness or durability of remedial measures relative to their application to nuclear power plant structures has not been established.
- Service Life Models—Service life models have been developed for estimating the remaining life of concrete structures. However, experience-based data are not readily available in a form suitable for use to refine and validate the models. Applications of these models have been primarily to new structures with corrosion of steel reinforcement being the primary ageing factor considered.
- Analysis Methods—Several activities are ongoing that continually provide improved analyses and modelling of non-linear and time-dependent conditions. Many of these developments should be applicable to analyses of nuclear power plant reinforced concrete structures.
- Structural Reliability Methods — Reliability-based methodologies provide a useful tool for quantitative assessments of current conditions and estimating future structural reliability and performance. The methodology can be used as a basis for selecting appropriate intervals for conducting in-service inspections and determining the extent of inspection and repair activities to help assure continued safe operation. Quantitative data for input into the methodology are limited and the reliability models for condition assessments have not been validated.
- Ageing Management Programmes—A number of national and international ageing management programmes are presently addressing ageing. The national programmes are driven by licensing arrangements, as opposed to design life considerations, and are application specific. Some information exchange has initiated at the international level through efforts of organisations such as IAEA, but are directed mainly at structures, systems, and components other than the concrete structures.

The Task Group recommended a set of topics for a series of workshops that address specific issues associated with ageing. These were as follows, in decreasing priority:

First Priority

- Loss of prestressing force in tendons of post-tensioned concrete structures
- In-service inspection techniques for reinforced concrete structures having thick sections and areas not directly accessible for inspection (a round robin testing activity could result from this workshop)

Second Priority

- Viability of development of a performance-based database
- Response of degraded structures (including finite-element analysis techniques, possibly leading to an International Standard Problem)

Third Priority

- Instrumentation and monitoring
- Repair methods
- Criteria for condition assessment

TENDON PRESTRESS LOSS IN NPP CONTAINMENTS.

To address the highest priority issue, a workshop was organised by EDF and IPSN at Civaux NPP (Poitiers, France), 25-26 August 1997. The main aim was to discuss operating experience in this area, so in order to encourage utility participation, the co-sponsorship of WANO was obtained. There were representatives from 14 countries. The proceedings of the workshop have been issued (ref. 2), but the final conclusions are still being discussed by the group. Some preliminary conclusions are given here:

1. The nuclear industry has adopted regulatory and codified methods for predicting the loss of prestress in nuclear power plant (NPP) prestressed concrete containments from international and national standards that are not necessarily specific to nuclear design. The application of the different methods to a specific case is likely to lead to significant differences in the predicted losses.

2. Theoretical and experimental research have established the importance of understanding how chemical, hygral, mechanical and thermal factors influence the short term and long term behaviour of prestressed concrete. In particular, they have differentiated between creep, drying shrinkage and relaxation of prestressing steel and identified the interdependency of these phenomena. However, research has, as yet, failed to formulate a universal and reliable model for predicting both short and long term loss of prestress in actual prestressed concrete structures. Current and proposed activities aimed at improving the prediction of loss of prestress include: the creep behaviour of concrete in a biaxial or multiaxial stress field, standardisation of creep experiments to provide reliable data; experiments on the effects of temperature on prestressing steels; and the development of approximate formulae and both empirical and semi-empirical models to improve the prediction of shrinkage and creep in concrete, and relaxation of steel.

3. Improved and simplified simulations of creep and shrinkage phenomena that can account for the environment and loading history of prestressed concrete containments and pressure vessels will assist: the development of design regulations/standards; the choice of concrete mix; the development of relevant monitoring programmes, and ageing management including plant life extension.

4. Prestressed concrete containments and pressure vessels use both grouted (bonded) tendons and ungrouted (unbonded) tendons. The workshop considered the relative merits of both systems.

- Grouted Tendons. The cementitious grout: surrounds the tendon in an alkaline environment that will inhibit corrosion of the steel, and prevents the ingress and circulation of corrosive fluids. In case of break of a tendon, due to the bond with the grout, part of the prestress remains transmitted to the concrete. Therefore grouted tendons are less vulnerable than ungrouted tendons to local damage. They reduce the risk of the containment being by-passed via tendon ducts, particularly important where the containment is unlined. However, grouted tendons can not be visually inspected, mechanically tested or re-tensioned in the event of greater than expected loss of prestress.
- Ungrouted Tendons. Prestressing force is transmitted to the concrete, primarily, at the location of the anchorages. Corrosion is prevented by organic petroleum based greases or corrosion inhibiting compounds. These are either applied to the surface of the tendon prior to installation or injected into the tendon duct following completion of the stressing sequence. Some countries use a combination of both coating and injection. Tendons can be removed for visual inspection/replacement; mechanically tested in-situ; and retensioned to maintain prestress. Ungrouted tendons are more vulnerable than grouted tendons to local failure and corrosive fluids can circulate along the ducts. Ducts may provide a route for containment by-pass in unlined containments, although the practice of keeping ducts filled with corrosion protection medium reduces the likelihood of by-pass.

5. Experience presented at the workshop indicates that comprehensive and regular monitoring of the behaviour of containments and pressure vessels at operational plant assist our understanding of the cause of loss of prestress. Containments around the world include instruments to measure: anchorage loads; concrete strain; structural geometry; concrete temperature; and surface cracking. Data collected from more than 150 structures aged between 3 and 40 years indicate that, for the majority, loss of prestress has been less than predicted. For a small number of containments, losses have exceeded predictions. Measured losses vary from containment design to containment design but significant differences have also been observed between containments in the same design series. The variation in measured losses has been attributed to a number of factors including: concrete composition; aggregate type; the presence of a liner; high relaxation of steel tendons; concrete temperatures; loading history and the environment. Regulatory and codified prediction techniques do not necessarily account for such factors and may underestimate loss of prestress.

6. Many plant include direct measurement of tendon loads at the anchorage. A number of papers reported problems with the reliability and accuracy of tendon load measurement. The use of tendon load to interpret loss of prestress requires careful consideration of the method used to measure the load and the design of the prestressing system.

7. Nuclear containments and pressure vessels are designed with large margins on structural integrity. Therefore, a higher than expected loss of prestress does not necessarily jeopardise the integrity of the structure. However, under accident conditions the margin on precompression of the concrete is reduced and therefore there is an increased risk of cracking. This may result in a corresponding increase in the leak rate of unlined containments. Periodic testing of the containment is used to evaluate its leaktightness.

8. The workshop discussed the corrosion protection media used for containments and pressure vessels having ungrouted tendons. For systems where the tendon duct is filled with protection media, greases have been developed that optimise: viscosity, resistance to penetrating concrete; water displacement; alkalinity and electrical conductivity. For systems using coated tendons, with time the grease looses its lighter oil component but the residue is still capable of providing corrosion protection to the tendons.

NON-DESTRUCTIVE EXAMINATION (NDE)

To address the other high priority topic, a workshop which considered the requirements for NDE of safety related concrete structures was held at Risley in the UK on 12 November 97. There were representatives from 11 countries. The proceedings have been issued (ref. 3). The workshop considered a draft report on the subject, which was altered in the light of the workshop discussion, and issued separately later (ref. 4). The objective of this report was to provide a basis for assessing development priorities for NDE of safety related concrete structures in nuclear plants, taking account of both the benefit and the cost of potential developments in NDE techniques.

NDE techniques have the potential to satisfy at least some of the needs of the nuclear industry. NDE techniques have been used successfully on a variety of reinforced and post-tensioned concrete structures, notably highway and reservoir structures. However, there is limited experience of their use to evaluate typical nuclear safety related structures having thick sections, steel liners or access to one side only.

There is a general lack of confidence in the techniques because there is very little independent advice on their applicability, capability, accuracy and reliability. The information obtained by techniques such as RADAR, ultrasonics, stress wave and radiography appears qualitative rather than quantitative and there is concern that NDE procedures lack the necessary qualification to permit their use on safety critical structures. There is no authoritative international guidance or standard for NDE of concrete structures.

NDE of concrete structures is often based upon equipment developed for other materials and technologies, eg. examination of steel, evaluation of ground conditions. Other industries are developing equipment specifically for civil engineering applications and at the recent OECD workshop a number of relevant national and European programmes were identified. The nuclear industry should maintain its awareness of developments and should seek to influence the development of equipment.

The quantification of the capabilities of NDE techniques is seen as a priority area for development. The provision of authoritative documentation in the form of reports and Standards is desirable. However, the industry lacks an international standard for quantifying the NDE of nuclear safety related concrete structures. Qualification is important to the successful deployment of NDE techniques and will need to be considered when addressing this issue.

The high cost of developing software and equipment, with no guarantee of success, means that the nuclear industry is unlikely to consider this to be a priority area for funding. However, it is important for the industry to establish national networks with groups that are funding development. There is support for the principle of establishing a group of international experts to monitor national developments.

The recommendations of the report are:

- More formal liaison with other industries that use NDE techniques should be established and opportunities to work with suppliers to influence the development of new equipment should be sought
- Experts should be identified to monitor national programmes with the aim of improving the understanding of the availability and capability of NDE techniques within the nuclear industry
- CSNI should review this topic in approximately 3 years
- At the time of the review, consideration should be given to quantification of the capabilities of NDE techniques by means of a standard test specimen specification
- As a longer term issue qualification should be considered.

PERFORMANCE-BASED DATABASE

After detailed discussion, it was considered that development of a performance based database by OECD-NEA was not feasible at present and was to a large extent being covered by IAEA programmes.

FINITE ELEMENT ANALYSIS OF DEGRADED CONCRETE STRUCTURES

To address a further topic identified in the status report, a workshop on Finite Element (FE) analysis of degraded concrete structures was held at Brookhaven National Laboratory in the USA, on 29-30 October 1998. This was hosted by US NRC, and it was jointly organised with the PWG3 sub group on the seismic behaviour of structures, as both static and dynamic aspects were considered. There were representatives from 14 countries. The workshop considered the use of FE analysis in safety assessments, concrete containment structures under accident loads and concrete structures under extreme environmental loads. Although currently in preparation, the proceedings (ref. 5) have not yet been issued and the conclusions have not yet been finalised.

FUTURE ACTIVITIES

Work on addressing the list of topics in the status report and other items is continuing and a future programme to cover the third priority issues and issues arising is under development.

- Currently it is planned that a workshop dealing with instrumentation and monitoring will be held in Belgium in the first quarter of 2000. As a result of discussions during the workshop on the FE analysis of degraded concrete structures, the use of instrumentation in structures to validate numerical models will be included as a topic.

- There was a recommendation from the NDE workshop that steel corrosion should be considered as a subject for a separate dedicated workshop. Topics for this additional workshop would include corrosion of reinforcement and embedments, inspection, monitoring, solutions such as cathodic protection, and design and installation of systems. As a first step a report will be prepared on the subject and used as the basis for the workshop.
- The group works in co-operation with RILEM, a Paris based materials testing laboratories international organisation, which has a technical committee on the life management of concrete structures in NPPs. This technical committee is organising a final conference in Bratislava in July 1999, and PWG3 is cosponsoring this conference.

CONCLUSIONS

Some of the main functions of the CSNI are to exchange information, overcome discrepancies and to reach international consensus on technical issues. PWG3 and its sub groups participate actively in this effort. Examples have been given here in the area of the ageing of concrete structures in NPPs. The working group has progressively worked through the priority list developed during the preliminary study carried out by the Task Group. Currently two of the three levels of priority are effectively complete, although in doing so the committee has identified other specific items worthy of consideration. By working logically through the list of priorities the committee has maintained a clarity of purpose which has been important in maintaining efficiency and achieving its objectives. The performance of the group has been enhanced by the involvement of regulators, operators and technical specialists in both the work of the committee and its technical workshops and by liaison and co-operation with complementary committees of other international organisations. The workshop format that has been adopted (based around presentation of pre-prepared papers or reports followed by open discussion and round-table development of recommendations) has proved to be an efficient mechanism for the identification of best practice, potential shortcomings of current methods and identification of future requirements.

REFERENCES

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3. NEA/CSNI/R(97)28 Proceedings of workshop on Development priorities for NDE of concrete structures in nuclear plants, Risley, UK, November 1997

4. NEA/CSNI/R(98)6 Development priorities for NDE of concrete structures in nuclear plants.

5. NEA/CSNI/R(99)1 Proceedings of workshop on FE analysis of degraded concrete structures, BNL, NY, USA, October 1998 (to be issued)