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ORNL

FOREIGN TRIP REPORT

ORNL/FTR-3827

DATE: November 27, 1990

SUBJECT: Report of Foreign Travel of D. J. Naus, Manager, Structural Aging Program, Engineering Technology Division

TO: Alvin W. Trivelpiece

FROM: D. J. Naus

PURPOSE: To participate in the fourth meeting of Réunion Internationale des Laboratoires d'Essais et de Recherches sur les Matériaux et les Constructions (RILEM) 100-TSL, "Techniques for Service Life Prediction," the Fifth International Conference on Durability of Building Materials and Components, and to visit various foreign research laboratories to obtain information on time variation of material properties, performance of concrete material systems in nuclear power plant structures, techniques for repair of degraded concrete structures, methods for evaluation of concrete structures, and modeling to predict the effects of degradation factors on concrete materials.

SITES

VISITED:
11/5/90

Taywood Engineering, Southall, Middlesex,
Ltd. England

P. Barnforth
R. Crowder
P. Dawson
C. Fleischer
K. Treadaway

11/6/90

RILEM 100-TSL Brighton,
England

Participants

11/7-9/90

Fifth International Brighton,
Conference on England
Durability of
Building Materials
and Components

Participants

11/12/90

Électricité de France Lyon,
France

B. Barbé
Mrs. Chauvel
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M. Rameau
M. Soria

11/13/90

AEA Technology

Oxfordshire,
EnglandA. Atkinson
A. Harris
P. Lawrence
C. Naisch
C. Wilding

ABSTRACT: The traveler participated in the fourth meeting of RILEM 100-TSL, "Techniques for Service Life Prediction," and "The Fifth International Conference on Durability of Building Materials and Components." In addition, the traveler met with staff members at Taywood Engineering Ltd., Électricité de France, and AEA Technology. The meetings pertained to performance of concrete materials in nuclear power plant structures, time variation of concrete material properties, methods for evaluating concrete structures, and modeling to predict the effects of degradation factors on concrete materials. As many of the concrete structures in general civil engineering applications as well as nuclear power plant applications in Europe are aging, there is increasing emphasis on assessing the durability of these structures. Information was provided of direct application to the Structural Aging Program which would not have been available without these visits. Of equal, or possibly more importance, was the individual contacts established at the organizations visited. Each organization was extremely interested in both the approach and scope of the Structural Aging Program and requested that they be informed of progress. The initial steps were taken to cooperate with several of these researchers and this should help the Structural Aging Program keep abreast of related European activities. In summary, information obtained during this trip will benefit the ongoing Structural Aging Program by informing Oak Ridge National Laboratory (ORNL) of the extensive European research programs addressing the durability of concrete structures, and also by forming and strengthening acquaintances with counterparts in other countries, thus enhancing the basis for possible international cooperation.

INTRODUCTION

The purposes of this trip were to participate in the fourth meeting of RILEM 100-TSL, "Techniques for Service Life Prediction," and "The Fifth International Conference on Durability of Building Materials and Components," and to hold discussions with staff members of European research laboratories that are conducting R&D activities related to performance of concrete materials in nuclear power plant structures, time variation of concrete material properties, methods for evaluating concrete structures, and modeling to predict the effects of degradation factors on concrete materials. The laboratories visited included Taywood Engineering, Ltd., (Southall, Middlesex, England), Électricité de France (Lyon, France), and AEA Technology (Oxfordshire, England). Appendix A presents the itinerary.

TAYWOOD ENGINEERING LIMITED

Discussions at Taywood Engineering, Ltd., were primarily in three areas: (1) potential contribution of data to the Structural Materials Information Center which has been developed at ORNL, (2) concrete repair procedures, and (3) inspection of concrete structures.

Taywood Engineering, Ltd., has been involved in prestressed concrete pressure vessel (PCPV) technology for about 30 years. During this period they have conducted numerous research and development activities in support of the design and construction of PCPVs as well as their operation that has produced data and information of interest to the Structural Aging Program, e.g., long-term concrete creep data for Wylfa and Hartlepool, and annual inspections at Wylfa, Hartlepool, and Heysham stations. As a result of their close working relationship with Nuclear Electric (nuclear segment of Central Electricity Generating Board which was not privatized and has responsibility for the Magnox and Advanced Gas-Cooled Reactors), Taywood Engineering, Ltd., potentially also has access to data of interest from other United Kingdom plants. A second potential source of data arises from a study Taywood Engineering, Ltd., recently completed for the Commission of European Communities (CEC) on deterioration assessment of nuclear power stations. This activity addressed the likelihood of occurrence of durability problems in reinforced concrete components of buildings and structures at nuclear power stations during a period of up to 140 years. The 140 years is based on maximum periods of 40-years operation and 100 years of storage. Three Magnox-type plants and one Advanced Gas-Cooled Reactor plant in the United Kingdom and the French plants at Chinon and Marcoule were investigated to provide several exposure conditions, various degrees of deterioration, and a range of concrete types. The emphasis of the investigation was on deterioration caused by corrosion of the steel reinforcement, i.e., corrosion due to chloride ingress and carbonation penetration. Based on these two primary corrosion processes and the environmental factors of importance, techniques for on-site measurements were selected and surveys (visual, testing, and sampling) of accessible components at each of the six plants were undertaken. In particular, the corrosion initiation stage (incubation period) was studied to identify means for predicting the likely time scales for occurrence of reinforcement corrosion with respect to the 100-year envisaged decommissioning period following 40 years of operation, i.e., whether or not corrosion of the steel reinforcement would be expected during the decommissioning period. Results of the site surveys indicated that the concrete in these plants was generally in good condition. Detailed results of this program are contained in the Nuclear Science and Technology report, EUR 12758 EN, "Long-Term Performance of Structures in Nuclear Power Plants (1990)." More recently, a second program has been accepted by the CEC for funding and has the intent of building on and expanding the work undertaken in the CEC's 1984-88 program noted previously. The overall scope of this program is to develop data base systems, to reexamine initial models developed for prediction of corrosion occurrence in nuclear power plant structures, and to improve the methods developed to predict future performance of concrete structures in nuclear power plants. The work encompasses six tasks: (1) reinvestigation of the six nuclear power stations visited 6-7 years ago to obtain additional data on penetration of carbonation and chloride ions (additional data will enable the estimated rates of degradation to be verified); (2) extension of data base through examination of additional nuclear power plants in England, France (St. Laurent), and Italy (Garigliano); (3) development of a data base to provide a systematic method for compiling and retrieving data developed from the plant examinations; (4) development of a planned inspection and maintenance system which would identify appropriate requirements for future monitoring activities and preventative maintenance measures; (5) formulation of methods to predict the behavior of typical prestressed concrete structures for periods up to 100 years following end of operational life (i.e., establish minimum performance criteria to ensure that the structure satisfies appropriate requirements for the containment of nuclear

radiation); and (6) investigation of nondestructive monitoring techniques to evaluate the condition of the prestressing tendons with the emphasis on postoperational monitoring of tendon condition. The possibility of the Structural Aging Program participating in the CEC study was discussed and Taywood Engineering, Ltd., will pursue this with the CEC. Other areas where Taywood Engineering, Ltd., could provide information suitable for incorporation into the Structural Materials Information Center includes data recently provided from concrete core samples taken at Wylfa, data from the yearly inspections of the prestressing systems at several of the United Kingdom nuclear stations (Wylfa, Hartlepool, Heysham), and irradiation effects on concrete (samples of concrete have been removed from the Wynscale Advanced Gas-Cooled Reactor which started operation in the early 1960s).

In the area of repair of concrete structures, Taywood Engineering, Ltd., has three programs which are in progress, and a fourth program that has been submitted to the CEC for funding. The first of these programs is funded by BRITE/EURAM and is entitled "The Development of Standardized Performance Tests and Criteria for Concrete Repair Systems." A discussion of this program will not be provided since it was addressed in a previous trip report (ORNL/FTR-3641, dated July 9, 1990). The second BRITE Program has the objective of extending the lifetime of concrete structures before a repair procedure is required. Basic activities of this program include: (1) examining the effect of incorporating additional materials into the concrete mixes (chemical admixtures) or partial replacement of the cement by alternative cementitious materials (ground granulated blast-furnace slag, silica fume, pulverized fly ash, etc.), (2) investigation of specialized coatings (polyurethanes, acrylics, silanes, siloxanes, and special emulsions) to protect concrete against severe environments, and (3) development of life prediction models to provide reliable assessments of deterioration rates (emphasizing rebar corrosion). The third program is also funded by BRITE and has the objective of providing, by March 1991, a state-of-the-art report on concrete repair procedures used by CEC member countries. Included in this report will be the identification and evaluation of specific techniques and materials that have been used for repair. The intent of this program is to provide a basis for future research. Finally, Taywood Engineering, Ltd., has submitted a proposal to BRITE which will address the effect of repair techniques on structural performance. Five intensities of damage, ranging from corrosion to seismic effects, are proposed for use in the evaluation of various repair procedures. The status of this program should be determined by the end of this year. Results of Taywood Engineering, Ltd's., repair programs are of great interest to the Structural Aging Program as they address many of the areas contained in the FY 1991 planned activity to identify, describe, and quantify the effectiveness of techniques which are available for use in repair of degraded civil engineering structures.

With respect to inspection of concrete structures, Taywood Engineering, Ltd., has been actively involved in the inspection of several of the Central Electricity Generating Board (CEGB) nuclear facilities. Typical measurements performed on an annual basis include foundation settlement, strain gage readings, thermocouple readings, in-service visual inspections, prestressing system loads and constituent material characteristics, etc. As a result of these measurements, an extensive data base has been established. Taywood Engineering, Ltd., has prepared a proposal for CEGB to develop an inspection methodology, but it was felt that CEGB has such an extensive data base available from the annual inspections performed at each plant that the program is not needed. A second proposal related to the inspection and monitoring of nuclear facilities has been prepared and submitted to the CEC for funding. The proposal again addresses the decommissioning period for nuclear power plants and includes development of a monitoring program to guarantee the structural integrity of the PCPVs throughout the decommissioning period. One question to be addressed is whether all or part of the prestressing can be removed during the decommissioning period.

RILEM 100-TSL/CIB W80 Techniques for Service Life Prediction

This was the fourth meeting of RILEM 100-TSL/CIB W80 and was attended by 16 experts (the committee consists of 37 members representing 22 countries). The overall purpose of the committee is to develop information on the service life prediction of building materials and components. The committee's main activities are to: (1) encourage and aid in the implementation of the generic methodology developed by the joint CIB/RILEM W80/71-PSL (present committee's predecessor) and contained in International Council for Building Studies and Documentation (CIB) Publication 96 "Prediction of the Service Life of Building Materials and Components (1986)," (2) further develop and detail this methodology, and (3) provide a focal point for service life research and contribute to advancing the knowledge base of service life prediction for structures and components. The meeting was divided into three segments (1) discussion of CIB report Nos. 127 and 128 prepared by the committee, (2) presentation of proposals for new working programs on prediction of service life, and (3) technical presentations.

Two reports have been prepared by the committee (1) Publication 127 "Feedback from Practice of Durability Data" and (2) Publication 128 "Feedback from Practice of Durability Data Appendix - Examples of Field Investigations." Both of these reports are available from the CIB, Rotterdam. Contained in the first report is the generic methodology for the prediction of service life proposed by CIB/RILEM 100-TSL. The methodology includes five sections: (1) definition (user needs, performance requirements and criteria, and material characterization); (2) preparation (type and range of expected degradation, effects of degradation, and how in-use degradation can be induced by aging tests), (3) pretesting (preliminary short-term aging tests to demonstrate representative failure occurrence), (4) testing (design and performance of predictive service-life tests), and (5) interpretation and discussion (develop relationship between test results and predictive service-life tests and long-term aging tests). Other sections of the first report cover the role of exposure environment in service-life prediction, data from experimental long-term aging studies under in-use conditions (field tests, experimental buildings, and in-use testing), and feedback from practice by inspection of buildings (inspection routines, field applicable evaluation techniques, sampling of objects to inspect, methods for measurement and description of exposure environment, and reporting of in-service durability data). The second report presents concepts for prediction of service life of concrete structures with respect to corrosion of mild steel reinforcement, two case studies (reevaluation and repair of a tunnel damaged by a fire, and extension and strengthening of a building), and a methodology for condition surveys of parking structures.

The work of RILEM 100-TSL/CIB W80 is scheduled to end in 1990. Two new programs on the prediction of service life have been proposed for the time period 1991-1995. The first proposal entitled "Design for Durability" has been submitted for acceptance by the CIB. Basic components of the proposal include: (1) providing an international focal point for discussions on design approaches for utilizing the knowledge on building materials and component's durability as established by the prediction of service life research, (2) increasing the understanding of deterioration processes among designers, and (3) providing practical knowledge on building design as a basis for recommendations at both the national and international level (design guides and education). The second proposal entitled "Prediction of Service Life of Building Materials" has been submitted for acceptance and joint funding by CIB/RILEM. The program consists of five tasks: (1) data assemblage from field exposure testing, in-use testing, and experimental buildings for service-life prediction; (2) environmental characterization, including equipment for monitoring; (3) material characterization, including monitoring of degradation; (4) mathematical modeling; and (5) design of short-term test methods (accelerated aging). Indications are that both of these proposals will be supported.

Finally, technical presentations were made by the traveler ("Overview of the Structural Aging Program") and Mr. T. Nireki, Head, Materials Division, Building Research Institute (BRI), Ministry of Construction, Japan ("Some Recent Practical Activities on Durability and Service Life Prediction in Japan"). Mr. Nireki provided a brief overview of three programs that have been conducted in Japan between 1981 and 1988. The first of these studies (1981-1985) addressed improvements in service life of buildings. Guidelines were developed for reinforced concrete, steel-framed structures, timber construction, external finishings, water proofing, openings and service installations. The results of this study have been published in nine volumes (in Japanese) and include a model for service-life prediction. The second of the studies (1985-1987) addressed improvement of durability of concrete structures, provides information on design methods, estimation of service life, maintenance impact on service life, and presents examples of service-life prediction for several construction types. The results of this study are presented in "Principal Guide for Service Life Planning of Buildings" (in Japanese) issued in 1988 by the Architectural Institute of Japan. The third study (1987-1988) addressed development of repair and rehabilitation methods for existing external finishings and water proofing systems. The study provided a general rule for application of maintenance procedures, plans for development of repair activities, and required conditions for application of various repair methods. The final report for this work is scheduled to be issued prior to March 1991. In private discussions with Mr. Nireki, he indicated that the Building Research Institute may have data of interest to the Structural Aging Program, i.e., change of concrete material properties with time and under the influence of environmental stressors. Mr. Nireki will be contacted by the traveler.

FIFTH INTERNATIONAL CONFERENCE ON DURABILITY OF BUILDING MATERIALS AND COMPONENTS

Conference Description

The "Fifth International Conference on Durability of Building Materials and Components," held in Brighton, England, was attended by over 180 delegates from 24 countries. Themes of the conference addressed: modeling of destructive mechanisms in building materials, microstructure and interfacial effects, effects of microclimate on building deterioration processes and measurement of microclimate in and around buildings, studies of the in-situ behavior of materials and components, studies of composite actions between disparate materials, and manufacturing practice and durability. A total of 45 papers were presented in 12 technical sessions. In addition, each day there were poster presentations available for viewing. Appendix B presents the conference program. Proceedings of the conference were provided to each delegate. The Sixth International Conference on Durability of Building Materials and Components will be held in Tokyo, Japan, in 1993.

Highlights

Although the conference addressed all types of building materials, concrete was the subject of over 45 of the 75 technical and poster presentations. Concrete was so prominent in the presentations because of the extensive durability problems that are occurring in Europe and Asia. The source of the durability problems is primarily corrosion of the steel reinforcement due to carbonation or chloride penetration. Of the conference papers that addressed durability of concrete materials and structures, four were of particular interest to the Structural Aging Program in that they either provided information on the development

of steel reinforcement corrosion models, long-term performance of concrete, or structural monitoring.

Mr. S. Morinaga, Research Institute of Shimizu Corporation, Tokyo, Japan, discussed the corrosion rate of reinforcing steel due to chloride attack and carbonation, and presented a conceptual degradation model for service-life predictions of concrete structures suffering from either of these effects. The corrosion rate due to chloride attack was investigated by evaluating the influence of: (1) design conditions (kind of concrete, water-cement ratio, chloride content, reinforcement size, and concrete cover), and (2) environment (temperature, relative humidity, and oxygen concentration). Carbonation effect studies addressed velocity of carbonation (concrete prisms stored in CO₂ chamber with depth of carbonation measured at several ages) and corrosion rate due to carbonation (mortar prisms containing an embedded rebar were carbonated to depth of rebar followed by exposure to various environmental conditions). Results of the chloride and carbonation tests were used to establish conditions for concrete cracking and to formulate models to predict the life of reinforced concrete under various exposure conditions. Mr. Morinaga noted that a much more extensive version of his paper is available in English. The traveler will contact Mr. Morinaga to obtain this paper because the results will have direct application to the current and reliability-based future condition assessments of concrete structures' activities being conducted by Professor Ellingwood at Johns Hopkins University for the Structural Aging Program. Corrosion of steel reinforcement is believed to be one of the major degradation mechanisms that potentially can impact the performance of concrete structures in nuclear power plants.

Mr. M. D. A. Thomas, Building Research Establishment, Garston, England, presented material property results on two mass concrete structures, a buttress dam, and a sea wall, both constructed over 30 years ago. The primary purpose of the study was to compare concretes with and without pulverized fly ash. Of interest to the Structural Aging Program was the change in concrete properties over the 30 plus years of the structures' existence, particularly since the baseline characteristics of the concretes used to fabricate these structures were well documented. Concrete cores were obtained from each structure to determine density, water absorption, compressive strength, indirect tensile strength, initial surface absorption, depth of carbonation, and oxygen permeability. Compressive strength results for the 30 plus year old concretes indicated strength gains of 160 to 238% relative to 28-day strengths. Although not provided as a part of the paper, a companion poster presentation by Mr. Thomas indicated that five additional structures have been investigated with respect to strength gain, carbonation depth, and oxygen penetration: (1) water storage tank (2.5 years old), (2) road bridge (10 years old), (3) dam (10 years old), (4) sea wall (30 years old), and (5) turbine foundation (33 years old). A copy of Mr. Thomas' extended paper will be requested as it may contain information suitable for incorporation into the ORNL Structural Materials Information Center.

Mr. Hergenroeder, Technical University, Lehrstuhl für Massivbau, Munich, Germany, presented results on investigations of 23 prestressed concrete beams (I or inverted-tee cross sections). The investigations were necessitated as a result of brittle failures of the quenched prestressing wires in several of the beams due to stress corrosion cracking. As the damaged beams could not be identified by simple test methods (visible damage did not precede collapse), nondestructive test techniques had to be established. Two techniques were identified, infrared thermography to detect defects in the concrete cover and magnetic field measurements to detect wire failures. Infrared thermography investigations of 23 beams indicated that the technique was capable of locating voids in concrete greater than 6-mm in diameter, i.e., when the beams are exposed to infrared radiation, areas of defects exhibit temperature differences relative to areas of dense concrete which are detectable by an infrared thermography device. Magnetic field measurements on 20 beams indicated that the technique is capable of identifying wire breaks in beams, i.e., when the prestressing steel is subjected to a magnetic field, a wire break sets up a dipole which can be located by a sensing element as it moves along the length of the beam. Additional details

of this work will be requested from Mr. Hergenroeder and forwarded to Construction Technology Laboratories where nondestructive evaluation methods for concrete structures are being assessed for the Structural Aging Program.

Mr. R. Wolff, Strabag Bau-AG, Cologne, Germany, described the use of optical fiber sensors to provide continuous monitoring of concrete structures. The optical fibers can be cast directly into the concrete or incorporated into high-performance glass fiber composite prestressing elements. The optical fiber sensor uses light attenuation resulting from mechanical stress (applied strain) as the measurement principle. In addition to measuring the stresses in concrete structures, back-scattering techniques can be utilized to locate local defects, e.g., cracks. The optical fiber sensor was stated to be capable of locating and monitoring cracks from 0.1- to 10-mm in width with a 0.02-mm detection sensitivity. The feasibility of the use of optical fiber sensor technology was demonstrated through presentation of results obtained from testing of a 1-m-deep by 20-m-long prestressed concrete beam (T-section). Also, three glass fiber prestressed concrete bridge applications where optical fiber sensors had been utilized were described. As the optical fiber sensors provide a potential means of continuously monitoring the integrity of concrete structures as well as detecting cracking, additional information will be requested from Mr. Wolff and provided to Construction Technology Laboratories for use in their nondestructive evaluation study.

Informal Discussions

Professor H. K. Hilsdorf, Institut für Massibau and Baustofftechnologie, Karlsruhe, Germany, is one of the foremost researchers in the area of irradiation effects on the properties of concrete. Although the results of his studies have been presented at Structural Mechanics in Reactor Technology Conferences, the detailed results were not provided in the conference proceedings. Professor Hilsdorf was contacted to see if he would provide a detailed presentation of his results so that they could be incorporated into the ORNL Structural Materials Information Center. Professor Hilsdorf indicated that he would provide the extended results of his irradiation studies. This data will provide a valuable addition to our data base in that data on the effects of irradiation on concrete properties is extremely limited due to the difficulty in performing meaningful tests and the cost of the studies.

Professor G. Fagerlund, Division of Building Materials, Lund Institute of Technology, Lund, Sweden, discussed relevant research activities in Sweden. At Lund Institute of Technology, Professor Fagerlund is conducting concrete research in three areas: (1) fracture mechanics, (2) moisture migration, and (3) high strength. Fracture mechanics studies have been ongoing for 15 years and are investigating the interactions of the concrete microstructure and several fracture mechanics-related parameters (uniaxial tensile strength, modulus of elasticity, and fracture energy). The application of this work is to the investigation of the fracture process of specimens subjected to fatigue loadings above the static fatigue limit. Dr. Fagerlund's second area of research addresses moisture diffusion in well-cured concretes where water-cement ratio and relative humidity are treated as variables. The drying process of concrete is being modeled taking into account the effects of degree of hydration and the moisture content. The application is self-desiccation of high-strength concretes. The third area of research is investigating high-strength concretes (water-cement ≥ 0.2). The program is just initiating and will investigate the hydration process, strength development, internal stability of the hydration phases, and freeze-thaw behavior. One of the applications of this work is in evaluation of the service life of high-strength concretes exposed to frost action. Increased use of high-strength concrete is occurring in the construction industry because of the potential to provide reduced member cross-sections (columns) and improved durability (lower permeability). Other research in Sweden, which

Dr. Fagerlund identified, included modeling of the risk of thermal cracking in concrete as it hydrates (Dr. M. Emborg, Lulea Technical Institute), moisture movement in porous materials under load and humidity gradients (Dr. J. Claessan, Lund Institute of Technology), modeling of the corrosion process of steel reinforcement in concrete (Mrs. K. Pettersson, CBI, Stockholm), modeling residual service life of concrete exposed to acids (Mr. L. Rombin, CBI, Stockholm), modeling the internal structure of cement paste containing rendered materials (Professor L. Nilsson, Chalmers University of Technology, Goteborg), and creep and shrinkage modeling of concrete exposed to moisture gradients (Professor S. Thelandersson, Lund Institute of Technology). Several potential sources of data on long-term concrete properties were identified: Professor Malinowski (Chalmers University of Technology, Goteborg), Professor Petrossian (U.S.S.R.), archives of the state power board of Sweden has data on dams which are up to 80 years old (Dr. J. Alemo, Stockholm), and data on bridges tested by the State Road Authority (Prof. H. Ingvarsson, National Swedish Road Administration, Borlange). In addition, Dr. Fagerlund noted that there is a report reviewing the long-term properties of concrete in connection with the storage of nuclear waste (KBS-Report No. 12, CBI, Stockholm, 1978).

Dr. M. Geiker, G. M. Idorn Consult A/S, Birkerød, Denmark, has developed a test to rapidly assess the chloride permeability of concretes with and without mineral admixtures (silica fume and fly ash). Dr. Geiker also noted that G. M. Idorn Consult A/S has been involved for several years in the prediction of the service life of concrete building materials and structures. Currently they are developing monitoring techniques and methodologies for use in predicting the service life of mature structures where trending data (performance history) are not available. Since this is the same problem that is being addressed in the assessment of concrete structures in nuclear power plants for continued service, this work is of great interest to the Structural Aging Program. The traveler will contact Dr. Geiker to obtain more details on their previous studies related to development of service life models and the present program to predict residual life of mature structures.

ÉLECTRICITÉ DE FRANCE

Électricité de France (EDF) consists of four divisions: Research and Development, Engineering, and Construction, Electricity Generation and Transmission, and Distribution. The traveler visited Service Etudes et Projets Thermiques et Nucléaires (SEPTEN), which is the central design department for thermal nuclear projects of the Engineering and Construction Division. SEPTEN has basic responsibilities for development of reference technical specifications for fossil and nuclear power plants as well as their design and construction. Primary topics of discussion included: (1) evolution of pressurized-water reactor (PWR) containment designs, (2) national aging program, (3) material property data, (4) burial vaults for low- and medium-level nuclear waste storage, and (5) power plant cooling towers.

France has approximately 55 PWR power plants presently in service: 34 900 MW(e) and 21 1300 MW(e). The containment enclosure of the 900 MW(e) plants (types CP1 and CP2) consists of a prestressed concrete wall 0.9-m thick, a 0.8-m-thick prestressed concrete dome, and a slightly prestressed 3.5-m-thick basemat. The inner surface of the containment is covered with a 6-mm-thick steel liner for leak tightness, which is joined to the concrete by studs and metal angles. After about 1977 the three-loop 900 MW(e) plant designs were replaced by four-loop 1300 MW(e) plants (types P4 and P'4) whose containments consisted of two concentric concrete shells with no liner. Any leakage through the 0.9-m-thick wall (1.2-m-thick for P'4) or 0.95-m-thick dome of the inner containment is contained in the ~2-m-wide annular space between the concentric shells which is maintained at a slightly negative pressure (>15 mbar). The outer containment (not prestressed) also serves to protect the inner shell from external influences. More recently,

1400 MW(e) plant designs (type N4) have been developed and are being utilized to build plants at Chooz B (2 units) and Civaux (1 unit). With the exception of a slightly higher design pressure and elimination of basemat prestressing, the design of the type N4 plants is essentially the same as the type P4 plants. Starting as early as 1995 it is felt that new plants may have to be constructed in France. These plants will differ from previous ones in that severe accidents resulting from both internal and external events will have to be addressed. Three groups are presently developing conceptual designs for the future plants (type PWR 2000): EDF, Framatome/KWU, and French Safety Authorities. A concept will be selected in about one year. Some of the possible changes noted for the new generation containments are that the outer reinforced concrete shell thickness will be increased from 0.55 m to 1 m to account for aircraft impact, high strength concretes (70 MPa) will be utilized to reduce creep and certain section thicknesses, and external circumferential prestressing may be utilized so that the inner prestressed concrete containment wall thickness can be reduced. Although the vertical tendons will still be embedded and grouted, greased prestressing tendons (strands within a plastic sheath or strands with each individual wire encased in a polyethylene sheath for corrosion protection) are being considered as the external prestressing system. The interest in greased tendons is because the approximately 20% force loss due to friction that occurs in 150-m-long tendons can be regained.

Power plants in France are licensed for 20 years. Since several of the 900 MW(e) plants have been in operation for over 10 years, the French have started a national program on aging with the goal of extending the service life of the plants to 40 years. In setting up their aging program, they are relying very heavily on their experience with nuclear power plants which started in 1952 at Marcoule. In addition to their broad experience, the French have two other factors which should make their structural aging assessment studies somewhat easier than the problem we are facing in the United States: (1) the use of standardized designs (as noted previously), and (2) the availability of a large data base on the in-service performance of the structures. Before a nuclear power unit in France is commissioned, the containments are subjected to a leak rate and structural integrity test. Leak rate and structural integrity tests are repeated 2 years after completion of construction and every 10 years thereafter. Also, the containment domes are inspected for cracks every 10 years, and the first unit of each plant type contains extensive instrumentation which is monitored every 3 months, e.g., vibrating wire strain gages, pendulums for displacement measurements, and dynamometers for force measurements on the control ungrouted tendons. Secondary units contain a reduced amount of instrumentation which is placed in key areas. If an abnormality occurs, the instrumentation is read at more frequent intervals. This large data base enables the performance of these structures to be trended for use in service-life predictions. One interesting item noted as a result of monitoring was that the prestressed concrete pressure vessel at St. Laurent, after 10-15 years operation, started to show an expansion (as opposed to an expected contraction) which was detected by the instrumentation. The concrete was examined to determine if the cause was alkali-silica reaction, but the results were inconclusive. Although the unit has been taken out of service, it is being continuously monitored because the second unit at St. Laurent, which is still in operation, is starting to show similar behavior. Both units will be continuously monitored until the second unit is removed from service in about two years for economic reasons. Another problem noted was that there was a borated water leak from the fuel pool at Gravelines about five years ago that was detected by drains that had been installed specifically for that purpose. Since there was concern about the effects of the borated water on the concrete, concrete core samples were obtained and tested, and an assessment of rebar corrosion performed. The borated water had not significantly affected the concrete strength or steel reinforcement. Also, one of the French containments was noted to be approaching the design curve with respect to loss of prestress force, but instrumentation (monitored monthly) is showing concrete creep to be leveling off so that the minimum allowable force value will not be crossed. Potential future areas of concern as the French plants age were noted to be corrosion of the

steel liner, particularly near the wall-basemat junction where it is inaccessible for inspection; failures of tendon anchorheads similar to that which occurred at Byron, Farley, and Bellefonte in the U.S.; and the durability of cooling towers since they have experienced significant cracking due to thermal gradient effects (new design concept for future plants discussed later). Several of the examples cited above demonstrate the advantage of instrumenting structures to provide data to monitor performance throughout their life.

After an overview of the Structural Aging Program, and in particular a description of the Structural Materials Information Center, EDF was asked if they had data on the time variation of concrete material properties or the effects of environmental stressors such as elevated temperature or irradiation. They said that they did not, but that Mr. Salomon at Centre Experimental de Recherches et d'Etudes du Bâtiment et des Travaux Publics (CEBTP) in Paris had an extensive data base on the durability of concrete developed from French and European research. Mr. Salomon will be contacted by the traveler.

The use of concrete burial vaults approximately 1.4-m-diam. by 1.3-m-high with a 451 liter volume for low- and medium-level radioactive waste storage for at least 100 years is being studied at EDF. The vaults are a composite of normal weight and heavyweight (hematite aggregate) concretes. The French do not have service-life models to predict the durability of the burial vaults but are basing the longevity on the fact that structures using similar aggregates have lasted 60-80 years. The 100-year estimated life is merely an extrapolation. They have taken and tested concrete core samples from several structures. Their belief is that if the structures are properly built, using demonstrated materials, they will last. This may be a big assumption for general civil engineering structures but, for their application, may be more achievable since the vaults are precast under tightly controlled conditions.

The last specific area addressed was cooling towers at power generation facilities. The cooling towers at the nuclear plants have walls with a shape similar to a hyperbolic torus and are supported on a large number of columns, diagonals or other supports linked by an annular footing which transmits loads to the ground. The structures, which can reach 180-m-high with a base diameter to 140 m, have a wall thickness that ranges from 18 cm to 25 cm. Two layers of reinforcement are contained in the walls with horizontal reinforcement amounts ranging from 0.34 to 0.50% and vertical reinforcement amounts from 0.13 to 0.50%. The towers are subjected to severe environmental effects which have produced cracks at all plants near the top and bottom of the tower (up to 1000 defects occurred in a single plant). Because of the likelihood of cracking and steel reinforcement corrosion occurring, the structures are monitored topographically and visually (structures are not instrumented). A repair method which uses a textile system has been developed and applied at one plant to rebuild a cooling tower in six months that had failed. Two approaches are being investigated to increase the durability of the cooling towers: providing an improved support system (radial columns) and the use of a silica fume concrete (low permeability, freeze-thaw resistance, and reduced shrinkage and cracking). These concepts have been applied successfully at Civaux. Cooling towers are believed to be potentially the biggest durability problem at the French plants, but the structures are not limited to plant operation because they are repairable and replaceable, unlike other large concrete structures at nuclear power plants.

AEA TECHNOLOGY

AEA Technology, formerly UKAEA, Harwell, has recently been realigned to expand its work scope, i.e., offset declining work in nuclear energy. Under the old system, each of the UKAEA facilities was organized into laboratory units with each acting as an individual management site. Each facility now is restructured into business organizations with more than one business organization present at a facility, e.g., Safety and Reliability,

Decommissioning and Radwaste are two of the business organizations at AEA Technology. The traveler visited the Materials Chemistry Department to discuss the durability of concrete, nondestructive examinations, and corrosion of steel reinforcement in concrete.

Dr. Atkinson is primarily involved in research related to predicting how steel and concrete are likely to perform as barriers to radionuclide release from a repository. In England, it is planned that low- and intermediate-level waste will be buried in a deep repository (500-1000 m). A number of engineered barriers are included in the repository to prevent the movement of radionuclides into the geosphere: wasteform itself (usually cement based), metallic containers, structural concrete elements, and a cement-based backfill. The radionuclides are contained by physical means for the short term (steel containers) and mainly by chemical means over the long term. Processes likely to dominate the degradation of the engineered barriers include corrosion of the steel rebar and reaction with groundwater. Specific research areas address localized corrosion of carbon and stainless steel in oxygenated (aerobic) conditions, general corrosion of steels in oxygen-free conditions (anaerobic), transport of gases and dissolved radionuclides through concrete, the durability of concrete, and the ability of concrete to control repository chemistry. In addressing these areas, key processes are identified, mechanistic models are developed for each of the processes, and experiments are conducted to confirm the predictions of the models over practical experimental time scales. Basic results to date on this study indicate that: (1) under anaerobic conditions 5-mm-thick steel containers should remain intact for about 300 years; (2) good quality structural concrete should have sufficient durability for 300-mm-thick sections to provide useful engineering properties for several hundred years providing an effective barrier to contain cesium and strontium for over 100 years and tritium for over 25 years; (3) suitable choice of cementitious backfill should provide an average pH > 10.5 for > 10^5 years to provide long-term chemical containment of many radionuclides; and (4) transport of gases (such as hydrogen) through intact saturated structural concrete is difficult but, if it occurs, the high permeability of the backfills should allow the gases to escape without disrupting the structure. With respect to interaction with groundwater, the dominant reaction is likely to be with groundwater sulfate. Accelerated laboratory tests and field concretes indicate that if the concretes are of high quality, they can have sufficient durability to act as physical barriers and structural supports for several hundred years. Work is continuing to provide a better understanding of this degradation mechanism.

AEA Technology has a long involvement in the nondestructive testing of concrete. As a result, expertise has been developed related to potential mapping surveys for steel reinforcement corrosion, ultrasonic pulse velocity measurements, tomographic inspection, and high-energy radiography. Two relatively new techniques discussed included laser beam inspection of concrete and corrosion monitoring using electromagnetic flux exclusion. A Nd-YAG laser has been developed to detect defects in bridge decks (≤ 25 cm). The device has advantages relative to presently used methods in that it is noncontact and much more rapid than conventional methods. A large electromagnetic flux exclusion device has been developed for detecting pitting in inaccessible (nonvisible) areas of storage tank floors. This technology is believed to be adaptable so that it is capable of monitoring corrosion of steel reinforcement in concrete. Additional information on each of these techniques will be provided to the traveler.

Discussions related to the corrosion of metallic materials were primarily with respect to problems that need to be addressed. Two items were noted pertaining to cathodic protection: (1) where structures have been repaired by epoxy injection, the epoxy may limit the effectiveness of cathodic protection; and (2) there was some uncertainty expressed as to whether or not cathodic protection works for corrosion due to carbonation. In order to evaluate the condition of a structure with respect to corrosion, three items are needed: (1) the amount of corrosion that has occurred, (2) time variation of corrosion rate, and (3) the amount of corrosion product required to cause concrete spalling. Laboratory techniques have been developed where a current is imposed on the surface and data are extracted on

rebar corrosion, but the technique is not applicable to thick structures. A magnetic flux perturbation technique has been successfully used in the laboratory to detect rebar cross section losses greater than 20%, but it has not been successfully demonstrated in the field where cross-bars present problems. It was noted that Professor Bazant (Northwestern University) has developed a conceptual model for corrosion of steel reinforcement in concrete. "Corrosion of Reinforcement in Concrete," published by the Society of Chemical Industry in May 1990, was recommended as a good information source for steel reinforcement corrosion in concrete.

APPENDIX A

Itinerary

November 3-4, 1990	Travel	Knoxville, TN, to London, England
November 5, 1990	Meeting	Taywood Engineering, Ltd., Southall, Middlesex, England
November 5, 1990	Travel	London, England, to Brighton, England
November 6, 1990	Meeting	RILEM 100-TSL, "Techniques for Service Life Prediction," Brighton, England
November 7-9, 1990	Meeting	"Fifth International Conference on Durability of Building Materials and Components," Brighton, England
November 10-11, 1990	Weekend and Travel	Brighton, England, to London, England, to Lyon, France
November 12, 1990	Meeting	Électricité de France, Lyon, France
November 13, 1990	Travel	Lyon, France, to London, England
November 14, 1990	Meeting	AEA Technology, Oxfordshire, England
November 15, 1990	Travel	London, England, to Knoxville, TN

APPENDIX B

Conference Program

Three Day International Conference

**FIFTH INTERNATIONAL CONFERENCE
ON DURABILITY OF BUILDING
MATERIALS AND COMPONENTS**

7th to 9th November 1990

The Corn Exchange
Brighton

PROGRAMME

Organised by the Building Research Establishment

Sponsored by ASTM, CIB, NIST, NRCC, RILEM.

WEDNESDAY 7TH NOVEMBER

Session 1 Chairman: J M Baker, Deputy Chief Executive, BRE, UK

- 0900 Opening Address J M Baker
 0910 Keynote Address Professor P L Pratt, Imperial College

Destructive Mechanisms in Building Materials and Modelling.

- 0950 Prediction of service lives of reinforced concrete buildings
 based on the corrosion rate of reinforcing steel.
 S Morinaga
 1010 Solar UV, wetness and thermal degradation maps in Japan.
 T Tomiita
 1030 Fundamental concrete carbonation model and application to
 durability of reinforced concrete.
 V G Papadakis, G G Vayenas & M N Fardis
 1050 Morning Coffee

Session 2 Chairman: L W Masters, NIST, Gaithersburg, USA

- 1110 Fundamental studies of frost damage in clay brick.
 V Prout & V D Hoff
 1130 Durability of concretes mixed with sea-water.
 A Yeginobali & F Mujahed
 1150 Common factors affecting alkali reactivity and frost
 durability of aggregates.
 P P Hudec
 1210 Poster Presentations
 1230 Lunch
 1330 Poster Presentation:

Session 3 Chairman: Prof. P L Pratt, Imperial College, UK

- 1400 Deterioration mechanisms in sandstone.
 C L Searls & S E Thomasen
 1420 Durability tests for natural building stone.
 D Hart, K Ross & R N Butlin
 1440 Suggestions for a logically consistent structure for
 service life prediction standards.
 G Prohnsdorff & L W Masters
 1500 Afternoon Tea

Session 4 Chairman: Dr J G H Wood, Mott MacDonald Special Services, UK

Microstructure and Interfacial effects.

- 1520 Consolidation & hydrophobic treatment of natural stone.
E Wendler, D Klemm & R Snethlage
- 1540 Alteration of moisture characteristic and microstructure
of impregnated stone materials.
D Honsinger & H R Sasse
- 1600 Changes of surface characteristics of sandstone caused
by cleaning methods applied to historical stone monuments.
H Werner & G Pohle
- 1620 Microstructural changes in cement paste and concrete
caused by degradation reactions.
K L Scrivener

THURSDAY 8TH NOVEMBER

Session 5 Chairman: Professor T Nireki, Building Research Institute,
Japan.

Studies of in-situ behaviour of materials and components.

- 0900 Carbonation, Exposure and Concrete quality: Field survey results
from some 400 structures.
J H Brown
- 0920 Weathering effects on withdrawal and head pull through of nails
and staples in wood based panels.
Poo Chov, D McNatt & Li Zhao
- 0940 Cathodic protection of Portcullis House: 5 year trial proves the
system.
C C Morton (Presented by R N Cox)
- 1000 Collection of in-service performance data: state of the art &
approach by CIB W80/RILEM TC 100-TSL.
C Sjoström & Brandt
- 1020 Morning Coffee

Session 6 Chairman: Dr R D Browne, Taywood Engineering Ltd. UK

- 1040 In-situ behaviour of structures reinforced with galvanised
reinforcement.
R N Svamy
- 1100 Hygroscopic salts: Influence on the moisture behaviour of
structural elements.
H Garrecht, J Kropp & E K Hilsdorf
- 1120 Long-term behaviour of slabs with prestressed beams in cattle
stables.
M Bergenroeder

Manufacturing practice and durability.

- 1140 Methods for predicting the service life of concrete.
J R Clifton
- 1200 Evaluation of metal fastener performance in CCA treated timber.
J N Cross & G Bailey
- 1230 Lunch
- 1330 Poster Presentations

Session 7 Chairman: Prof. H K Hilsdorf, Karlsruhe University, Germany

- 1400 A comparison of the properties of OPC & PFA concretes in 30 year old mass concrete structures.
M D A Thomas
- 1420 Durability tests on precast concrete wall panels with exposed aggregate finishes.
S L Lee, C T Tan, V J Ng, S K Ting & Y H Loo
- 1440 Comparative sulphate resistance of SRPC and portland slag cements.
J J Kollek & J S Lumley
- 1500 Performance of parking garage decks constructed with epoxy coated reinforcing steel.
G G Litvan
- 1520 Afternoon Tea

Session 8 Chairman: Dr K G Martin, CSIRO, Australia

- 1540 Durability of concrete ornaments on structures.
S E Thomason & C L Searls
- 1600 Improving durability by environmental control.
P Lambert & J G M Wood
- 1620 Design charts for crack control in concrete members reinforced with welded wire fabric.
K B Tan, M A Mansur, K Kasiraju & S L Lee

FRIDAY 9TH NOVEMBER

Session 9 Chairman: Dr C Andrade, Institute Eduardo Torroja, Spain

Assessment Methods.

- 0930 Interpretation of Data obtained by AASHTO T 277-831, rapid chloride permeability test.
M Geiker, N Thaulow & P J Andersen
- 0950 Assessment of concrete durability by intrinsic permeability.
R K Dhir, P C Hewlett & Y N Chan
- 1010 XPS studies of coatings on sheet metal.
P Jernberg, D Lala & C Sjoström

- 1030 Measurement and evaluation of abrasion resistance of concrete surfaces.

R Kunterding & B K Hilsdorf

- 1050 Morning Coffee

Session 10 Chairman: Prof. S L Lee, National University of Singapore

- 1110 Monitoring of surface moisture by miniature moisture sensors.

P Norberg

- 1130 Proposed methods of test for chemical resistance of concrete and cement paste in aggressive solution.

K Shirayama & A Yoda

- 1150 Application of FTIR spectroscopy and XPS to polymer mineral joint systems.

S Vagener & B Hocker

- 1210 Assessing carbonation in concrete structures.

L J Parrott

- 1230 Lunch

- 1330 Poster Presentations

Session 11 Chairman: Dr G G Litvan, National Research Council of Canada

- 1400 Applications with optical-fibre sensor systems for monitoring for monitoring prestressed concrete structures.

R Wolff & B J Miesslerer

Composite action and coatings.

- 1420 Comparative resistance to soft water attack of mortars and fibre-cement products made with OPC and blends of OPC & milled quartz, OPC & PFA and OPC & GGBS.

J B Kruger & S Visser

- 1440 Long term durability of GRC.

A J Majumdar & B Singh

- 1500 Afternoon Tea

Session 12 Chairman: Mr C Sjoström, Building Research Institute, Sweden

- 1520 Probabilistic approach to service life prediction of ferrocement roof slabs.

S T Quek, S L Lee & P Paramasivan

- 1540 Adhesion of Silicone Sealants.

V S Gutowski, A Cerra & L Russell (Presented by Dr K Martin)

- 1620 Durability of SRPC when held in sewage water.

M A Sanjuan, A Moragues, B Bacle & C Andrade

Poster Presentations: Wednesday

Trial manufacture of an apparatus for testing the deterioration of building materials due to rainfall.

Y Kitsutaka, K Kamimura & T Shiire

Statistical field survey of exterior building materials degradation.

N Tolstoy, G Andersson, C Sjoström & V Kucera

Service life prediction system of polymeric building materials using a personal computer.

T Tomita

Effects of PFA on corrosion of steel in concrete.

Y H Loo & S K Ting

Rebar corrosion on blast furnace slag concrete exposed to chlorides.

A Porro, A Santamaria, E Mz de Iturrate, I Recalde,
J Bilbao, J M Barcena & T Fernandez.

Mechanical discussions about load distribution in stone fabrics and the effects of silicate esters.

K Haberl, A Rademacher & G Grassegger

Durability of glass.

N A Nilsson

Study on the protection of steel in concrete by penetrative anti-corrosion inhibitor.

S Ushijima, A Kobayashi, I Komuro & M Koshikawa

Carbonic acid water attack of OPC based concretes.

Y Ballim & M G Alexander

Chloroaluminate and total chloride ion amounts in concrete exposed to natural sea water.

J L Sagrera & S Goni

The effect of Silica Fume to reduce expansion due to ASR in concrete.

A M Dunster, P J Nixon & B Kavano

Influence of microcracking on air permeability of concrete.

S Nagataki & I Ujike

Mechanism and Evaluation method of frost deterioration of cellular concrete.

O Senbu & I Kamada

Poster Presentations: Thursday

The effect of admixtures on the water tightness of concrete.

T Al-Kadhimi, I Al-Kurvi, H S Jamil & J A Al-Mulla

Study on the influence of some parameters of the mix design on the permeability of hardened concrete.

J M Galligo, F Rodriguez.

Development of thermal degradation load map for elastomeric roofing sheets in Japan.

K Tanaka & M Koike.

Service life estimation for multi-ply flat roof membranes.

F Aköz & M S Akman.

Influence of C₃S level on concrete durability.

S Kelham & G K Moir

Durability of PVC-coated fabrics for membrane structures.

T Nireki, H Toyoda & Y Onuma

An approach to design for durability of the building technological system.

A Lucchini

The durability of polymer concrete.

P J Koblishek

Poster Presentations: Friday

Progressive concrete & mortar deterioration as measured by computer controlled multiple sonic pulse method.

P P Hudec & Wei Wang

Surface moisture on facade materials.

B Svennerstedt

Models for the evaluation of the service life of technical solutions in building.

A Lucchini

Some studies with the use of concrete coatings to protect rebars from corrosion.

C Alonso, A M Garcia & C Andrade

A study on durability of thick anti-corrosive coatings.

N Murakami, S Shiraishi & T Hirano

Durability of non-asbestos fibre reinforced cement.

J M West

Ten year durability test results on external wall masonry coating systems.

T Nireki, H Kabeya, N Hirama, T Inoue & K Omata

Durability of aerated lightweight concrete panels with surface coating systems.

T Nireki, H Kabeya, N Hirama & T Inoue

Contribution to the design for durability of the building technological system: A methodology for the evaluation of the reliability of the functional models.

P N Maggi, S Croce, M Rejna, P Boltri, A Lucchini,
L Morra, A Gottfried & B Daniotti.

APPENDIX C

Literature Acquired

1. R. D. Browne et al., "Instrumentation of Large Structures," Colloquium on Instrumentation of Structures, Pembroke College, Cambridge, England, July 1983.
2. R. D. Browne et al., "Measuring the Performance of Concrete Structures in Service," PP1/84, Taywood Engineering, Southall, Middlesex, England, 1984.
3. A. McLeish, "Analysis of Defect and Repair Systems for Concrete Structures," PP1/85, Taywood Engineering, Southall, Middlesex, England, 1985.
4. R. D. Browne, "Investigation of Concrete Structures - Methods Used to Establish the Nature of Problems," PP10/85, Taywood Engineering, Southall, Middlesex, England, 1985.
5. R. D. Browne et al., "Repair of Concrete Structures," PP4/86, Taywood Engineering, Southall, Middlesex, England, 1986.
6. R. Paull, "Inspection of Concrete Structures for Steel Reinforcement Corrosion," PP16/87, Taywood Engineering, Southall, Middlesex, England, 1987.
7. K. N. Baker and A. McLeish, "Evaluating the Strength of Concrete Structures," PP7/88, Taywood Engineering, Southall, Middlesex, England, 1988.
8. D. C. Pocock et al., "Deterioration Assessment of Nuclear Power Station Buildings and Long-Term Stability and Leak Tightness of Reactor Containments," PP6/89, Taywood Engineering, Southall, Middlesex, England, 1989.
9. "Durability of Building Materials and Components," Proceedings of the Fifth International Conference held in Brighton, England, November 7-9, 1990, Van Nostrand Reinhold, New York, 1991.
10. E. Efstathiadis, "Greek Concrete of Three Millenniums," Research Center of the Hellenic Ministry of Public Works, Athens, Greece, April 1978.
11. H-J. Miesslerer and L. Preis, "High Performance Glass Fiber Composite Bars as Reinforcement in Concrete and Foundation Structures," Strabag Bau-AG, Köln, Germany, 1990.
12. R. Wolff and H-J. Miesslerer, "Glassfiber Composite Materials as Prestressing Elements in Concrete Structures," Strabag Bau-Ag, Köln, Germany, 1990.
13. "Applications of Heavy Duty Composite Prestressing Tendons," Strabag Bau-AG, Köln, Germany, 1990.
14. J. C. Bertel et al., "The French Nuclear Containment-Contributions of Prestressing in Cost Saving on the Project," Tenth International Congress of the FIP at New Delhi, India, February 16-20, 1986.
15. J. L. Costaz, "Nuclear Containment in France," *Nuclear Engineering and Design* 100, pp. 151-156, North Holland, Amsterdam, 1987.

16. G. Ithurralde, "Double Walled Nuclear Containment in France," International Conference on Thermal Reactor Safety, Avignon, France, October 2-7, 1988.
17. J. L. Costaz, G. Ithurralde, and F. de Larrard, "Future Prospects of High Tech Concrete in Nuclear Power Plants," GPE 1039 H, Électricité de France, Villeurbanne Cedex, France, 1990.
18. A. Atkinson and G. P. Marsh, "Engineered Barriers: Current Status 1989," NSS/G110, Harwell Laboratory, UKAEA, England, June 1989.
19. A. Atkinson and G. P. Marsh, "Performance of Engineered Barriers for Intermediate and Low Level Waste Disposal," Harwell Laboratory, UKAEA, England, 1990.
20. A. Atkinson, D. J. Goult, and J. A. Hearne, "An Assessment of the Long-Term Durability of Concrete in Radioactive Waste Depositories," *Materials Research Society Symposium*, 50, pp. 239-246, 1985.
21. A. Atkinson et al., "Mass Transfer in Water-Saturated Concretes," *Materials Research Society Symposium*, 176, 1990.
22. A. Atkinson and J. A. Hearne, "The Hydrothermal Chemistry of Portland Cement and Its Relevance to Radioactive Waste Disposal," NSS/R187, Harwell Laboratory, UKAEA, England, July 1989.
23. A. Atkinson, A. Haxby, and J. A. Hearne, "The Chemistry and Expansion of Limestone-Portland Cement Mortars Exposed to Sulphate Containing Solutions," NSS/R127, Harwell Laboratory, UKAEA, England, August 1988.
24. A. Atkinson, N. M. Everitt, and R. M. Guppy, "Time Dependence of pH in a Cementitious Repository," *Materials Research Society Symposium*, 127, pp. 439-446, 1989.
25. A. Atkinson and J. A. Hearne, "Mechanistic Model for the Durability of Concrete Barriers Exposed to Sulphate-Bearing Groundwaters," *Materials Research Society Symposium*, 176, 1990.

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