



Issues Related to Durability of Concrete Structures in the Context of Decommissioning of NPP

L. R. Bishnoi and Prabir C. Basu

Atomic Energy Regulatory Board, India

ABSTRACT: Some concrete structures of a nuclear power plants may have to be maintained in place in sealed condition for a specified time of decommissioned period. Durability of these structures is a major concern. Deterioration of concrete structures is caused primarily due to corrosion of steel and degradation of concrete mass. Information regarding Quantification of the effect of corrosion is available, but there is hardly any information with regard to quantification of the degradation of concrete due to chemical and physical attacks. Author propose an expression for reduction factor (R_f) of service life, for this purpose, in terms of environmental condition, durability attributes of concrete, in-service inspection, reparability of structure and the effect of change in structural geometry. Various coefficients of this expression are to be determined from the in situ condition of the structures, Suggestion has been made for tests of the structure for this purpose.

INTRODUCTION

Decommissioning activities of NPPs can be broadly identified in three stages^{1, 2}, which are: (1) discharge of fuel and bringing the plant into un-operational safe condition with continuing surveillance, monitoring and inspection; (2) reduction of the plant installation to the minimum possible (or converted for new purpose) without penetration into the highly radioactive areas; and (3) release of the plant and the site for unrestricted use. All three stages can be accomplished in continuation without any waiting period between them, called prompt decommissioning, or with time gaps between completion of one stage and starting of next stage, called delayed decommissioning. One of the major factors affecting the choice between prompt versus delayed decommissioning of an existing nuclear facility is the condition of civil engineering structures and establishing how it will change in long term.

Majority of the civil engineering structures of an NPP is concrete structure which are prone to many long-term deterioration processes. Some of the civil engineering structures may have to be maintained in place in sealed and stable condition for a few years to many decades after final shutdown of a Nuclear Power plant (NPP), depending on the strategy adopted of decommissioning³. Structural integrity and functional capability of these structures need to be ascertained during this period. Therefore durability of these structures needs to be looked into.

Properties of concrete undergo change over time due to continuing reactions among its constituents as well as with external environment. The later type of reactions is mainly responsible for deterioration of concrete structures. Measures can be adopted at one or more

stages of engineering of concrete structures to control deterioration over time and improve durability^{4,5}. However, codal provisions and practices are silent on quantification of structures for durability in terms of time.

Durability aspects of concrete structures are addressed in the paper in quantitative format along with test requirements for concrete qualification and acceptance, and need for further work, particularly in the context of decommissioning of PPS. Two phenomena, corrosion of reinforcements and degradation of concrete are found primarily responsible for loss of durability of concrete structures. Attempt has been made, in this paper, to discuss these two phenomena in quantitative format. Though information on mathematical modeling related to corrosion aspects is available in literature but the same for degradation of concrete is scanty. Authors propose, for this purpose, expression of service life reduction factor.

DURABILITY DESIGN

Decommissioning was not considered to be a design issue during design of NPPs earlier^{6,7} in earlier days. However, studies and experience have now demonstrated that decommissioning requirements need consideration at design stage. In this respect consideration of durability of concrete structures for NPPs at the design stage assumes great significance^{4,5,8}

Majority of the deterioration processes affecting durability of concrete structures is either chemical or physical processes. Most common forms of chemical attack on concrete are^{10,11,12} leaching, sulphate attack, acids and bases, carbonation, and alkali-aggregate reactions. Physical phenomena of concern for concrete structures of nuclear facilities^{10,11,12} are shrinkage, creep, abrasion, erosion, cavitation, thermal cycles, wetting-drying cycles, irradiation, fatigue/vibration, settlement, salt crystallization, and frost attack in cold climates. Causes of degradation of reinforcing and prestressing steel are corrosion, elevated temperature, irradiation, and fatigue.

In case of prestressed structures, loss of prestressing over long period due to steel relaxation as well as creep and shrinkage of concrete could become cause of concern^{11,12} for safety and serviceability. The most generic problem affecting long term performance of concrete structures is the corrosion of reinforcing steel. Major processes responsible for steel corrosion in concrete are identified as chloride ion penetration, carbonation and leaching of calcium compounds.

Corrosion of tendons and loss of prestressing force are major causes of concern for durability of prestressed structures. In case of prestressed concrete containment structures in NPPs, there is no method available as yet for assessing loss of prestressing force for grouted cables. Grout is intended to protect cables against corrosion. It may be sufficient to ensure integrity of prestressed containment structure as a reinforced concrete structure against the loading conditions during decommissioned period and durability against relevant deterioration processes in case quantitative assessment of condition of prestressing cables with respect to corrosion is not possible.

The idea behind the durability design is to ensure avoidance of large-scale damage to the structures, which could otherwise render them prematurely unserviceable. The authors believe that three pronged approach to durability is desirable for concrete structure of NPPs, especially those which may be required to be in service during decommissioned period. The approach is as follows: (1) Adequate care during strength design and construction for those aspects which have bearing on durability; (2) positive protection against specific environments with suitable ageing management program; and (3) explicit durability design and quantification of life for generic durability problems i.e. steel corrosion and degradation of concrete.

REINFORCEMENT CORROSION

Reinforcement corrosion in concrete is an electrochemical process. It is manifested in the form of staining, cracking or spalling of cover concrete. Excessive loss of cover concrete can cause loss of bond between the bar and concrete that may result in loss of integrity of the reinforced concrete member. Corrosion can also cause reduction of effective steel cross-section and capacity.

Service life of a concrete structure with regard to corrosion can be viewed as sum of the time-to-initiation of corrosion and the time-to-significant damage after initiation. The time-to-initiation depends on the processes responsible for depassivation of reinforcing steel as well as the quality and thickness of concrete cover. The time-to-significant damage depends on definition of significant damage, corrosion rate, shape of the structural member, and strength, thickness and quality of cover concrete.

Reinforcement bar in concrete is initially covered with an adherent passive iron oxide film, which is chemically stable in highly alkaline ($\text{pH} > 12$) conditions surrounding the bar. At pH below 11, the iron oxide layer become unstable and metallic iron of reinforcement becomes available for formation of corrosion cell. Reduction of the concrete pH can occur as a result of carbonation of concrete or leaching. The passivity of iron oxide film can also be destroyed by penetration of chloride ions even at high alkalinity. The following three conditions should be satisfied for initiation of reinforcement bar corrosion in concrete: (1) depassivation of reinforcement bars; (2) availability of oxygen; and (3) availability of electrolyte. For sustained corrosion, steady supply of oxygen and availability of electrolyte (wetness) are essential.

Models to Predict Time-to-Initiation of Corrosion

Carbonation

The depth of carbonation is traditionally described by the equation¹¹:

$$X = K t^{1/2} \quad (1)$$

The constant K is a function of the concentration of CO_2 in the atmosphere, its effective diffusivity in concrete and the amount of CO_2 consumed in the reaction with hydrated cement. Diffusivity of CO_2 is affected by the presence of surface cracks whereas its reactivity with hydrated cement is significantly affected by the relative humidity.

Leaching

Leaching is found to be a major factor affecting durability of concrete water retaining and basement structures in nuclear industry. Leaching can cause depassivation of reinforcing steel and it weakens the concrete matrix also. There are two important parameters which affect the time-to-initiation of corrosion by leaching. One is rate of percolation of water through concrete and other is rate of hydrolysis/dissolving of calcium compounds. The rate of percolation depends on water permeability of concrete. However water permeability of concrete will undergo change due to progressive dissolving of calcium compound in water. The process of leaching, as regard to the time-to-initiation of corrosion, appears to be analogous to the process of carbonation. Hence eq.(1) may be adopted for leaching also. The constant K in eq.1 is now dependent on water permeability and hydrolysis/dissolving rate of calcium compounds in percolating water.

Chloride Penetration

Ionic diffusion is the primary process of migration of surface chlorides into the concrete. This can be described by Fick's second law:

$$\partial C / \partial t = D_c (\partial^2 C / \partial x^2) \quad (2)$$

Where, C is chloride concentration at surface, D_c is chloride diffusion coefficient, t is time, and x is depth of penetration of chloride ions. D_c is a function of the pore structure of the concrete and ambient temperature. If C_s and C_x are the chloride concentrations at surface and at depth x respectively at time t, then solution to eq. (2) yields the following:

$$C_x = C_s [1 - \text{erf} \{ x / (2\sqrt{D_c t}) \}] \quad (3)$$

Where, "erf" is the error function. Eq.(3) can be used to obtain the time-to-initiation for a given cover depth or vice-verse by putting C_x equal to the threshold chloride concentration for depassivation.

It is important to note that quantification of the value of C_s right on the exposed surface is difficult due to cycles of deposition and washing, particularly in splash zone of marine structures, and due to rains or fluctuating water tables in land based structures, and also because of reverse migration of already penetrated ions due to negative ion gradients created by surface washing. However, studies indicate that C_s values slightly inside the surface (@ 15mm) would build up with time¹³. Such a build up can be described by a suitable time dependent function with a saturation limit, C_s (max), and eq.3 can be solved for such time varying boundary conditions¹⁴. But, the important aspect of this problem is the selection of the time dependent function to describe C_s . Such a function is better derived from chloride deposition rates obtained by direct measurement from the environment.

Concrete Cover

The quality and the thickness of the cover concrete play major role in service life models concerning reinforcement corrosion. Values of K in eq.1 D_c in eq.2,3 are dependent on the quality and the cracking condition of the cover concrete, both of which may undergo change due to ageing effects. Thickness of cover is a variable parameter, which depends on the level of quality control in actual construction and the construction methodology. This variation is found to follow Gaussian distribution, as found from actual field measurements¹⁵. This can be suitably incorporated in service life models depending upon the level of protection desired for the reinforcing steel¹⁴.

Prediction of Time-to-Significant Damage

Time-to-significant damage can be estimated by finite element analysis of the cover region with proper consideration of cover thickness, bar diameter, bar spacing, concrete tensile strength, stiffness parameters of concrete, steel and corrosion products, and the rate of expansion of steel due to corrosion. The rate of expansion depends on the rate of corrosion. The actual thrust due to increased volume of the corroding reinforcing steel may be influenced by the permeability of the cover region.

DEGRADATION OF CONCRETE

Degradation of concrete may occur in the form of loss of cementing properties, loss of concrete cross section, deterioration of its mechanical properties or it may cause increased

risk of reinforcement damage. Chemical attack is generally confined to cover concrete, but it may also affect the entire cross section of the concrete depending on the duration of attack as well as the quality and the cracking condition of the concrete. Physical attacks are mainly responsible for the cracking of concrete. One way of ensuring long term safety of concrete structures against environment related degradation is to augment the structural design to compensate for degradation of strength and stiffness properties of concrete at later stages of service life. For this purpose, appropriate reduction factors can be applied to strength and stiffness parameters of concrete. No mathematical model is available in this respect. Authors propose the following expression of reduction factors for service life of structural elements:

$$R_f = \{ E + D + I + R + S \} (L/5) \quad (4)$$

R_f is the reduction factor to account for possible degradation for a given service life. When $R_f \leq 0$, its value should be taken as 1.

In the above expression factor E stands for exposure environment. Values for E may be taken between 0 for normal environment and N1 for extreme environment. D accounts for related durability attribute. Values for D may be taken between -N1 and 0; for example, where the related durability attribute is permeability of concrete, -N1 may be assigned for highly impermeable concrete and 0 for normal permeability concrete. Other durability attributes could be the relative reactivity or inertness of the concrete with the degrading chemical agent, alkalinity of the concrete and presence or absence of positive protection measures such as thermal shielding or cooling arrangement against temperature rise, lining/membrane/coating against reactive acids or bases, etc. In-Service inspection is accounted through the factor I. Values for I may be taken as 0 for frequent inspections (say annual) and N2 for areas not accessible for inspection. For less frequent inspections intermediate values between 0 and N2 may be taken. Repairability of the structural element is accounted through R. For easily repairable elements R may be taken as 0 while a value of N2 may be taken for those elements, which can not be repaired. For elements, which are difficult to repair, intermediate values may be adopted. Performance of some concrete structures is highly sensitive to small variation in geometry or degradation such as shells and folded plates while beams, columns and walls are not so sensitive. This may be accounted through factor S by assigning a value of 0 for less sensitive structural elements and N3 for highly sensitive elements. The multiplying factor L in eq.4 is meant to account for service life. For a service life upto 50 years it may be taken as 1 and for subsequent each 25 years the value of L may be suitably augmented.

As a hypothetical example, let us consider a dome structure designed to serve for fifty years. It is built with highly impermeable concrete, but exposed to coastal environment. Due to certain constraints the dome can be inspected once in five years and it is difficult to repair. Then, $R_f = [4 - 4 + 2 + 2 + 2] (1/5) = 1.2$. For illustration, values of N1, N2 and N3 are taken as 4, 4, and 2 respectively. For design purpose, values of N1, N2 and N3 need to be corroborated with adequate size of data on changes in material performance and its trend obtained from the existing structures under different exposure conditions.

TESTS FOR DURABILITY

Mechanistic models described earlier for service life prediction are still in evolutionary phase and hence require extensive experimental work for establishing model parameters as well as material qualification, and conservative assumptions wherever the available knowledge is insufficient. Effort is made here to suggest some experimental work in this direction. As

regards the conservatism of assumptions, there are two issues with respect to reinforcement corrosion process, which need attention. One is the availability of oxygen and another is the presence of electrolyte. Due to insufficient data, it is prudent to conservatively assume that oxygen and electrolyte are continuously available once the reinforcing steel is depassivated. In addition, rainfall/wind directions influence chloride deposition rate and presence of other pollutants like SO₂ affect reactivity rate of CO₂. Here again one may conservatively select the upper values of these parameters obtained from environmental data.

Tests for Climatic Data

These tests are required to know the concentration of deleterious agents in the immediate environment of the structure as well as other climatic parameters such as temperature, relative humidity and rainfall/wind, which affect the rates of deterioration processes. All these parameters should be measured for the site/region over extended period of at least a few cycles of climatic seasons and values to be used for design should be derived from these data.

Tests for Carbonation

Carbonation of concrete involves many parameters. Suggested equation for carbonation is empirical. These aspects make it very difficult to suggest direct and simple tests for qualification of concrete against carbonation. However co-relations may be established between measured values of constant K (eq.1) and the air permeability of concrete. Concrete specimens prepared from different types of mixes may be exposed to the environment for periods extending over a few years (say 5 years) and depth of carbonation may be measured at the end of each climatic season or even shorter interval. Some specimens from corresponding mixes may be tested for air permeability at similar intervals. Measurements of carbonation depth can be used to calculate K using eq.1 and these K values can be correlated with air permeability test results. Such co-relations can be continuously improved with more data obtained over long periods. Based on these correlations qualification and quality control tests can be specified in terms of air permeability requirements.

Tests for Leaching and General Durability Index

Water permeability of concrete can be used as a measure of soundness against leaching as well as a general durability index. For determination of water permeability of concrete over a short period, falling head permeameter can be used¹⁶. Faces of test specimen should be sealed with suitable waterproof sealant except those faces, which would be exposed to water head. One important aspect of such a test is the effect of stratification of concrete in the specimen. In order to overcome inconsistency due to stratification, the specimens should always be tested along the direction of filling of the casting mould.

Tests for Chloride Penetration

Concrete specimens from different trial mixes can be subjected to very high chloride concentrations, either in air or in solution depending on the environmental condition so as to obtain measurable surface deposition and penetration in shortest possible time period. Chloride profiles in the specimens can be determined at the end of the test and D_c can be determined using eq.3. The specimens will require some treatment (i.e. sealing with epoxy resin etc.) before exposure to allow unidirectional chloride penetration. For quality control during concrete production, specimens can be tested in appropriate chambers of very high chloride concentration as explained earlier and acceptance can be based on absence of chloride ions at pre specified depth after specified period of exposure.

Correction for Field Conditions

Values of K in eq.1 and D_c in eq. (2,3) should be the effective values smoothened over the service period. For this purpose, co-relations can be obtained between K , D_c and their effective values by comparing values determined by direct measurements on existing structures with those of laboratory determined values from test samples of identical mix design provided complete mix design details of the existing structures are known.

DURABILITY OF EXISTING STRUCTURES

Early decision on the mode of decommissioning has many advantages with regards to durability aspects of concrete structures of operating NPPs. Early detection of any deterioration process may help in effective intervention/control to keep the structures in reckoning for extended service and the ageing management program can be suitably tuned for all those structures which are likely to remain in service for extended period of decommissioning. Another important aspect is the collection of necessary climatic data and tests. Periodic collection of data directly from relevant structures through suitable monitoring scheme, NDT measurements or samples may provide necessary input for residual service life models as well as trending of structural performance.

While considering these structures for extended service in the context of decommissioning, the prudent approach is to carry out condition assessment of such structures and evaluate their adequacy for future intended use with or without repairs. Methodologies for condition assessment and evaluation of concrete structures important to safety have been adequately described in literature^{10,11,12}.

CONCLUSION

Durability of safety related concrete structures is an important issue in the context of decommissioning of NPPs. Major factors affecting durability of concrete structures are either chemical or physical attacks of environment which may act individually or in synergy. Corrosion of reinforcing steel and degradation of concrete are the generic problems of durability of these structures.

Carbonation, leaching and chloride penetration is the general processes responsible for initiation of steel corrosion in concrete. Rate of these processes can be quantified through suitable mathematical models. Parameters governing the rate of these processes are influenced by many factors, the most significant are the concentration of relevant pollutants and the quality of concrete, particularly the pore structure and the permeability.

Safety against the effects of degradation of concrete under known exposure can be assured for a known service period by means of augmentation of the related durability attributes and consideration of these effects at design stage by applying appropriate reduction factors on strength/stiffness parameters of concrete.

Suitable tests can be designed to obtain information on the concentration of pollutants as well as for qualification/acceptance of concrete for durability attributes. For application of the models for reinforcement corrosion as well as for consideration of concrete degradation at design stage, large data base need to be generated on the performance of the existing structures and suitable co-relations need to be established with laboratory test results.

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