Nuclear Energy Standards Coordination Collaborative

Codes and Standards for the Repair of Nuclear Power Plant Concrete Structures:

Recommendations for Future Development

2013

NIST National Institute of Standards and Technology • U.S. Department of Commerce

ANSI American National Standards Institute

Nuclear Energy Standards Coordination Collaborative
National Institute of Standards and Technology
American National Standards Institute

Codes and Standards for the Repair of Nuclear Power Plant Concrete Structures: Recommendations for Future Development

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Preface

The Nuclear Energy Standards Coordination Collaborative (NESCC) is a joint initiative of the American National Standards Institute (ANSI) and the National Institute of Standards and Technology (NIST) to identify and respond to the current needs of the nuclear industry. NESCC was created in June 2009. More details on NESCC and its activities can be found on the following website:
(http://www.ansi.org/standards_activities/standards_boards_panels/nescc/overview.aspx?menuid=3)

In July 2011, NESCC formed a task group, "Concrete Codes and Standards for Repair of Nuclear Power Plants," referred to as the Concrete Repair Task Group (CRTG) in this report. This report summarizes the recommendations for nuclear power plants as prepared by the committee and submitted to NESCC on March 2013. Only limited international literature on the subject was reviewed, though it is recognized that relevant documents do exist (e.g., EN 1504). Such documents can be used as an important source of knowledge for the update or development of future U.S. reports, guides, and codes.

Membership

This report was prepared by the NESCC Concrete Repair Task Group (CRTG). Membership in the CRTG was open, i.e., no attempt was made to limit the membership. Efforts were made to include representatives from standards development organizations (SDOs) and the construction industry, who are involved in the repair of reinforced concrete structures in nuclear power plant construction.

Chair: The Chair of the CRTG was Chiara F. Ferraris, National Institute of Standards and Technology, Gaithersburg, MD (USA)
Co-Chair was Nathan D. Sauer, P.E., SIMCO Technologies, Baltimore, MD (USA)

The table below lists the organizations that participated and their representatives as CRTG members.

Organization represented (in alphabetical order)	**Name**
ACI	Matthew Senecal; Doug Sordyl;
AMEC	Corina Aldea
ASTM	Joe Koury & Steve Byrne
BASF	Fred Goodwin; Dana Hanson
Bechtel Power	Javeed Munshi; Mukti Das; Sanj Malushte
Ceratechnic	James Hicks
Concrete Engineering Group	Charles S. Hanskat
CTL group	Peter Kolf; Tim Tonyan
EPRI	Maria Guimaraes, Joe Walls; John Gaetner; Neal Murray
Exelon	Ronald Janowiak
Fluor	Clayton T Smith; Carl Lockwood
FMC Lithium Division	David Stokes
HDR Engineering, Inc	Chuck Hookham
Moffat & Nichol	Robert A. Dameron; Thomas Spencer
Northern Arizona University	Robin Tuchscherer
Oak Ridge National Laboratory	Dan Naus; John Jy-An Wang
Ohio State Univ.	Halil Sezen
Olson engineering	Larry Olson
Penn State	Paul Brown
Premier Construction Products Group	Claudio Manissero
Pullman	David Bird
RJ Lee Group	James Conca
S&ME	John Love
Sargent & Lundy (Chair 359)	Arthur "Curt" Eberhardt; John McLean
Sika Corporation	Aamer Syed
Simpson Gumpertz & Heger	Liying Jiang; R. Scott Silvester; Matthew R. Sherman
SNC-Lavalin Nuclear	Namho Lee
Structural Group	Scott Greenhaus

Organization represented (in alphabetical order)	**Name**
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THP Limited	William M. Judd
Tourney Consulting	Paul Tourney
TRRC	Antonio Nanni
University of Kansas	David Darwin
University of South Carolina	Paul Ziehl
US-NRC	Madhumita Sircar; Herman Graves; Gene Carpenter
VTT	Erika Holt; Miguel Ferreira
Walker Restoration Consultants	K. Nam Shiu
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Western Michigan University	Upul Bandara Attanayake
Wiss, Janney Elstner Assoc Inc.	Carl Larosche, Paul Gaudette

Reviewers (not NESCC-CRTG members)

Organization represented (in alphabetical order)	**Name**
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AECOM Technical Services	Bernard Hertlein
BAKER concrete	Mike Schneider
Burns & McDonnell	Jason Draper
Canadian Nuclear Safety Commission	Nebojsa Orbovic
Concrete Reinforcing Steel Institute (CRSI)	Mike Mota
Concrete Science	Ashok Kakade
Constellation Energy Source	Joseph Crunkleton Jr.
CORE, Inc	J.K. August
CVM Facilities Renewal (chair 364)	David VanOcker
CVM Facilities Renewal (Chair 563)	Tracy Marcotte
DOE	Jensen, Scott A
Dominion Virginia Power	Chuck Zalesiak
Electro Tech CP	Paul Noyce
Freyssinet	Andre Coudret
Georgia Institute of Technology (Chair 562)	Lawrence Kahn
German Instruments	Claus Petersen
ICRI	Kelly Page
Kinectrics Inc., Concrete Assessment & Repair Group	Ron Cullen
Lafarge Cement	Julie Buffenbarger
Levelton Consultants Ltd	Oliver Gepraegs
NACE	Linda Goldberg; Ed Barrett
NEXTera Energy	Ted Vassallo
NFPA	Paul May
NIST	Nancy McNabb
Palo Verde Nuclear Generating Station	Mahab Khatib
PCI	James Toscas
RJ Lee Group	Michael Silsbee
S&ME	John Pearson
Savannah Riva national Lab	Christine Langton
Shaw Group	Harini Santhanam; Ufuk Dilek
Tec services	Shawn McCormick; Kurt Heinrichs
U.S. Department of Energy	Richard Reister
Univ. of Maryland	Richard A. Livingston
Univ. of Utah	Luis Ibarra
Vector Corrosion Technologies	Chris Ball; David Whitmore
Westinghouse	Tod Baker; John Duryea; N.F. (Eric) Koniet

ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ACI-CT	ACI concrete terminology
AMP	Aging Management Programs
ANSI	American National Standards Institute
ARDM	Aging Related Degradation Mechanisms
ASCE	American Society for Civil Engineers
ASME	American Society of Mechanical Engineers (now ASME)
ASR	Alkali-Silica Reaction
ASTM	American Standard testing of materials (now ASTM)
B&PV	Boiler and Pressure Vessel
CFR	Code of Federal Regulations
CLB	Current Licensing Basis
CRTG	Concrete Repair Task Group – part of NESCC
DEF	Delayed ettringite formation
DOE	Department of Energy
DOT	Department of Transportation
EN	European Standards
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway administration
GALL	Generic Aging Lessons Learned
IAEA	International Atomic Energy Agency
ICRI	International Concrete Repair Institute
IEEE	Institute of Electrical and Electronics Engineers
IP	Inspection Procedures
NDE	Non Destructive evaluation
NDT&E	Nondestructive testing and evaluation
NDT	Non Destructive testing
NESCC	Nuclear Energy Standards Coordination Collaborative
NIST	National Institute of Standards and Technology
NPAR	Nuclear Plant Aging Research
NPP	Nuclear power plants
NQA	Nuclear Quality Assurance
NRC	Nuclear Regulatory Commission
NUREG	NRC report
QA	Quality Assurance
QA/QC	Quality Assurance/Quality control
R&D	Research & Development
RG	NRC Regulatory Guide
RILEM	International union of laboratories and experts in construction materials, systems and structures
SAG	Structural Aging Program
SASW	Spectral Analysis of Surface Waves
SCM	Supplementary cementitious materials

SDO	Standards Development Organizations
SEI	Structural Engineering Institute
SRP	Standard Review plan
SRS	Savannah River Site
SSC	Systems, Structure and Components
UFSAR	Updated Final Safety Analysis Report

TABLE OF CONTENTS

Chapter 1 INTRODUCTION

The Nuclear Energy Standards Coordination Collaborative (NESCC) is a joint initiative of the American National Standards Institute (ANSI) and the National Institute of Standards and Technology (NIST) to identify and respond to the current needs of the nuclear industry. NESCC was created in June 2009. More details on NESCC and its activities can be found on the following website:
(http://www.ansi.org/standards_activities/standards_boards_panels/nescc/overview.aspx?menuid=3)

In July 2011, NESCC formed a task group, Repair of Concrete of Existing Nuclear Power Plants, referred to as the Concrete Repair Task Group (CRTG) in this report. The request (Appendix A) for the formation of the task group had the following scope:

- Establish coordination and consistency for safety and non-safety concrete repairs in existing nuclear power plants: evaluate the concrete structure, assess the repair strategy, design and implement the repair, and monitor the repair.
- Identify repair requirements for safety-related concrete components, and develop a plan to incorporate these new requirements into codes and standards. Collaboration with standard development organizations (SDO) will be required.
- Identify U.S. Nuclear Regulatory Commission (NRC) Regulatory documents related to concrete repair for existing nuclear power plants and identify any needs.

How these goals were addresses will be summarized in the conclusion. The CRTG started immediately recruiting members to solicit active participation of representatives from relevant Standards Development Organizations (SDOs) and concrete industry organizations involved in the repair and rehabilitation of existing nuclear power plants. At the conclusion of its work, there were 62 members representing 43 organizations including the NRC and NIST. There were also 45 reviewers representing an additional 37 organizations.

The group met regularly via virtual meetings and face-to-face interactions at ACI Conventions (October 2011, March 2012, and October 2012). Each member was asked to contribute on topics related to their expertise and to review the report. Comments were requested regularly and formal votes were conducted to ensure that the concerns of all members were addressed. Two formal ballots were conducted by e-mail. Each time, a report and a ballot form were sent to members and reviewers. The comments were, as assigned by the voter, either **Primary (P)** comments identifying technical issues, or **Editorial (E)** comments identifying editorial issues. All CRTG members and reviewers were invited to vote, comment, and resolve the **P** comments. The Chair and Co-Chair addressed the **E** comments directly. After each informal call for comments and ballots, a new report in “track-changes” format was sent to the members to address the primary comments.

The report was divided in chapters that would follow the logical progression from inspecting the structure to monitoring the repair, through the design and implementation of the repair. It should be noted that this report is limited to a discussion of concrete construction. The following list is developed in Chapters 4 to 7:

- Evaluation of concrete structure

- Development of the concrete repair strategy and design
- Repair implementation
- Monitoring quality control

Chapter 2 OBJECTIVES OVERVIEW

2.1. Introduction

The phrase "concrete repair" (*see also discussion under Section Definitions*) is a generic term that generates the picture of an operator patching a hole in a concrete structure. However, in this report, "concrete repair" encompasses a larger domain. Here the word "repair" is intended to signify a goal to extend the service life of a structure, i.e., the nuclear power plant. From the Concrete Repair Manual [1], the topics that are relevant are: Condition Evaluation, Concrete Restoration, Contractual, Strengthening, and Protection. This report is a compilation of all relevant standards and other literature documents on the topic; it is not a code or guide. The goal of a repair is to restore the function of the structure and prolong its life. Codes, standards, and specifications need to be used to achieve the repair. The issue is which codes and specifications should be used: the original when the structure was built, or the one in use at the time of the repair? ACI 562 committee adopted the philosophy that in repairs related to fire or seismic activity, the current code needs to be used, while if only structural damage, the original code could be used.

In this report, the word repair will be used to include a broader definition of the whole process, from evaluation of the structures to the actual repair of the structure (see section 2.2.1 for a list of definitions). Thus, the report will include:

- ***Evaluation of the concrete structure***: Structural analysis, forensic analysis, remaining service life analysis. This step should provide adequate information to make the repair, rehabilitation, or replacement decisions. (Chapter 4)
- ***Concrete repair strategy and design***: Special analysis of the existing structure to determine the most appropriate repair type to extend the structure service life. This step should also evaluate the time of repair, i.e., immediate/emergency repair or scheduled repair that can be executed during a planned outage. Repair design should also incorporate the protocols to execute the repair. (Chapter 5)
- ***Repair implementation (materials, protocols, standards, etc.)***: This is the execution phase of the repair Effectiveness of a repair depends on the quality of the material, compatibility of new and existing material, exposure conditions (during repair and in-service conditions), and the workmanship. (Chapter 6)
- ***Monitoring: quality assurance of the repair****:* After the repair is completed, there must be a process to monitor over years that the repair is still performing as designed. (Chapter 7)

For each of these chapters, Objectives 2 to 4 of the CRTG (Appendix A) were addressed for each stage of the repair:

2) *Identify relevant repair concrete codes and standards missing from the NRC-regulatory documents.*
3) *Identify technologies and new research that could be translated into new standards and codes to be adopted by an SDO, for instance seismic retrofitting of structures, waterproofing, corrosion repair, pre-stressing tendons, and related system repair.*

4) *Identify new technology and research needs to fill knowledge gaps in existing repair concrete codes and standards.*

The last objective that was listed as the first one in the CRTG (Appendix A) proposal will be addressed in Chapter 3. The NRC and DOE documents related to inspection, quantifying and extending service life, and operating license renewal were examined, and recommendations for update as needed were produced.

1) *Categorize all codes and standards related to concrete repair that are referenced in NRC-regulatory documents.*

To ensure that the recommendations in this report were clearly stated, a uniform format was adopted. Each recommendation will be structured in the following way:

Title
a) ***Status today***
b) ***What needs to be changed*** *for application to a nuclear power plant?*
c) ***Why does it need to be changed?*** *Rationale for the change, with a reference or example*

It should be noted that this report is intended to be an overall snapshot on what should be done to improve the repair of NPP concrete. This report is neither a code nor a standard, but only a set of coordinated recommendations to the SDOs involved with concrete repair of nuclear power plants in the hopes of "harmonizing" commonly cited concrete codes and standards. These recommendations only identify gaps, overlaps, or conflicts in existing codes and standards. Inasmuch as there are CRTG members representing the various SDOs involved in this report, there will be ample opportunity to clarify any recommendation that is potentially unclear to a committee that is assigned to address these recommendations. It is the hope of the CRTG that this document will be on the agenda of the appropriate SDO committees in 2013. Individual SDO committees will need to expend the appropriate amount of time to thoroughly discuss, effectively resolve, and publish code/standard requirements that are clear, logical, and understandable.

2.2. Definition of Repair from the Standards Organizations

The word repair means a lot of different things to a contractor or an engineer. Some will imagine that repair is the material used for patching a hole or scaling on the concrete, while for others it could be the rebuilding of a portion of a structure. The International Concrete Repair Institute (ICRI) and ACI have both developed definitions for the various terms. This section will examine the various definitions available and make recommendations on the best definitions.

2.2.1 International Concrete Repair Institute (ICRI) definitions

ICRI and ACI have developed a "Concrete Repair Manual,"[1] which contains some definitions. Only the general terms to define the domain covered by this report would be discussed here:

- ***Preservation:*** the process of maintaining a structure in its present condition and arresting further deterioration

[1] *Concrete Repair Manual*, 3rd ed., ACI- ICRI, 2008

- ***Protection:*** the process of maintaining a concrete structure in its present or restored condition by minimizing the potential for deterioration or damage in the future
- ***Repair:*** to replace or correct deteriorated, damaged, or faulty materials, components, or elements of a structure
- ***Repair Systems:*** the materials and techniques used for repair
- ***Maintenance:*** taking periodic actions that will delay damage or deterioration or both
- ***Strengthening:*** the process if restoring the capacity of weakened components or elements to their original design capacity, or of increasing the strength of components or elements if a concrete structure

Other words are also used, such as *Restoration* and *Rehabilitation*, but they are not relevant for Nuclear Power plants. Restoration's goal is preserve the era of the structure, while rehabilitation's aim is to modify the structure for changing the usage.

Two other words are also defined by ICRI[1] relevant to this report: *aging* and *service life*, as defined below. Aging is a state, while service life is the useful life left in a structure[2]:

- ***Aging:*** the cumulative effects of time on the properties of materials and substances
- ***Service life:*** an estimate of the remaining useful life of a structure based on the current rate of deterioration or distress, assuming continued exposure to given service conditions without repairs

2.2.2 American Concrete Institute (ACI) documents

The American Concrete Institute has a terminology[3] document that is available online. This document was standardized in 2012, and contains definitions as collected from various ACI documents. Also, there are three specific documents related to repair:

- ACI, 2010, ACI Concrete Terminology (updated 2012)
- ACI 546R-04: Concrete Repair Guide
- ACI 562-12: Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Buildings
- ACI 349.3R: Evaluation of Existing Nuclear Safety-Related Concrete Structures

In this section, the various relevant definitions from all three documents will be examined.

ACI, 2010, ACI Concrete Terminology (ACI-CT)

- ***Repair, structural****:* increasing the load-carrying capacity of a structural component beyond its current capacity or restoring a damaged structural component to its original design capacity
- ***Repair****:* to replace or correct deteriorated, damaged, or faulty materials, components, or elements of a structure
- ***Repair systems:*** the combination of materials and techniques used in the repair of a structure

[2] http://www.icri.org/GENERAL/RepairTerminology2010.pdf

[3] ACI, 2010, *ACI Concrete Terminology*, American Concrete Institute, Farmington Hills, MI, http://terminology.concrete.org (accessed May 20, 2010)

ACI 546R-04, Concrete Repair Guide*: "This document provides guidance on the selection and application of materials and methods for the repair, protection, and strengthening of concrete structures. An overview of materials and methods is presented as a guide for making a selection for a particular application. References are provided for obtaining in-depth information on the selected materials or methods.*" [Preface of the document]

- ***Nonstructural repair****:* a repair that addresses local deterioration and is not intended to affect the structural capacity of a member
- ***Protection****:* the procedure of shielding the concrete structure from environmental and other damage for the purpose of preserving the structure or prolonging its useful life
- **** Repair****:* to replace or correct deteriorated, damaged, or faulty materials, components, or elements of a structure
- **** Repair systems***: the combination of materials and techniques used in the repair of a structure
- ***Strengthening****:* the process of restoring the capacity of damaged components of structural concrete to its original design capacity, or increasing the strength of structural concrete
- **** Repair, Structural****:* a repair that re-establishes or enhances the structural capacity of a member (also in CCT, but not exactly verbatim)

The three definitions marked with an asterisk (*) are also present in the ACI-CT verbatim, with the exception of "Repair, Structural," but slightly different wording.

ACI 562-12, Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Buildings*:* this is the first repair code. From the preface of the draft code, "*This code provides the minimum requirements for the evaluation, repair, and rehabilitation of existing concrete structures and where applicable in nonbuilding structures."*

- ***Repair process:***
  - complete process of evaluating an existing structure, the design and implementation of stabilization measures, and repairs. The repair process is complete when the use of the repaired structure is transferred to the Owner and/or the repair contract terms are completed.
  - procedure of evaluating an existing structure and the design and implementation of stabilization measures and ensuring that repair objectives are achieved
- ***Repair reinforcement****:* reinforcement used to provide additional compressive, tensile, shear strength, or confinement to the repaired member
  - ***Evaluation:*** an engineering review of an existing concrete nuclear structure with the purpose of determining physical condition and functionality of the structure
  - ***Service life****:* estimate of the remaining useful life of a structure based on the current rate of deterioration or distress, assuming continued exposure to given service conditions without repairs
  - <u>economic service life:</u> time in service until replacement of the structure (or part of it) is economically more advantageous than keeping it in service
  - <u>functional service life:</u> time in service until the structure no longer fulfills the functional requirements or becomes obsolete due to change in functional requirements

- technical service life: time in service until a defined unacceptable state is reached, such as spalling of concrete, safety level below acceptable limits, or failure of elements

ACI 349.3R-02: Evaluation of Existing Nuclear Safety-Related Concrete Structures: "This report recommends guidelines for the evaluation of existing nuclear safety-related concrete structures. The purpose of this report is to provide the plant owner and engineering staff with an appropriate procedure and background for examining the performance of facility structures and taking appropriate actions based on observed conditions." The following definition can be extracted from the report, which does not contain a definition section.

2.2.2.1 Non –official definitions from Vision 2020

The American Concrete Institute - Strategic Development council (ACI-SDC) developed a document, Vision 2020[4] to illustrate the needs of the repair industry. In September 2011, a workshop was held, during which an alternative description of the goal of repairing a structure was discussed. The definition that was developed by the participants was "increasing the longevity, resiliency, durability, utility, and sustainability of concrete structures by providing tools to repurpose, protect, upgrade, extend the life, and maintain" or "sustaining concrete structures."

- ***Durability****:* ability of a material to resist weathering action, chemical attack, abrasion, and other conditions of service as well as the ability of a structure or its components to maintain serviceability in a given environment over a specified time
- ***Expected service life (of a building component or material)****:* the period of time after installation or repair during which the performance satisfies the specified requirements when routinely maintained.

2.2.2.2 Recommendations for ACI

- **Homogeneity of the definitions among various documents**
  a) ***Status today*****:** From the documents above, it is clear that some words are used in different documents with their own definitions. There is no coordination between the documents. The challenge would be to determine consistent and correct definitions.
  b) ***What needs to be changed?*** As the ACI-CT is being standardized and will be updated annually, it should be considered the repository of all definitions. The documents should use the ACI-CT, instead of generating new definitions. A committee that has improved definitions should submit it to the ACI-CT, and it should go through the standardization process. Then, both the document and ACI-CT should adopt the definition as standardized.
  c) ***Why does it need to be changed?*** Multiple definitions in different documents create confusion for the reader who needs to use the code and other documents to determine how to proceed or to specify the repair.

- **Definition of repair**
  a) ***Status today****:* There are various definitions of repair or repair systems or process in the ACI documents that represent the same concept. What is a repair?

[4] *Vision 2020: A Vision for the Concrete Repair, Protection and Strengthening Industry*, ACI –SDC; http://www.concrete.org/COMMITTEES/committeehome.asp?committee_code=0000SDC-43 (2006)

b) ***What needs to be changed?*** There should be only one definition, and the concept should be explicitly clear on what constitutes the process of repair. This recommendation suggests that the definition that should be adopted is "repair process" as provided in ACI 562 draft.
c) ***Why does it need to be changed?*** Using one word differently in similar contexts causes confusion.

- **Adopt a definition for *service life***
  a) ***Status today:*** There is no definition in the ACI-CT for service life. This concept is paramount if the repair can be expected to last for decade in a NPP.
  b) ***What needs to be changed?*** The definition of service life as provided in ACI 562-12 must be adopted and added to the ACI-CT at the next update.
  c) ***Why does it need to be changed?*** A successful repair should include monitoring, and the cost will depend on how durable the repair is. A non-durable repair will imply that the structure will need to be repaired frequently with, causing technical and economic problems.

2.3. Overview of the Repair Domain

A significant amount of research has been conducted to determine the best process to perform a durable repair process (ACI 562). The main debate is determining the decision tree to ensure that the best method is selected, balanced with cost effectiveness. In this section, two papers illustrate the steps for a successful repair.

The first paper by Milman et al.[5] defines the repair domain as "a systematic and rigorous evaluation of design, construction, operation and maintenance data in order to assess the effect of aging degradation on structures, establish their current condition and provide prognosis for future performance with associate recommendations. The condition assessment will identify changes, which are necessary and sufficient in order to address issues related to aging effects, and may include economic opportunities for improvement." The author's emphasis is that the root cause of the deterioration observed in the structure or material must be discovered before any repair is performed. The process is referred to as an Aging Related Degradation Mechanisms (ARDM). Failure to identify the root cause or ARDM could lead to accelerated deterioration of the parent material as well as the repair.

The second paper, written by Snover et al.[6], provides a schematic of the repair process (Figure 1). The figure shows the decision tree with the headers, *Comprehensive Condition Evaluation* and *Evaluation of the Deterioration*, which will aid in the discovery of the root cause of the observed damage. The rest of the tree is dedicated to the steps to design and specify the repair. The tree does not continue with the implementation and monitoring of the repair.

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[5] Milman J., Aziz T.S., Biswas J. K., *Assessing and Managing Aging of Nuclear Safety-related Concrete Structures – Recent AECL Experiences*, Transactions, SMiRT 19 paper # H02/4, Toronto, 2007

[6] Snover R.M., Vaysburd A.M., Bissonnette B., *Concrete Repair Specifications: Guidance or Confusion?*, CI Vol. 33#12, December 2011

The report by IAEA-TECDOC[7] presents the results of an overview of the current (1998) techniques to determine the remaining service life of concrete structure, from inspection to monitoring and mitigation of aging degradation. The document contains an extensive list of standards from various countries. It also has a useful table on deterioration mechanisms for concrete, an extensive list of techniques to detect degradation, instrumentation for measurements, and guidelines for assessment and repair of ageing effects. It would be useful if the document were to be updated with the technology of today.

This report will cover all the aspects shown on Figure 1 in the following way:

- Chapter 4: Comprehensive Condition Evaluation and Evaluation of deterioration
- Chapter 5: The rest of the graph, i.e., design and specification of the repair
- Chapter 6 and 7 related to *Repair implementation* and *Monitoring Quality Control* are not covered in the graph. They happen after the *Design* and *Specifications* are selected.

Snover et al.[6] discuss how a durable repair should be specified. Ideally, repairs should be planned so that the structure extended service life required performance is specified, i.e. 10, 20 or more years. Unfortunately, performance of a repair is not always easy to define, in part due to the lack of specific information. Here are recommendations from the paper by Snover et al. [6]:

> ***Status today***: Can performance be specified? Snover states: ". . . specifying the end result is generally a good one, it is not as yet suitable for the concrete repair field. Challenging as they may be, performance requirements cannot be successfully adapted and used to the exclusion of prescriptive specifications until required performance criteria and reliable evaluative techniques have been developed and widely accepted."
> ***What needs to be changed?*** It is simple to repeat what is clearly stated by Snover: "development of performance criteria and reliable evaluative techniques." This can be achieved only through research that combines measurement techniques, such as sensors, with modeling of the environment and the materials properties for the desired service life of the structure.
> ***Why does it need to be changed?*** Durability of repair is paramount for NPP as well as non-NPP applications. Therefore, the only way to ensure durability is to understand and predict performance and be able to monitor performance for numerous years.

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[7] Assessment and Management of Major Nuclear Power Plant Components Important to Safety: Concrete Containment Buildings, IAEA-TECDOC-1025 (Vienna, Austria: International Atomic Energy Agency, June 1998).

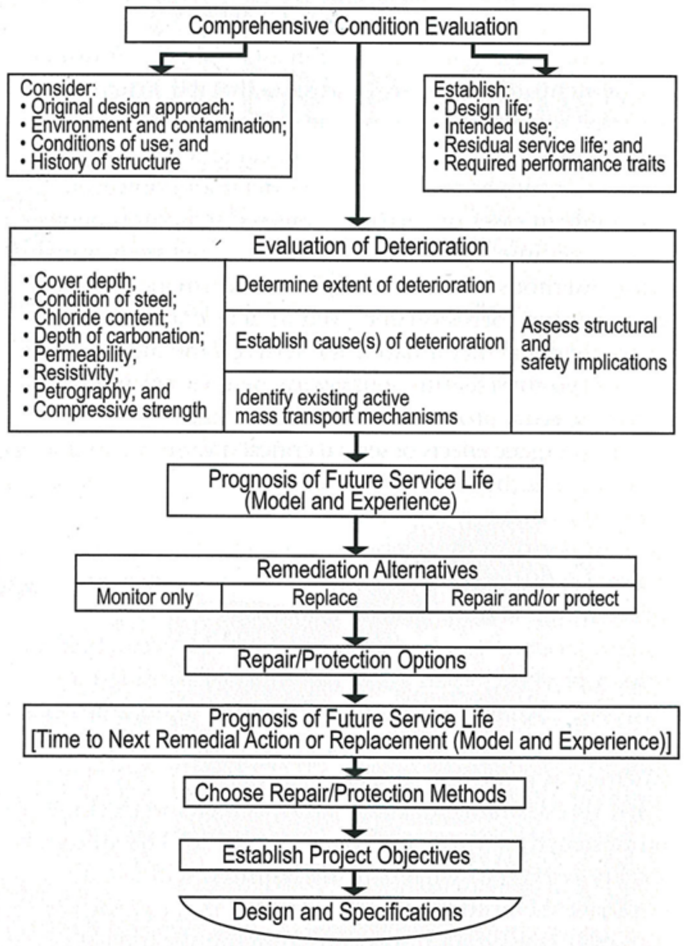

Figure 1: Designing a repair and writing the associate specification require that the engineer conducts a comprehensive evaluation of the existing conditions[6] (reproduced by permission of ACI-International)

2.4. Summary and Recommendations

This chapter covers the definition and domain of repair. The repair of a structure implies understanding of the desired service life of the structure, the usage, environment, and deterioration mechanisms. The complexity of the solution for how to repair the structure is compounded by the lack of predictive models and test methods to determine the residual service life. See also section 2.3.1.1.

- **Homogeneity of the definitions (Recommendation)**

  Status today [6]: ICRI and ACI have definitions related to repair, but they are not the same.

  What needs to be changed? ICRI and ACI should collaborate to determine the best definitions. They should coordinate in the future to ensure that definitions of the main domain of repair are clear and continue to be identical in the two organizations.

Why does it need to be changed? It is confusing for the specifiers and owners that one word might mean different things. For instance, repair could be intended only to apply the patch to the concrete, but a durable repair needs to include an evaluation of the root cause of the deterioration, or it is like painting over to cover the problem.

- **Selection of the best definitions (Recommendation)**

  From this chapter the following definitions should be adopted:

  - ***Expected service life (of a building component or material) (ACI_SDC):*** the period of time after installation or repair during which the performance satisfies the specified requirements when routinely maintained
  - ***Service life (ACI 562):*** estimate of the remaining useful life of a structure based on the current rate of deterioration or distress, assuming continued exposure to given service conditions without repairs
    - economic service life: time in service until replacement of the structure (or part of it) is economically more advantageous than keeping it in service
    - functional service life: time in service until the structure no longer fulfills the functional requirements or becomes obsolete due to change in functional requirements
    - technical service life: time in service until a defined unacceptable state is reached, such as spalling of concrete, safety level below acceptable (limits), or failure of elements
  - ***Repair process (ACI 562):***
    - complete process of evaluating an existing structure, the design and implementation of stabilization measures, and repairs. The repair process is complete when the use of the repaired structure is transferred to the Owner and/or the repair contract terms are completed.
    - procedure of evaluating an existing structure, the design and implementation of stabilization measures, and ensuring that repair objectives are achieved
  - ***Preservation (ICRI):*** the process of maintaining a structure in its present condition and arresting further deterioration
  - ***Protection (ICRI):*** the process of maintaining a concrete structure in its present or restored condition by minimizing the potential for deterioration or damage in the future.
  - ***Maintenance (ICRI):*** taking periodic actions that will delay damage or deterioration or both
  - ***Aging (ICRI):*** the cumulative effects of time on the properties of materials and substances

Chapter 3 INVENTORY OF NRC DOCUMENTS

3.1. Introduction

Under its responsibility to protect public health and safety, the U.S. Nuclear Regulatory Commission (NRC) has four principal regulatory functions: (1) establishing standards and regulations, (2) issuing licenses for nuclear facilities, (3) inspecting facilities and users of nuclear materials to ensure compliance with the requirements and(4) enforcement of the regulations. Thus, documents are prepared to guide the owners and operators of the NPP on specification and guidelines to ensure the safe operation of the NPP. The documents are of various types and may be based on consensus standards for the type of tests or methodologies that need to be followed. This chapter will explore the documents and programs endorsed by the NRC related to repair. Recommendations will be made on updates needed on the documents and program to ensure that the NPP can be repaired efficiently. Documents and standards that would enhance safety and which would benefit from NRC endorsement will also be identified.

The chapter will cover first the documents published by NRC which endorse standards followed by documents involving standards used for informational purposes or as a technical basis for regulatory programs..Then two programs for managing aging NPP will be discussed: "Generic Aging Lessons Learned" (GALL) and "Aging Management Programs" (AMP). Finally, the renewal process will be discussed and recommendations will be made.

3.2. NRC Documents

The NRC has issued three types of documents on repair: Inspection Procedures (IP), NUREGs, and Regulatory guides (RG). The NUREGs are typically informational documents that either summarize technical issues on a topic or serve as a technical basis for the NRC's regulatory process. They do not endorse specific standards. NUREGs are also used as standard review plans for NRC staff. The RG is defined by NRC thus: "reports or brochures on regulatory decisions, results of research, results of incident investigations, and other technical and administrative information."[8] The RG is defined by NRC thus: "The Regulatory Guide series provides guidance to licensees and applicants on implementing specific parts of the NRC's regulations, techniques used by the NRC staff in evaluating specific problems or postulated accidents, and data needed by the staff in its review of applications for permits or licenses."[8] Similarly, inspection procedures do not endorse standards. They provide guidance to NRC staff, particularly for the inspectors. The specific version of a standard which is used by the inspector is determined by the plant licensee's design basis. The NRC uses RGs to formally endorse the use of standards by licensee's.

Table 1 shows the documents found related to repair of existing NPP. Each of the documents will be summarized, and possible recommendations provided as needed. IPs entail the three types of inspections performed by NRC: baseline inspections, generic safety issues, and special inspections. IPs also provide guidance on supplemental inspections performed as a result of the risk of significant performance issues.

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[8] NRC website: http://www.nrc.gov/reading-rm/doc-collections/nuregs/

Table 1: NRC Documents identified related to repair (in chronological order)

Document	Title	Date
RG 1.127	Inspection of Water-Control Structures Associated with Nuclear Power Plants	Mar-1978 Draft for comments 2011, date of final publication unknown
IP46053	NRC Inspection Manual- Structural Concrete Work Observation	Jul-1983
IP46051	NRC Inspection Manual - Structural Concrete	Jul-1983
IP46061	NRC Inspection Manual - Structural Masonry Construction	Dec-1986
NUREG-1522	Assessment of In-Service Conditions of Safety-Related Nuclear Plant Structures	June-1995
NUREG/CR-6424	Report on Aging of Nuclear Power Plant Reinforced Concrete Structures	Mar-1996
IP 62002	Inspection of Structures, passive components, and civil engineering features at Nuclear Power plants	Dec-96
NUREG/CR-6679	Assessment of Age-Related Degradation of Structures and Passive Components for U.S. Nuclear Power Plants	Jul-2000
IP71002	NRC Inspection Manual - License Renewal Inspection	Feb-2005
NUREG/CR-6906	Containment Integrity Research at Sandia National Laboratories	Jun-2006
NUREG/CR-6927 ORNL/TM-2006/529	Primer on Durability of Nuclear Power Plant Reinforced Concrete – A Review of Pertinent Factors	Feb-2007
IP71003	NRC Inspection Manual - Post Approval Site Inspection for License Renewal	Feb-2008

RG 1.127 (***Mar-1978 Rev. 2011): Inspection of Water-Control Structures Associated with Nuclear Power Plants:*** This document describes how to develop an inspection program for water structures. It was first issued in 1978 and was sent for public comments in January 2011 (DG-1245).The NRC has received the comments, but the publication date is yet unknown (per private communication from NRC). The new draft the ACI 201 is cited with a date of 1997, while the current version is 2008.

Recommendation

a) ***Status today***: the document was under public comment in 2011, while citing ACI documents dated 1997 when more recent versions of those documents existed

b) ***What needs to be changed?*** Cite the latest ACI document version, i.e., 2008

c) ***Why does it need to be changed?*** Using the latest version of the ACI document would ensure that the most modern technology is used.

IP 46051-1983**: **NRC Inspection Manual - Structural Concrete: The scope of this document is to "determine whether the technical requirements detailed and referenced in SAR associated with structural concrete have been adequately addressed in the construction specifications." This document cites an extensive list of standards documents from ACI, ASTM, American Welding Society, AASHTO, U.S. Army Corps of Engineers, and the National Ready Mixed Concrete Association (NRMCA). While this list is long, the date of publication of the standard cited is not mentioned, and indicates, "The applicable edition or revision of codes and standards should be stated in the Licensee's safety analysis (SAR)." Thus, it would imply that the document allows that the inspection be conducted using the most recent version of the relevant code and standards. In fact, for the licensing basis of plants in the U.S., the version of the document in use at the time the plant was originally licensed is typically followed. This is traditionally spelled out in the plant's Updated Safety Analysis Report (USAR). Thus, it would be best if the most recent version of the code and standards could be considered, not necessarily the one used at the time of construction. It should be established whether it might be beneficial for the task at hand to use a more modern or updated version.

IP 46053-1983: NRC Inspection Manual- Structural Concrete Work Observation: This document addresses inspection during construction, and does not pertain to the topic of repair. The ASTM and ACI documents cited were written without specifying the year of publication, implying that the latest version was to be used. Again, this assumption is incorrect, as usually it would be implied that the version at the time of construction should be used. Consideration of the most recent version should be evaluated to ensure that all possible new technology is used for the benefit of the inspection.

IP46061-1986 NRC Inspection Manual - Structural Masonry Construction: The scope of this document is to "determine by review whether quality insurance plans, instructions and procedures have been established". The document suggests to use the recommendations outlined in ACI 531-79 (building code for concrete masonry structures and commentary). It also makes direct reference to ASTM specifications with publication dates of 1970 to 1973. The building code references have been extensively updated, and the current version is ACI 530/530.1-11 (Building Code Requirements and Specification for Masonry Structures and Related Commentaries). The ASTM standard specifications used in this IP are listed in Table 2, with their publication dates.

Table 2: ASTM Standards Specification cited in IP 46061-1986

ASTM Standard	Cited version	Most Current version
C90 - Standard Specification for Loadbearing Concrete Masonry Units	1970	2011
C129 - Standard Specification for Nonloadbearing Concrete Masonry Units	1973	2011
C145 - Specification for Solid Load-Bearing Concrete Masonry Units	1975	(Withdrawn 1990) and replaced by C90
C270 - Standard Specification for Mortar for Unit Masonry	1973	2012
C476 - Standard Specification for Grout for Masonry	1971	2010

<u>Recommendations for IP46061-1986</u>

***Status today*:** The document uses specifications and codes that are over 30 years old and in one case the standard (C145) was replaced by C90.

What needs to be changed? The code and specifications to be used in the inspections should reflect advances in technology and knowledge, and thus be the most recent version available. A comparison of the 1970s versions and the most recent version reveals the following issues:

- In all the standards examined here, some materials that are commonly used in 2012, such as fly ash, slag, or admixtures, are not mentioned in the 1970s versions. Thus, usage of the old version might result in a lesser quality product.
- C90:
  - In the 1970 version, there is a classification of the units that does not exist in the 2012 version. Thus, accepting only the 1970 version would force a vendor to provide something that is not available.
  - Specifications described in Table 3 (1970) or Table 1 (2012) are not the same. This would imply that the most recent values were obtained after 30 years of practice, and should be most useful.
- C129:
  - Two types of masonry were eliminated (Type I and II). Thus, they should not be specified.
  - Section 8.2.1 (2011) has a better description of what is acceptable under visual inspection, especially with maximum width of cracks acceptable.
  - There is a specification of shrinkage (2012) that was previously limited to Type I units (1973).
- C476:
  - The scope of the 2010 version was expanded to cover various types of grouts.
  - The mixture design is based on performance instead of prescriptive measures, and more type of grout mixtures are described.

- C270:
  - The test method section is more detailed and provides more guidelines on how to conduct the tests.
  - The requirements are more specific, with clear tables that provide various choices instead of one mixture design.
  - The appendixes, especially X1, provide further information on how to specify mortar.

Why does it need to be changed? It is clear from this typical analysis in comparing the old version and the current version of the same standards that significant progress has been made in the test method and specifications. In some cases, new materials were introduced and new requirements. Using potentially obsolete technology could result in sub-par inspection criteria and overlooking potentially unsafe situations or deterioration. Thus, it is recommended that the most recent version of a standard be evaluated promptly and systematically (as soon as it is issued by the SDO) to ensure that it can be used for NPPs.

IP71002-2005: NRC Inspection Manual - License Renewal Inspection: This document's objectives are to ensure that all components have a maintenance program and that documentation is available to ensure that procedures are followed. This document provides guidelines on how to conduct the inspection and documentation needed, and is relatively up-to-date.

IP71003-2008: NRC Inspection Manual - Post Approval Site Inspection for License Renewal: This document provides guidelines to conduct an inspection after the NPP's renewal license has been granted. As it is was updated in 2008, it is considered to be a current version of the document.

IP62002-1996: Inspection of Structures, passive components, and civil engineering features at Nuclear Power plants: This document's scope is to evaluate the license maintenance and monitoring program to ensure compliance with the Code of Federal Regulations (10 CFR 50.65). The document uses as reference ACI 349-96, ACI 207-85 and ASCE 11-90.

Recommendations for *IP62002-1996*

Status today: The document is cited as a guideline for the licensee to develop a maintenance plan, but the references are documents from ACI and ASCE that were withdrawn by the issuing organization.

What needs to be changed? The IP62002 should be updated to reflect the new technology by citing current documents, i.e., ACI 349-10, ACI 207-94 (08).

Why does it need to be changed? Guidelines for the licensee based on documents that are considered obsolete by the issuing organization do not ensure that the highest safety standards are encouraged.

NUREG/CR-6424/1996 Report on Aging of Nuclear Power Plant Reinforced Concrete Structures will be discussed under SAG in section 3.3.3.

NUREG/CR-6679/2000: Assessment of Age-Related Degradation of Structures and Passive Components for U.S. Nuclear Power Plants: This is a comprehensive overview of age-related degradation of structures, collected from Licensee Event Reports and other NRC documents. A computerized database was created to summarize all the parameters, analysis to determine trends in degradation causes, and structure types. The report concluded that "the structures and passive components that warrant further detailed evaluations are masonry walls, flat bottom tanks, anchorage, concrete structures (other than containments) and buried pipes." The report suggests that further research is needed to assess the effect of age-related degradation on the performance of structures. It implies that there will be a phase II of this study, but no reference was found.

> ***What needs to be changed?*** The research suggested as needed in this report should possibly be conducted to assess the effect of age-related degradation on the performance of structures.
>
> ***Why does it need to be changed?*** The knowledge of effect of aging in the performance of structures would allow better selection of materials and repair strategies related to the environment.

NUREG/CR-6906/2006 Containment Integrity Research at Sandia National Laboratories: This is a relatively recent (2006) overview of the research conducted at Sandia National Laboratories on the containment integrity. This report summarizes historical data and research conducted at SNL and elsewhere. It achieves the goal of giving guidelines on predicting containment behavior.

> ***What needs to be changed?*** Nothing, as this is a thorough overview, with guidelines that make a sound basis for further R&D.

NUREG/CR-6927/2007 (ORNL/TM-2006/529) Primer on Durability of Nuclear Power Plant Reinforced Concrete – A Review of Pertinent Factors: This report is an overview of the concrete deterioration process and the possible causes of such deterioration with time. It has some chapters directly related to NPP, as it addresses elevated temperature and irradiation. It provides a good overview, and is thus useful as background reading for concrete technology and causes of deterioration.

> ***What needs to be changed?*** Nothing, as this is a thorough overview, with guidelines that make a sound basis for further R&D.

***NUREG-1522/1995 Assessment of In Service Conditions of Safety-Related Nuclear Plant Structures*:** This report summarizes the results of inspection and survey conducted on several NPPs to determine the type of deterioration observed. It provides some information on how to conduct the inspection, as well as indicating the documents useful to NPP operators. The references cited are obsolete, but in some cases, more recent versions do exist and should be used. As this document is solely a case study, it could be used as a guideline and does not need to be updated.

> ***What needs to be changed?*** Nothing, as this is a thorough overview, with guidelines that make a sound basis for further R&D.

3.3. Programs to Monitor NPPs

NRC also developed documents that will be presented here in a broader fashion, as they provide the state-of-the-art on management, as well as lessons learned regarding power plants. Thus, this section is presented differently than the previous one, and the recommendations will be presented at the end on all documents.

NPPs need to be monitored to determine when and whether to intervene for repair of the structure or system. The monitoring should include evaluation of structure at various times to uncover the deterioration at its early stages. In the NRC documents, the term *aging management* is often used. This phrase implies a set of actions employed to slow down deterioration. Other terms are used as well for defining programs:

- Generic Aging Lessons Learned (GALL)
- Aging Management Programs (AMP), as used in Canada
- Structural Aging Program (SAG)

Several other documents regarding Structural Aging Programs were developed by NRC, but detailed comments on each of them are beyond the scope of this report. Nevertheless, some are listed here for further discussion:

- "Remnant Life Preservation of LWR Plant Structures," 12th International Conference on Structural Mechanics in Reactor Technology (SMiRT), 1993, Hookham and Gregor.
- "Design Code Requirements for Concrete Repository and Processing Facilities," International High Level Radioactive Waste Management Conference, 1993, Hookham.
- "Implications of Concrete Degradations in Nuclear Power Plants," Ashar, H., PRO 16, International RILEM Workshop on Life Prediction and Aging Management, 2000.

3.3.1 Generic Aging Lessons Learned (GALL)

The GALL Report[9] identifies Aging Management Programs (AMPs), which were determined to be acceptable programs to manage the aging effects of systems, structures, and components (SSCs) in the scope of license renewal, as required by 10 CFR Part 54, "Requirements for Renewal of Operating Licenses for Nuclear Power Plants." NRC issued an initial report in 2011 that was published under NUREG-1801 into two volumes. Volume 1 summarizes the aging management reviews that are discussed in Volume 2. Volume 2 lists generic Aging Management Reviews (AMRs) of SSCs that may be in the scope of License Renewal Applications (LRAs), and identifies GALL AMPs that are acceptable to manage the aging effects.

Revision 1 (2005) of the GALL Report incorporates changes based on experience gained from numerous LRA NRC staff reviews of LRAs and other insights identified by industry. If a license renewal application (LRA) references the GALL Report as the approach used to manage aging effects, the NRC staff will use the GALL Report as a basis for the LRA assessment consistent with guidance specified in the SRP-LR.

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[9] NUREG-1801, *Generic Aging Lessons Learned (GALL)* Report, http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1801/ (links includes the revisions)

The document is incorporated into NUREG-0800 Standard Review Plan for Review of License Renewal Applications for Nuclear Power Plants. The document was revised in 2005 and 2010.

3.3.2 Aging Management Programs (AMP)

A review of the international practices has shown that many utilities worldwide have been responding to the potential for age-related degradation of Reactor Buildings (RBs). Therefore, they have implemented Aging Management Programs (AMPs) in various forms.

The methodology set forth in the AMP for the concrete of the RB involves activities and tasks for periodic inspections to identify and assess defects; monitoring and mitigation of defects by existing, modified, or new maintenance activities; techniques for repair of defects; record keeping; continued integrity assessment; and trending assessment for continued service life determination. The AMP includes the following sequential steps:

1) Program organization and information gathering. This is related to the proposed definition of the AMP team, their responsibilities, and specific qualifications, as detailed in CSA N287.1[10] and ACI 349-3R; gathering and reviewing plant documentation; defining relevant areas for data collection, such as accessible and inaccessible areas; and conducting a general visual examination of the relevant areas identified.

2) Defect evaluation, including condition survey and evaluation of condition survey results. Defects identified in step 1 must be evaluated using acceptance criteria defined in step 2. Those defects that do not meet the stated acceptance criteria must be evaluated to determine corrective actions, re-inspections, and alternative or supplemental examinations. If the condition of the defects or deterioration suggests that further degradation data is required, materials testing and structural analysis are required.

3) Remedial actions should be taken to repair or replace the damaged components to mitigate the cause of deterioration. ACI 546R-04 and ACI 546.3R-06 provide detailed information and guidance on the selection and application of materials and methods for the repair, protection, and strengthening structures in general. CSA N287.2[11] and COG 04-4055[12] provide information regarding the material requirements for concrete containment structures for CANDU nuclear power plants, and patching and overlay materials for repairing concrete structures materials performance characteristics and repair specifications. The defects that need to be repaired are prioritized based on the safety significance and state of degradation of the concrete component, and the inspection results are reported and stored.

4) Continued service determination, including continued integrity assessment and trending refers to the evaluation of the effectiveness of the AMP to ensure safe and reliable operation of the plant. The factors controlling the service life of concrete and the

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[10] CSA N287.1-93 (R2009), *General Requirements for Concrete Containment Structures for CANDU Nuclear Power Plants*

[11] N287.2-08, *Material requirements for concrete containment structures for CANDU nuclear power plants*

[12] COG 04-4055, *Evaluation of patching and overlay materials for repairing concrete structures - long term performance monitoring for CANDU generating stations - Materials performance characteristics and repair specification*, 2006.

methodologies of predicting the service life of concrete presented in ACI 365.1R-00 can assist the integrity assessment and trending of the concrete of the RB.

It should be noted that for concrete of reactor buildings information regarding material requirements for patching and overlay materials for repairing concrete structures, materials performance characteristics, and repair specifications is available in COG (CANDU Owners' Group) publications[10,11].

IAEA has guidelines for AMP (Safety guide NS-G-2.12-2009[13]), which address time-dependent changes:

- Physical aging of structures, systems, and components, which result in degradation, i.e. gradual deterioration in their physical characteristics
- Obsolescence of structures, systems, and components, i.e. their becoming out of date in comparison with current knowledge, standards, and technology

This document is related to the first aging process, i.e., changes in physical characteristics. Figure 1 of the report by IAEA (page 5 of the report[13]) gives a clear picture of the process. These changes will require repair of the structure. The IAEA report advocates an approach called the "Plan-Do-Check-Act" cycle; details are illustrated in Figure 1. This approach seems mainly to target mechanical devices that could degrade and fail, more than the structure itself. But the underlying idea could be adapted to the concrete structure as well. In that case, clear knowledge of the degradation mechanisms and remedial or repair process is required. Related to the concrete, the report cites as aging mechanisms "aggressive chemical attack and corrosion of embedded steel," "cracks and distortion due to increased stress levels from settlements," "loss of prestress due to relaxation, shrinkage, creep and elevated temperature," and "loss of material (scaling, cracking and spalling) due to freeze–thaw processes." In summary, the process highlighted by IAEA stipulates that AMP should be considered from the construction of the NPP and monitored at regular intervals, not after stress is apparent.

3.3.3 Structural Aging Program (SAG)

The NUREG/CR-6424 is the comprehensive review on the work performed for seven years by the Structural Aging Program (SAG)[14]**.** It covers all the aspects of repair as defined in this report, i.e., from inspection to repair and prediction of the durability of the repair. It provides the state-of-the-art as it was in 1996. A number of standard documents are cited as support to the methodology on how to inspect and assess the remaining service life of a structure.

- Table 3 shows the list of all ACI documents cited.
- ASTM standards are cited, but often the year update is not mentioned.
- ASCE document "ASCE 11-90 (1991) Guideline for Structural Condition Assessment of Existing Buildings" was used extensively, particularly for its table and decision charts.

13 *Ageing Management for Nuclear Power Plants for Nuclear Power Plants*, IAEA -NS-G-2.12. IAEA http://www-pub.iaea.org/MTCD/publications/PDF/pub1373_web.pdf

14 The authors of this report are: D. J. Naus, C. B. Oland, ORNL, B. R. Ellingwood, JHU

This document also recommends the use of a database of material properties called SMIC or Structural Materials Information Center[15], based at the Oak Ridge National Laboratory. It was published in book format (four volumes in a loose-leaf binder for easy updates) and also in electronic version: "Structural Materials Electronic Database." The last version was published in 1994. If this idea should be pursued or better revived, the database needs to exist only in electronic form. The scope of this database was to catalog a "comprehensive review and assessment of existing material properties" with information on the aging process of the materials.

NUREG/CR-5314/ 1996 Insights for Aging Management of Major Light Water Reactor Components, Volume 2, Reinforced and Prestressed Concrete Containments: Forms part of the basis of the Generic Aging Lessons Learned (GALL report) and for other License Renewal Guidance Documents.

NUREG-1833, 2005, Technical Bases for Revision to the License Renewal Guidance Documents**:** States on page 110 that changes were made to existing aging management review items for containment structures (reinforced and prestressed) to add language recommending that inaccessible areas of plants (containments) located in moderate to severe environments be inspected.

3.3.4 Recommendations Summary

The GALL report is being regularly updated; the last version was in 2010, and thus no changes are recommended. The recommendation of AMP is that the AMP should already be considered during the construction of a new NPP. This idea is supported here.

The SAG goal was to have a "*Structural Materials Database*;" unfortunately, the latest version is mainly on paper and dates 1994. Thus, an updated version using modern electronic database capabilities would be a valuable asset for new NPPs as well as their repair.

The AMP was revised to clearly address both accessible and inaccessible areas for the following reason: Applicable aging management programs (AMPs) for concrete elements in the current Generic Aging Lessons Learned (GALL) report were not clearly stated, and some inconsistencies were found between Chapters II and III of the GALL report for the concrete elements.

3.4. Recommendations for all NRC documents

- **Update the document**
  Status today**:** This document is comprehensive, but it cites only research and information available up to 1996. The standards documents cited are 15 years old, and it is likely that some of the materials and techniques cited might not be available today. This document provided valuable information as a guideline for aging management, and also has the

[15] C.B. Oland, D.J. Naus, E.G. Arndt, *Research and development at the structural materials information center*, Nuclear Engineering and Design, Volume 142, Issues 2–3, 1 August 1993 , Pages 179-187

recommendation of using a database to provide information on material deterioration (SMIC).

What needs to be changed? The document should be updated and the material database should be continuously maintained in electronic format. Standards documents cited should be the current version, as they represent the state-of-the-art for that test method. Table 3 gives the new versions that could be used for each of the standards documents cited. This project ran out of funding due to more pressing industry issues. This will continue to be the case, as concrete has generally proven durable.

Why does it need to be changed? It is paramount that the owner of an aging NPP have up-to-date information that can be used to determine the best process to maintain the NPP.

- **Update ACI documents**

  ***Status today*:** Table 3 shows in bold italics the documents that are needed and require updates.

  What needs to be changed? The documents cited in this document (Table 3) should be updated and maintained.

  Why does it need to be changed? These documents are valuable for the owner to maintain a safe aging NPP; thus, the most technological advanced information should be available.

- **Update ASCE document**

  ***Status today**:* The NUREG cites the ASCE version published in 1991, while a more recent version exists.

  What needs to be changed? The ASCE version #11-99 published in 2000 should be used and ASCE should maintain this document with future updates.

  Why does it need to be changed? Usage of the most recent version will ensure that the most modern technology and methodology is used.

Table 3: List of ACI documents cited in NUREG CR-6424

Committee number	Document title	Year cited	Most recent version
359- Joint ASME	ASME Boiler and Pressure Vessel Code	1977	2010
116	Cement and Concrete Terminology	1985	Online Terminology http://www.concrete.org/Technical/CCT/ACI-Terminology.aspx
201	Guide to Durable Concrete	1977	2008 (201-2R)
201	Guide for Making a Condition Survey of Concrete In-Service	1968	2008 "Guide for Conducting a Visual Inspection of Concrete in Service"
207	***Practices for Evaluation of Concrete in Existing Massive Structures for Service Conditions***	***1979***	***1994 – reapproved 2008***
210 Since 2000 it is 207	***Erosion of Concrete Hydraulic Structures***	***1989***	***1993 (reapproved 2008) – in revision***
215	***Considerations for Design of Concrete Structures Subjected to Fatigue***	***1974***	***Reapproved 1997 In revision***
216	Guide for Determining the Fire Resistance of Concrete Elements	1981	2007 "Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies"
222	Corrosion of Metals in Concrete	1989	2001 – reapproved 2010 "Corrosion of Prestressing Steels" or "Protection of Metals in Concrete Against Corrosion"
224	Control of Cracking in Concrete Structures	1980	2001 – reapproved 2008
224	Causes, Evaluation, and Repair of Cracks in Concrete Structures	1984	2007
311	Guide for Concrete Inspection	1980	2005
318	Building Code Requirements for Reinforced Concrete	1971	2011
349	Code Requirements for Nuclear Safety Related Concrete Structure	1985	2006
349.1R	Reinforced Concrete Design for Thermal Effects on Nuclear Power Plant Concrete Structures	1980	2007
349.3R	Evaluation of Existing Nuclear Safety-Related	1995	2002 (reapproved in 2010)

Committee number	Document title	Year cited	Most recent version
	Concrete Structure		
364	Guide for Evaluation of Concrete Structures Prior to Rehabilitation	1993	2007 (under revision 2013)
437	Strength Evaluation of Existing Buildings	1982	2003
515	***A Guide for the Use of Waterproofing Damp proofing, Protective, and Decorative Systems for Concrete***	***1990***	***Under development***
546.1R	***Guide for Repair of Concrete Bridge Superstructures***	***1980***	***Re-approved in 1997 – inactive - In revision***

3.5. Research Needs

In 2008, NRC/DOE held a workshop to identify the research needs to extend the service life of NPPs beyond the originally approved 40 years. A report[16] was prepared which provides a list of potential research topics. The list is long, and was divided into three areas: degradation-related, inspection-related, and other research. In the degradation-related area, the recurring theme is that a better understating of the material degradation is needed to discover the root cause of the deterioration and to effectively mitigate and repair it. Another area for potential research would be using sensors to monitor degradation in concrete. Most innovations in recent years have been in applications in bridges and when automated and remote monitoring of vital properties of the bridge are developed and used. Nevertheless, none are developed for long-term monitoring of degradation in NPPs.

3.6. Renewal Process

The requirements to renew the licenses of an NPP are described in 10CFR Part 54[17]. This document outlines the procedure and information needed to obtain license renewal. It is clearly stated in the 10CFR Part 54 that an Integrated Plant Assessment (IPA) needs to be conducted that "demonstrates that a nuclear power plant facility's structures and components requiring aging management review … have been identified and that the effects of aging on the functionality of such structures and components will be managed to maintain the Current Licensing Basis (CLB) such that there is an acceptable level of safety during the period of extended operation." It also states that "time-limited aging analyses" should be conducted to "consider the effect of aging" on the structure and "involve conclusions or provide the basis for conclusions related to the capability of the system, structure, and component to perform its intended functions." Both of these requirements must be based on the assessment of the remaining service life of the structure.

[16] *Life Beyond 60: Workshop Summary Report*, DOE- 2008
[17] Part 54 *Requirements for Renewal of Operating Licenses for Nuclear Power Plants,* NRC website, 2010

This document does not mention how repairs, restoration, or rehabilitation could be taken into account to extend the service life of a structure.

The maintenance aspect is covered by the 10CFR §50.65[18], but it does not mention explicitly repairs/restoration to extend the service life of a structure.

U.S.-NRC has a list of documents that are related to the renewal process whose aim is to help guide the owner and inspectors of the NPP to determine the state of the structures. The entire list is posted on the NRC website under "Reactor License Renewal Guidance Documents."[19] There are very few documents directly related to repair. One is NUREG 1611, "Aging Management of Nuclear Power Plant Containments for License Renewal," published in 1997. This document should be updated. Most of the Nuclear Plant Aging Research (NPAR) is at least 10 years old.

3.7. Recommendations Summary

- **Evaluation of all the programs to monitor NPP**

  Status today: Multiple programs in various countries, and sometimes adapted to one NPP, are in application today to monitor aging and degradation of NPP structures.

  What needs to be changed? A combination of research and regulations could unify the various methodologies into a best practice that could be pre-approved by NRC to be used by any of the licensees.

  Why does it need to be changed? Unification of all the programs should improve safety and reduce cost by allowing a public discussion. The open discussion would allow the diffusion of new technologies and ensure that best practices are implemented.

- **Technology transfer from Non-nuclear structures**

  ***Status today*:** Most of the innovations in sensors to monitor degradation in concrete is for applications in bridges. Automated and remote monitoring of vital properties of the bridge are developed and used.

  What needs to be changed? The transfer of the monitoring technologies used for bridges to concrete in NPPs would be beneficial. NRC should have a protocol for adoption of such technology and maintain a database to approved methodologies.

  Why does it need to be changed? NRC and the licensee would benefit from technologies that are already developed for other applications. Monitoring of the degradation would be improved with none of the cost of the R&D.

18 10 CFR§50.65, *Requirements for monitoring the effectiveness of maintenance at nuclear power plants*, 2007
19 http://www.nrc.gov/reactors/operating/licensing/renewal/guidance.html#inspection

- **Prediction of service life**

  Status today: There are few models[20,21] and experimental techniques that would allow a prediction of the remaining service life of concrete while taking into account the past and future environments. In other words, for certain types of degradation mechanisms, models do exist that give some confidence in their outcome, especially when prior performance and knowledge of concrete composition is available. However, the use of models is prone to misuse/manipulation; therefore, there should be clarification on which models are used for which degradation mechanisms, and in what manner (indicating the constraint for the input). Many attempts to quantify service life, as defined in the NRC's Structural Aging Program and License Renewal Program, have determined such to be difficult and unreliable. However, proper concrete inspection, maintenance, and repair have been shown to have significant benefits in terms of long-term probabilistic behavior.

  What needs to be changed? A combination of models and measurement techniques needs to be developed to be able to predict remaining service life in all environments and for all deterioration mechanisms.

  Why does it need to be changed? Without the capability to predict the remaining service life of concrete, while considering the environment and most deterioration mechanisms, it would be hard to ensure that any repair would last 40 years and more, as is needed for the renewal process.

A number of research needs were discussed in section 3.5 and will not be repeated here.

[20] *Advances in Modeling Concrete Service Life*, Proceedings of the 4th International RILEM workshop, Ed. Andrade C., Gulikers, J., Sept 2010, http://www.springer.com/engineering/civil+engineering/book/978-94-007-2702-1

[21] Le Bescop, P., Lothenbach, B., Samson E., Snyder, K.A., *Modeling Degradation of Cementitious Materials in Aggressive Aqueous Environments*, State-of-the-Art Report, RILEM TC 211 - PAE, Vol. 10, ed. Alexander, Mark, Bertron, Alexandra and De Belie, Nele, 2013

Chapter 4 EVALUATION OF THE CONCRETE STRUCTURE

4.1. Overview

This chapter focuses on evaluation prior to repair and evaluation of a repair's effectiveness. The scope includes structural analysis, forensic analysis, and remaining service life analysis.

4.2. Condition Survey and Documentation

4.2.1 Status today

Condition assessment of reinforced concrete buildings (and other structures) is addressed in several documents published by ACI and two publications by ASCE/SEI. The documents ACI 318-11, 349-06, 437-12 and 562-12 have the status of "codes," while many of the other documents are reports generated by ACI Committees. ACI Committee Reports provide guidance in planning, designing, executing, and inspecting construction. Reports are intended to be used by individuals who are competent to evaluate the significance and limitations of the contents and recommendations within the report. Reports, therefore, are not written in mandatory language. The ASCE/SEI standards are intended as guidelines for the professional community when performing condition assessments. A brief summary of each document is provided below.

ACI 201.1R-08, Guide for Conducting a Visual Inspection of Concrete in Service: This report, developed by ACI Committee 201, provides terminology to perform and report on the visual condition of concrete in service. It includes a checklist of the many details that may be considered in making a report and descriptions for various concrete conditions associated with the durability of concrete.

ACI 224.1R-07, Causes, Evaluation, and Repair of Cracks in Concrete Structures: This report, developed by ACI Committee 224, summarizes the causes of cracks in concrete structures. The procedures used to evaluate cracking in concrete and the principal techniques for the repair of cracks are presented. Chapter 2 is specifically devoted to evaluation of concrete cracking, including the determination of location and extent of concrete cracking.

ACI 228.1R-03, In-Place Methods to Estimate Concrete Strength: This report (under revision), developed by ACI Committee 228, documents nondestructive test methods for predicting concrete strength, such as the rebound (Schmidt or Swiss) hammer, pull-out, ultrasonic pulse velocity, maturity, penetration resistance tests, etc. The methods are applicable to hardened concrete of varying ages, and provide information about the relative strength of concrete. However, care must be taken to properly correlate the results of the testing with conventional coring and testing if quantitative results are required.

ACI 228.2R-98 Nondestructive Test Methods for Evaluation of Concrete in Structures: This report (under revision), developed by ACI Committee 228, provides detailed discussions of most nondestructive test methods that can be used for evaluating concrete conditions for both new and mature concrete, including stress wave, ground penetrating radar, magnetic, nuclear, radiography, electrical, infrared thermography, penetrability, and other NDE methods for characterizing cracking damage, honeycomb/void, steel embedments, corrosion, dimensions, and other concrete conditions.

ACI 318-11, Building Code Requirements for Structural Concrete and Commentary**:** This is a "code"-level document that covers the materials, design, and construction of structural concrete used in buildings and other structures. In Chapter 20, this document also addresses the strength evaluation of existing concrete structures through load testing. This chapter is discussed later in Section 4.10, *Load Testing*.

ACI 349-06, Code Requirements for Nuclear Safety-Related Concrete Structures and Commentary: This is a "code'"-level document that covers the materials, design, and construction of structural concrete used in Safety-Related structures. In Chapter 20, this document also addresses the strength evaluation of existing concrete structures. In Chapter 20, the determination of required dimensions and material properties is addressed.

ACI 349.3R-02 (reapproved 2010), Evaluation of Existing Nuclear Safety-Related Concrete Structures: This is a report prepared by ACI Committee 349. This report provides guidelines for the evaluation of existing nuclear safety-related concrete structures. Methods of examination, including visual inspections and testing techniques and their applications, are cited.

ACI 364.1R-07 Guide for Evaluation of Concrete Structures before Rehabilitation: This report, developed by ACI Committee 364, presents general procedures for evaluation of concrete structures before rehabilitation. Among the subjects covered are preliminary investigation, detailed investigation, documentation, field observation and condition survey, sampling and material testing, evaluation, and final reporting. Evaluation to identify seismic deficiencies is beyond the scope of this report.

ACI 369R-11 Guide for Seismic Rehabilitation of Existing Concrete Frame Buildings and Commentary**:** This report, developed by ACI Committee 369, describes methods for estimating the seismic performance of both existing and new concrete components in an existing building. The report was developed based on the format and content of ASCE/SEI 41-06, Chapter 6.0, "Concrete," and is intended to be used with the analysis procedures and Rehabilitation Objectives established in ASCE/SEI 41-06 for the Systematic Rehabilitation Method. The guide provides recommendations for condition assessment of in-place materials and components as it relates to seismic rehabilitation.

ACI 437R-03 Strength Evaluation of Existing Concrete Buildings: This is a report prepared by ACI Committee 437. Its scope includes recommendations to establish the loads that can be sustained safely by the structural elements of an existing concrete building. The report covers conventionally reinforced cast-in-place concrete, precast-prestressed concrete, and post-tensioned concrete.

ACI 437-12 Code Requirements for Load Testing of Existing Concrete Structures (ACI 437) and Commentary: The purpose of this Code is to establish the minimum requirements for the test load magnitudes, load test procedures, and acceptance criteria applied to existing concrete structures as part of an evaluation of safety and serviceability.

ACI 562-12 Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Buildings and Commentary, an ACI provisional standard: This report provides the minimum requirements for the evaluation, repair, rehabilitation, and strengthening of existing concrete buildings and, where applicable, in non-building structures. Both prescriptive and performance requirements are discussed. Load combinations, evaluation and analysis, design of repairs, durability, construction, and quality assurance are addressed.

***ASCE 11-99 Guideline for Structural Condition Assessment of Existing Buildings*:** This Standard (an update of ASCE 11-90) provides the design community with guidelines for assessing the structural conditions of existing buildings constructed of combinations of material, including concrete. This volume contains of an overview of preliminary and detailed assessment procedures, materials properties and test methods, and evaluation procedures for various physical conditions of the structure.

ASCE 41-2006 Seismic Rehabilitation of Existing Structures" and ASCE 31-200 Seismic Evaluation of Existing Structures: The upcoming edition of ASCE 41 (2013) is a combination of current ASCE 31 and ASCE 41. The new standard includes both evaluation and rehabilitation methods for existing reinforced concrete and other structures. The standard makes recommendations for data collection, analysis procedures, rehabilitation strategies for different performance levels including "operational" and "collapse prevention." It includes detailed materials testing requirements for existing structures.

ICRI Guideline No. 210.3-2004 (formerly 03739): Guide to Using In-Situ Tensile Pull-Off Tests to Evaluate Bond of Concrete Surface Materials: This report addresses the important issue of testing to confirm that adequate bond strength has been achieved between the repair materials and underlying substrate. Basically, a small corehole is drilled through the repair materials and a bit into the underlying concrete substrate. A plate is then bonded to the repair material and a pull-off bond test is conducted. This guideline is currently being revised and should be updated in 2013.

ASTM C1583 / C1583M - 04e1 Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull off Method): This test method will provide the information to conduct the test. It was developed for both laboratory and field testing of concrete.

4.2.2 What needs to be changed?

The provisions of ACI 364.1R-07 and ACI 201.1R -08 provide a suitable start for the condition assessment for concrete structures at nuclear facilities. While some of the provisions may be applicable to certain portions of nuclear power plants, other portions of the facility would fall outside the scope of the above documents. Overall, a comprehensive document that combines the relevant portions of each of the above listed documents should be developed and tailored to nuclear power plant facilities.

ACI 349.3R-02 (reapproved 2010) Evaluation of Existing Nuclear Safety-Related Concrete Structures: This document may be used in combination with the above referenced documents to create a document which may be used for assessment of a nuclear power plant facility. Specifically, concrete containment vessels (ACI 359) are not addressed. The document concentrates on damage mechanisms resulting from the as-built environment. Although degradation as a result of external loading is addressed, discussion should be expanded. This document may also be modified to include the use of load testing as an evaluation technique.

4.2.3 Why does it need to be changed?

A comprehensive document for the condition assessment of nuclear power plant facilities is required to address the level of safety and associated durability requirements at nuclear power plant facilities, including provisions for seismic considerations. Specific conditions associated with designated “safe” structures, such as the external containment and spent fuel pools, should be addressed. Rationale: ACI 364.1R-07 and ACI 201.1R -08 could be combined and modified with the appropriate level of detail required for nuclear structures.

ACI 349.3R-02 (reapproved 2010), Evaluation of Existing Nuclear Safety-Related Concrete Structures: This document comprehensively addresses all safety-related portions of a nuclear power plant or Department of Energy facility and provides details regarding the evaluation specific to each portion of the structure (i.e., visual inspections and details where invasive or destructive testing should or should not be used for evaluation). The evaluation criteria set forth in the document may be modified to apply to other select structures within the facility. A revision of this document is expected to be issued for use in 2013/2014. Given that the source of this document is from the code-writing body for the design and construction of concrete safety-related structures, it is highly recommended for use in any NPP or DOE facility repair process.

4.3. Visual Inspection

4.3.1 Status today

ACI 201.1R-08 Guide for Conducting a Visual Inspection of Concrete in Service: This guide is summarized above in *Condition Survey and Documentation*.

ACI 201.2R-08 Guide to Durable Concrete**:** This report elaborates on factors related to durability of concrete. Durability of hydraulic-cement concrete is determined by its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration. Durable concrete will retain its original form, quality, and serviceability when exposed to its environment. Properly designed, proportioned, placed, finished, tested, inspected, and cured concrete is capable of providing decades of service with little or no maintenance.

This document describes various deterioration mechanisms as chemical, physical, or mechanical in nature, which originate from external or internal sources. Chemical and physical attacking mechanisms often work synergistically. Depending on the nature of attack, distress may be concentrated in the cement paste, aggregate, or reinforcing components of the concrete (or a combination thereof).

Various factors influence durability. Consideration should be given to the climate and particularly microclimate, to which the specific structural element is exposed. To provide durable concrete, the specific demands on the concrete in its intended use should be given careful consideration. Required service life, design requirements, and expected exposure environments (macro and micro) should be considered before selecting appropriate concrete mixture.

ACI 201 has various sections dedicated to 1) properties of concrete, 2) freezing and thawing, 3) alkali-aggregate reaction (AAR), 4) aggressive chemical exposure, 5) corrosion of metals, and 6) abrasion. The fire resistance of concrete and cracking are not addressed in detail, because they are covered in ACI 216.1, 224R, and 224.1R, respectively. ACI also has a special publication related to durable concrete, ACI 201.2R-3.

4.3.2 What needs to be changed?

Changes are needed to make the ACI guides mentioned in Section 4.3.1 more specific to the environments and conditions expected to be encountered for nuclear facilities. These include heat, radiation, and potentially limited access to exposed surfaces.

4.3.3 Why it needs to be changed?

These ACI guides mentioned in Section 4.3.1 were developed with buildings and bridges in mind; thus, they need to be adapted for the environment of a nuclear power plant.

4.4. Exploratory Evaluation

For this section, the recommendations will be provided for each document.

ACI 437R-03 Strength Evaluation of Existing Concrete Buildings has been generally summarized above. This document provides guidance for the preliminary investigation. Review of the existing information is discussed, including construction materials, construction records, and service history. Guidelines for visual inspection as well as in-place tests for concrete strength are discussed (see also ACI 228.1R-03). In-place tests for locating reinforcing steel are described, along with tests for identification of internal abnormalities. Guidance is provided on the sampling of concrete including statistically based techniques. Discussion of petrography and chemical methods are included, with an emphasis on chloride concentration and depth of carbonation (ACI 222R). Regarding steel reinforcement, the determination of yield strength is addressed, and a table with reinforcing bar specifications and properties from 1911 to the present is provided. The report provides guidance for selection of the proper method of evaluation. Supplementing of the evaluation through load testing is also addressed (see section on load testing below).

> ***What needs to be changed?*** While not intended for nuclear structures, much of the guidance provided in this report is of a general nature, and therefore applicable to nuclear structures. However, the specific aspects related to nuclear structures, including very thick concrete cover and thickness, temperature differentials, and radiation effects require additional care in the evaluation. Coring, evaluation of the reinforcing steel, and in-place methods for concrete strength determination that result in cracking or spalling need to be restricted to locations where cracking is allowable. The section of the report related to load testing is not applicable to nuclear structures and other structures of special design; therefore, specific load testing methods and acceptance criteria must be developed.

Why does it need to be changed? Many of the methods described in this report are destructive or semi-destructive in nature. One example is the load testing method and loading magnitude/protocol, which may result in significant cracking for many structures. Therefore, consideration must be given to the special serviceability considerations for nuclear structures.

ASTM C42-12 S***tandard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete:*** This test method provides guidelines on testing for the compressive strength of the in place concrete.

What needs to be changed? The test methods themselves are appropriate. But, consideration should be given to the taking of cores and sawed beams from nuclear facilities. Thus guidelines should be drafted
Why does it need to be changed? It is essential for a repair to know where and how to safely table cores in a nuclear power plant.

ACI 228.1R-03 In-Place Methods to Estimate Concrete Strength has been generally summarized above. Guidance is provided on nondestructive strength prediction, combined with the destructive sampling and strength correlations with NDT results for concrete strength, including statistically based techniques. ACI 228.2R-98: "Nondestructive Test Methods for Evaluation of Concrete in Structures" has also been summarized above. A number of methods can nondestructively characterize and even image internal concrete conditions to determine the extent of internal flaws and cracking damage, as well as reinforcement, including radiography (2-D X-ray and 3-D radiography), ultrasonic/sonic tomography, 2-D/3-D ground penetrating radar, impact echo, ultrasonic shear wave pulse echo, and spectral analysis of surface waves, magnetic, and other methods. With a particular regard to exploratory evaluation, this document provides guidance for the preliminary to detailed investigation. In-place tests for locating reinforcing steel are described, along with tests for identification of internal damage/flaws. A related application-oriented guideline that references the more detailed ACI 228 documents is ICRI Technical Guideline 210.4-2009, "Guide for Nondestructive Evaluation Methods for Condition Assessment, Repair, and Performance Monitoring of Concrete Structures." This document provides assistance in understanding which specific conditions related to the condition assessment of a structure can be suitably evaluated using various NDE methods with example uses as follows:

- Prediction of in-place concrete strength (relative strength comparison, unless correlated with laboratory strength tests, e.g., core compressive strength tests);
- Location and extent of delamination due to reinforcement corrosion;
- Location, size, and distribution of reinforcement bars;
- Location and extent of concrete cracking;
- Severity, location, and extent of fire and frost damage;
- Location and extent of void honeycombing;
- Determination of concrete thicknesses; and
- Evaluation of reinforcement corrosion activity and rate.

Per the document, "This guideline offers assistance in selecting appropriate NDE methods to determine the properties and/or conditions of concrete prior to repairs (diagnosis), for quality assurance (QA) and quality control (QC) during repairs, and for long-term performance monitoring of repaired structures."

What needs to be changed? While not intended for nuclear structures, much of the guidance provided in this report is of a general nature, and is therefore applicable to nuclear structures. However, the specific aspects related to nuclear structures, including very thick concrete cover and thickness, temperature differentials, and radiation effects, require additional care in the evaluation. Coring, evaluation of the reinforcing steel, and in-place methods for concrete strength determination that result in cracking or spalling need to be restricted to locations where cracking is allowable. The section of the report related to load testing is not applicable to nuclear structures and other structures of special design; therefore, specific load testing methods and acceptance criteria must be developed. The correlation interpretation of NDT results is where the bulk of additional investigation is needed. The guidelines listed provide good references for conducting the tests, but not for the interpretation. Experience with NPPs has shown that there are vastly different requirements of different entities for the development of "ground truth" data, interpretation, and use of NDT data. Reviewers of this data in the nuclear environment have a very difficult time dealing with the uncertainties and imprecision of NDT. A key industry need is guidance for the level of correlation interpretation needed.

Why does it need to be changed? Many of the methods described in this report are destructive or semi-destructive in nature. One example is the load testing method and loading magnitude/protocol, which may result in significant cracking for many structures. Therefore, consideration must be given to the special serviceability considerations for nuclear structures.

4.5. Laboratory Testing

4.5.1 Petrographic analysis

ASTM C 856-11 Standard Practice for Petrographic Examination of Hardened Concrete: *This report* outlines the standard procedures for performing petrographic examination of hardened concrete samples made of hydraulic cement concrete, grout, plaster, stucco, terrazzo, and mortar specimens that have been exposed in natural environments or simulated service conditions, or subjected to laboratory tests. This Standard can be used to microscopically analyze concrete cores obtained from nuclear facilities.

Objectives of the test: The primary objectives of the petrographic services are as follows:

1) Determine constituents of concrete including presence of mineral admixtures such as fly ash,
2) Determine the condition of concrete, cement hydration, estimated water-to-cement ratio, construction techniques, presence of surface coatings and dry-shakes, depth of carbonation, and other general properties of concrete,
3) Determine the cause and degree of deterioration in concrete, and
4) Determine degree of deterioration due to ASR, alkali-carbonate reaction, sulfate attack, fire, and other harmful environmental exposures.

What needs to be changed? No changes needed.

4.5.2 Transport properties

4.5.2.1 Status today

ACI-318-11 Building Code Requirements for Structural Concrete and Commentary lists the chloride limits in concrete in Table R4.3.1. It should be emphasized that the chloride limits, sulfate limits, and other requirements given in ACI 318 are construction limits that are set conservatively high to avoid any problems. They are not thresholds for reactivity or distress. This is a very important key factor that might need more research.

ASTM C1152-06 (2012) Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete is designed to analyze the acid- soluble chloride content (total chloride) in concrete.

ASTM C1218-99 (2008) Standard Test Method for Water-Soluble Chloride in Mortar and Concrete is designed to analyze the water-soluble chloride content in concrete.

ASTM C1543-10a Standard Test Method for Determining the Penetration of Chloride Ion into Concrete by Ponding: This test method is designed to determine the penetration depth of chloride by analyzing the chloride content at different depths of concrete specimens that have been ponded with sodium chloride solution. It is a direct measurement of chloride penetration.

ASTM C1202-12 Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration: This is a relatively rapid and cost-effective test to provide an indication of the concrete permeability, but the test may overstate the differences between low-permeability concretes, especially when admixtures or pozzolans that alter the concentration of the charge-carrying ions within the concrete.

ASTM C876-09 Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete: This is a test method for establishing the probability of corrosion of in-place steel. The methodology relies on half-cell determinations carried out by locally exposing embedded steel and then systematically mapping the local corrosion potentials. This is typically done by laying out a 12" by 12" grid on a concrete surface for which there is concern regarding the corrosion of the embedded steel below that surface. This test is directly applicable to nuclear structures. More sophisticated tests such as Linear Polarization Resistance, Galvanostatic Pulse, and Electrical Impedance Spectroscopy can be used to estimate corrosion rates of reinforcement and electrical resistivity measurements can indicate areas of low resistance with increasing likelihood of corrosion (see ACI 228.2R-12 pending revision).ASTM C-876 provides an indication of whether corrosion is or is not likely to be present. A corrosion rate is not provided through this test method. Corrosion rate information is needed to assess the degree of mass loss in the reinforcing steel.

4.5.2.2 Summary of changes needed for transport properties

What needs to be changed? Most of the tests are adequate, but 1) better determination of the safety limits (ACI 318) should be investigated further and 2) recognition of the newer nondestructive testing and evaluation methods for condition assessment of concrete, QA/QC and monitoring of repairs. The requirement for direct correlation to observations and testing must be emphasized. The strength of NDT lies in its use as a multiplier of existing information. If used in a vacuum or with insufficient correlation, it is of limited value. Thus, further research for correlation should be developed; 3) Method to improve ASTM C876 to include corrosion rates would allow better prediction of service life

Why does it need to be changed? The newer non-destructive test will provide a better evaluation of the condition assessment of concrete.

4.5.3 Carbonation

Status today: The risk of steel reinforcement corrosion in concrete is increased when the concrete cover is carbonated. The depth of concrete cover and the depth of carbonation should be measured to determine the degree of protection of the reinforcement. The most commonly used method of measuring carbonation depth is by using the phenolphthalein indicator (EN 14630). Above a pH value of approximately 9, the indicator gives the concrete a purple color. Only concrete which is purple in color is alkaline enough to passively maintain the steel reinforcement. Another more precise but cumbersome method is based on petrographic techniques (ASTM C856, mentioned previously) by the observation of calcium carbonate. Concrete mixes with large amounts of additions (SF, GGBS, FA) have naturally lower pH values than OPC concretes. This, in addition to the darker color of some of these concretes, can influence the interpretation of the color indicator front.

> ***What needs to be changed?*** Possibly create an American standard equivalent to the EN 14630. Potentially study the use of alternative color indicators.
>
> ***Why does it need to be changed?*** Assure identical approach/procedure for carbonation depth measurements.

4.6. Creep and Temperature Effects

For this section, the recommendations will be provided for each document.

ASTM C 512-02 Standard Test Method for Creep of Concrete in Compression outlines a test method for the determination of creep of molded concrete cylinders. The test method utilizes sustained loading and is limited to concrete with maximum aggregate size not exceeding two inches. *Significance and use:* The test method measures load-induced time dependent strain under a controlled environment. Suitable loading frames, test specimens (both loaded and control), storing conditions, and strain measuring devices are described. A logarithmic expression is utilized to approximate creep behavior for purposes of comparing different concretes. Ages of loading are described to address the test objective.

> ***What needs to be changed?*** The document is limited to determination of creep behavior of freshly cast specimens, and therefore is not directly applicable to the evaluation of existing structures unless the constituents of the existing materials as well as the curing conditions and loading conditions are well understood. The procedure should be specialized to the case of cores or other specimens that are taken from nuclear structures.

The two inch maximum aggregate size may also be limiting for nuclear structures in some cases.

Why does it need to be changed? For evaluation and repair, the procedure should be changed to address the use of cores or other specimens from nuclear structures, taking into account safety consideration.

ACI 209R-02 **Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures:** The report specifically states that it is not applicable to special structures including nuclear structures. The report provides for a simplified, deterministic method related to the prediction of creep and shrinkage effects in an environment that is generally isothermal and relatively uniform. Basic creep and drying creep are defined in the document, and the differences are discussed. Simplified equations for the prediction of concrete compressive strength, modulus of rupture, direct tensile strength, and secant modulus of elasticity as a function of time for different weight concretes are provided. The basic equations are based on "standard conditions" that address loading age, differential shrinkage, initial moist curing, ambient relative humidity, average thickness of the member, and volume-to-surface ratio. For "other than standard conditions," adjustment factors are provided. The report makes it clear that actual tests and service inspection data will be more accurate than the predictive equations provided.

What needs to be changed? The document is intended to provide general guidance, and specifically states that it is not applicable to nuclear structures. While a means for differential predictions is provided, the main focus of the document is on prediction of volumetric changes for new structures. The document itself makes it clear that statistical methods are needed to account for variability in the many factors affecting creep and shrinkage.

Why does it need to be changed? For evaluation of the structure prior to repair, the most meaningful approach to address creep will be testing of core samples. This case is not discussed within the document, and it is unlikely that the equations provided will be suitable. The uncertainty related to the constituent materials, age of loading, temperature history, and other effects (such as radiation) are not addressed within the report, and these should be considered for nuclear applications. A statistical approach to the predictions should also be pursued.

4.7. Chemical Attack

4.7.1 Alkali-Silica Reaction

Alkali-Silica Reaction (ASR) is a chemical reaction between the reactive aggregate particles and hydroxyl groups in the pore solution of the concrete that are charge-balanced by alkalis released from the cement hydration. The reactive aggregates are normally amorphous silica or cryptocrystalline or microcrystalline silica, including opal, trydmite, cristobolite, chalcydene, chert, strained quartz, and acidic volcanic rocks. The reaction produces an amorphous gel that swells upon absorption of moisture, resulting in expansion and cracking of concrete. For ASR to occur, three conditions must be present simultaneously: relatively high alkali content, reactive aggregate, and a moist environment**.**

4.7.1.1 Status today

In 2011, deterioration was discovered that was attributed to alkali-silica reaction (ASR)[22, 23] in some structures at the Seabrook Station, (Seabrook, NH, USA). The origin of the ASR degradation in that station or others is not clear, and appears to have been due to a combination of factors.

There are a number of standardized tests that are designed to test the potential reactivity of aggregate or a combination of aggregate and cementitious materials. There are also standard guides on how to mitigate ASR in new concrete construction and on how to monitor the progression and effect of the ASR in existing structures; however, there is no single approach that can be applied to any situation. Ideally, ASR should not occur at all by a proper selection of the aggregates and cementitious binder and environmental exposure during the design, construction and operation phase. Application to NPPs of knowledge obtained for the monitoring, evaluation, and response to ASR-affected bridges (FHWA, 2010[24], RILEM 2000[25]) are currently under review by the NRC. Research in this topic exists, but it has not reached a level that would allow the repair and prediction of service life. A combination of measurement techniques and models is necessary to be able to monitor the progression of any ASR and to predict the remaining service life before and after any repair. Protocols for the selection of repair materials and monitoring also need to be developed.

RILEM Technical Committee 219-ACS, Alkali Aggregate Reaction in concrete structures: performance testing and appraisal: The purpose of this technical committee is to enable engineers to design concrete structures that will not be susceptible to alkali reactions and, in the case of structures that are affected by such reactions, to enable the engineer to better appraise, manage, or repair the structure. Initially, the objectives of the TC, as described in their mission statement, were:

- developing test methodologies for the reliable accelerated performance testing for susceptibility to alkali reactions of particular concrete mixes (including those containing recycled aggregates) for use in concrete structures,
- reviewing computer models of the reaction, in order to prepare practical guidance for their effective and dependable application,
- producing guidance on the appraisal, management, and repair of concrete structures that are affected by alkali reactions, and
- to assist in ensuring a long service life of concrete structures, it will develop a test methodology for determining the long-term contribution of alkalis in certain aggregates to the alkali reaction in the concrete.

Work within the TC has resulted in the development of a performance test for alkali reactions in new concrete mixes, guidance on the management and repair of structures affected by AAR, assessment of the value of modeling in the study and management of structural deterioration

[22] NRC Information notice 2011020: http://pbadupws.nrc.gov/docs/ML1122/ML112241029.pdf

[23] http://www.ucsusa.org/assets/documents/nuclear_power/concrete-degradation.pdf

[24] FHWA-HIF-09-004. *Report on the Diagnosis, Prognosis, and Mitigation of Alkali-Silica Reaction (ASR) in Transportation Structures*. 2010

[25] Recommendations of RILEM TC 106-AAR: *Alkali aggregate reaction, Materials and Structures,* Vol 33, Issue 229, 2000, pp. 283 - 293

caused by AAR, the production of a petrographic atlas of reactive rock types, and the development of a way of assessing reactive alkalis in aggregates.

The TC intends to publish new RILEM[26] guidance on the appraisal, management and repair of concrete structures that are affected by alkali reactions. It will also publish new RILEM test methodologies for the project-specific performance testing of concrete mixes for use in concrete structures, to ensure non-susceptibility to alkali reactions and for determining the long-term contribution of alkalis in certain aggregates to the alkali reaction in the concrete. In fact, in the case of the development of a performance test, a comprehensive state-of-the-art-report has already been produced.

ASTM has a number of standard tests that are designed to test the potential reactivity of aggregates or aggregate/cementitious material combinations. A standard practice on reducing the risk of ASR in new construction is currently being developed. Similar practices or guides have been developed by FHWA and AASHTO. There is no standard guide on mitigation of ASR in existing concrete.

ASTM C227-10 Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar Bar Method): This test requires the preparation of mortar bars using aggregate, job cement, laboratory cement, or a combination of cement and pozzolans, and monitoring the length change of prepared mortar bars stored at 38±2°C and 100 percent relative humidity periodically. If the length change exceeds a predetermined value, the aggregate or the aggregate/cementitious materials combination is considered reactive. This test cannot be used reliably to determine the reactivity of aggregate or aggregate/cementitious material combinations. Limitations of the method have been noted[27].

***ASTM C289 Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method)*:** This test method is designed to determine the reactivity of an aggregate as indicated by the amount of reaction during 24 hours at 80°C between 1N sodium hydroxide solution and crushed aggregate that was retained between 150 (No. 100) and 300 µm (No. 50) sieves. It is a quick test, but not reliable for slow-reaction aggregates or aggregates containing carbonates. Therefore, this test is not recommended.

ASTM C295 Standard Guide for Petrographic Examination of Aggregates for Concrete: This method provides guidance on quantitatively determining the composition of a coarse or fine aggregate sample using petrographic examination, including the components that may be potentially reactive in concrete. When the petrographic examination indicates no potentially reactive component, the aggregate can be considered non-reactive; however, when the petrographic examination detects potentially reactive components, the actual reactivity of the

[26] RILEM TC 219-ACS-P: *Literature survey on performance testing* : FA 3.2 Service Life : SP 3.2.4 Alkali aggregate reactions. SINTEF research reports. SINTEF A21305. Lindgård Jan, et al., 2011 http://www.sintef.no/home/Publications/Publication/?pubid=SINTEF+A21305

[27] Sorrentino, D, Isabelle, H., Yves Clément, J., Ranc, R., *Limits of Application of the ASTM C 2274 Mortar Bar Test. Comparison with Two Other Standards on Alkali Aggregate Reactivity*, Concrete and Aggregates (CCA) / Volume 16, Issue 1 (June 1994)

aggregate should be tested using other standard test methods. Aggregates used in new construction should be examined petrographically to provide a baseline for future reference.

ASTM C441 Standard Test Method for Effectiveness of Pozzolans or Ground Blast Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction: This method is based on the determination of length change of mortar bars prepared using portland cement and pozzolans or slag and borosilicate glass, stored in the same condition as ASTM C227. This test is designed to assess the effectiveness of a cementitious system to mitigate ASR, not the potential reactivity of an aggregate or aggregate/cementitious materials combination. Because it is a derivative of ASTM C227, it inherits all the problems associated with ASTM C227. In addition, it does not use aggregates intended for use in the construction, but rather a highly reactive borosilicate glass. The composition and supply of the glass may change with time, thus rendering unreliable results. This method should not be used.

ASTM C1260 Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method): This method tests the potential reactivity of aggregate. It involves measuring the length change of mortar bars that have been prepared using portland cement and the aggregate in question and immersed in 1N NaOH solution at 80°C for fourteen days. This test is the most widely used ASR test in the industry, but the testing conditions are harsh and can generate some false positives. It is also known that some aggregates that have passed the test resulted in deleterious ASR in concrete[27]. Nevertheless, this is one of the better screening tests available.

ASTM C1293 Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction: This test is designed to test the potential ASR reactivity of aggregate or a combination of aggregate and cementitious materials by measuring the length change of concrete prisms, prepared using portland cement and the aggregate in question, or a combination of aggregate and cementitious materials, stored at 38°C (100°F) and 100 percent relative humidity for one year. NaOH is added to the mix to bring the Na2Oeq content up to 1.25 percent. This is the most realistic and reliable standardized test, and is therefore recommended.

ASTM C1567 Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method): This test is essentially the same as ASTM C1260, but is designed to test the mitigation effect of supplementary cementitious materials on the potential reactivity of aggregate and cementitious material combinations. It has both the benefits and drawbacks of ASTM C1260, and is widely used in the industry.

AASHTO PP65-11 Standard Practice for Determining the Reactivity of Concrete Aggregate and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction: This practice provides a guideline on how to determine the potential reactivity of aggregate. In the case of a potentially reactive aggregate, the practice indicates how to mitigate the reactivity by performing a combination of testing that includes ASTM C295, C1260, C1293, and C1567.

FHWA-RD-03-047-2003 Guidelines for the Use of Lithium to Mitigate or Prevent Alkali-Silica Reaction: This document provides a guideline on how to use lithium nitrate to mitigate

ASR in new concrete construction. However, recent ASR studies indicate that this method may not be an effective treatment for ASR, especially for repair of damaged concrete[28].

4.7.1.2 What needs to be changed?

There is not a single reliable or relatively quick laboratory test that can be used to determine the potential reactivity of an aggregate. Therefore, a guideline is needed in regard to determining the potential reactivity of an aggregate and how to mitigate the reactivity in concrete for a nuclear power plant. AASHTO PP65-11 is a guideline designed for highway construction or applicable to new materials (i.e. potentially for repair materials used in NPP). It needs to be modified to be consistent with the service environment of nuclear power plants.

The current RILEM TC 219-ACS is drawing to an end, but a new one will replace it to continue the work. Some of the key aspects that have been identified as requiring further research, and that are expected to be addressed with in the new TC are

- prevention: look at the influence of the composition of SCM in mitigation of AAR, and improving guidance and specifications;
- management of AAR affect structures: address structural effects and improve performance modeling; monitoring after repair to understand performance and efficiency, and prestressing effect of confined regions with AAR;
- mechanism: look at the source of alkalis from aggregates and SCM, and combined forms of degradation (i.e. DEF & AAR or freeze-thaw & AAR);
- test procedures: address need for longer-term information from exposure sites; increased emphasis on quantification of damage, and increase working on reference materials (i.e. petrographic atlas).

4.7.1.3 Why does it need to be changed?

Due to the unique service conditions of concrete for a nuclear power plant, a more conservative approach is needed to test and mitigate the ASR potential of aggregate and concrete.

4.7.2 Delayed Ettringite formation

Delayed ettringite formation (DEF) is an internal distress that may occur within the cement paste of the concrete. When the plastic concrete is exposed to temperatures above approximately 70ºC, due to either elevated temperatures during curing or heat of hydration, the concrete may become susceptible to DEF several years later. DEF is believed to occur due to the interruption of the normal formation of ettringite, a calcium aluminate sulfate hydrate, in the early hydration process of cement, normally resulting from elevated concrete temperatures. After the concrete is in service and exposed to moisture, chemical components will migrate to form ettringite crystals in the already hardened paste, resulting in paste expansion, which can manifest into cracking of the concrete. Characteristics of DEF distress typically include gap cracking around aggregate particles, clusters or “nests” of ettringite crystals in the paste, deposits of abundant secondary ettringite crystals in cracks and voids, and pattern cracking and expansion of the affected structure. The amount of ettringite formed, the degree of expansion, and the extent of cracking

[28] Folliard, K.J., Thomas, M.D.A., Ideker, J.H., East, B., and Fournier, B., (2008), *Case Studies of Treating ASR-Affected Structures with Lithium Nitrate*, Proceedings of the 13th International Conference on Alkali-Aggregate Reaction in Concrete, Trondheim, Norway, pp. 90-99

depend on the composition of the cement used in the concrete, the temperature regime, and service conditions.

Status today: There is no standard test or guidelines regarding DEF in concrete.

What needs to be changed? As no standards are currently in place, a new guideline needs to be developed.

Why does it need to be changed? A new guideline needs to be developed to deal with the DEF potential in concrete for nuclear power plant.

4.7.3 Other forms of chemical attack

There are other forms of chemical attack in concrete, such as chemical and physical sulfate attack; the latter is also known as salt crystallization. Chemical sulfate attack is well understood, but physical sulfate attack is not yet understood by industry. While there is broad understanding on how to prevent chemical sulfate attack in concrete, there are no standard guideline specifically designed for this issue. There are likewise no tests or guidelines for physical sulfate attack either.

Status today:*ACI-318-2011 Building Code Requirements for Structural Concrete and Commentary* lists different exposure conditions and the corresponding class in Table 4.2.1. Table 4.3.1 gives mix design requirement for different exposure conditions.

What needs to be changed? Tests or guidelines should be developed to address these forms of chemical attack in concrete as well as in concrete repair materials.

Why does it need to be changed? Tests or guidelines are needed for the more severe environment presented by nuclear structures.

4.8. Effect of Radiation

The effects of combined heat and radiation on concrete are not well understood. The conference paper[29] summarized below serves as a literature review on the subject.

4.8.1 Status Today

This is a conference proceeding related to the radiation levels and types of concrete used at Savannah River Site (SRS) reactor facilities. Comparisons with commercial nuclear reactor facilities are made. A review of the radiation levels that damage concrete is provided. Concrete in the biological shield surrounding the reactor and in the disassembly basins is discussed. The document discusses high density (with barite aggregate) and normal weight (with gravel aggregate) concretes used in the reactor shields.

[29] Acevedo C.E., Serrato M.G., *Determining the effect of Radiation on Aging Concrete Structures of Nuclear Reactors-10243*, WM2010 Conference, March 7-11, 2010, Phoenix AZ

The paper provides a literature review of previous studies indicating that radiation damages concrete, particularly when combined with high temperature (approximately 200 deg. C). Mechanisms include expansion of aggregates, shrinkage of the paste and micro-cracking. The paper references discussion regarding the cause of concrete damage with respect to high temperature or radiation. Radiation induced alkali-silica reaction is also discussed.

Degradation in the disassembly basins is discussed. The cause of the degradation is attributed to causes other than radiation. The study concludes that the effects of radiation are not detrimental to the biological shield at SRS as they are below the threshold values. However, reductions in compressive strength have been documented at other facilities.

4.8.2 What needs to be changed?

This paper is directly related to the facilities at Savannah River Site (SRS). The radiation levels at the site are different than those in commercial reactors, and the temperature range may also be different. The materials used for construction at SRS may also differ from those in commercial reactors. Increased research on the effect of radiation level as encountered in the nuclear power plants is paramount to ensure service life of the existing and repaired concrete.

4.8.3 Why it needs to be changed?

The lack of knowledge prevents decision making in the selection of materials for repair of concrete and understating of deterioration mechanisms.

4.9. Structural Analysis

4.9.1 Status today

10 CFR 50.55a- 2012, *Codes and Standards* specifies that structures, systems, and components of boiling and pressurized, water-cooled nuclear power reactors must be designed, fabricated, erected, constructed, tested, and inspected according to the requirements of the ASME Boiler and Pressure Vessel (B&PV) Code as amended by NRC Regulatory Guide 1.84, Design and Fabrication and Materials Code Case Acceptability. The ASME publishes a new edition of the B&PV Code, which includes Section III for nuclear power every three years, and new addenda every year. The latest editions and addenda of Section III that have been approved for use by the NRC are referenced in 10 CFR 50.55a(b). The ASME also publishes Code Cases quarterly. Code Cases provide alternatives developed and approved by ASME or explain the intent of existing code requirements. Regulatory Guide 1.84 identifies the Code Cases that have been determined by the NRC to be acceptable alternatives to applicable parts of Section III.

Division 2 (comprised of Subsection CC) of Section III "establishes rules for material, design, fabrication, construction, examination, testing, marking, stamping, and preparation or reports for prestressed and reinforced containments." The containments covered by Subsection CC include the "structural concrete pressure resisting shells and shell components, shell metallic liners and the penetrations liners extending the containment liner through the surrounding shell concrete." Subsection CC applies for containments having a design pressure greater than 5 psi (35 kPa). For "parts and appurtenances of concrete containments not backed by structural concrete for load carrying purposes, the rules of Division 1 apply." Section III, Division 2 was prepared and is maintained by the Joint ACI-ASME Technical Committee on Concrete Components for Nuclear Service under the sponsorship of the American Concrete Institute and the American Society of Mechanical Engineers. This standard is also designated as ACI 359, Concrete Components for Nuclear Reactors.

4.9.2 What needs to be changed?

These nuclear-specific standards and their non-nuclear counterparts provide some fundamental guidance as to minimum requirements for analysis of concrete structures. In particular, for example, the standard concrete structure building code, ACI 318 gives minimum analysis guidelines and standard design formulae in Chapter 8, and provides guidance for Strut & Tie Modeling in Appendix A. However, none of these codes or standards provide guidance for analysis of repaired structures. Therefore, there remain particular concerns for analyzing repaired structures, both before (assessing vulnerability) and after the repair (assessing effectiveness).

<u>For assessing vulnerability</u>

- What material properties should be assigned to cracked, eroded, or chemically damaged concrete?
- What material, section, and bond properties should be assigned to corroded reinforcing bar, or reinforcing bar located in damaged, partially spalled concrete?
- In particular, for example, the standard concrete structure building code, ACI 318 gives minimum analysis guidelines and standard design formulae in Chapter 8, and provides guidance for Strut & Tie Modeling in Appendix A, and for design and analysis of anchorage in Appendix D. However, none of these codes or standards provide guidance for analysis of deteriorated materials, anchorage in damaged concrete, or repaired structures. Therefore, there remain particular concerns for analyzing repaired structures both before (assessing vulnerability and determining the need for and timing of any repairs) and after the repair (assessing effectiveness).

<u>For assessing repair effectiveness</u>

- There should be a guideline requiring repair designers/analysts to address the existing stress states of the repaired and new material to evaluate effectiveness, and evaluate the structure in the repaired condition.
- Analysis should show that repair material will actually be engaged by the existing structure to help carry future loads. What is the load transfer mechanism? If the pre-repaired structure is not unloaded prior to repair, does the repair material see any stress?
- Will the interface between new and old material perform as well as in a new design (which is the usual assumption in analysis)?

The other primary NPP design and analysis guidance document is NUREG-800, the Standard Review Plan. The SRP also invokes NRC regulatory guides and reports for details on various subjects. For example, a report with very detailed finite element analysis guidelines for concrete containments is referenced in the SRP discussion of severe accident analysis, namely, NUREG/CR-6906. To our knowledge, no specific guidance is given in the aforementioned ASME, ACI, or NUREG codes and guides addressing analysis issues which are unique to repaired concrete structures.

4.9.3 Why does it need to be changed?

The behavior of deteriorated structures and repaired structures differs significantly from that of new structures. The current provisions are lacking in terms of guidelines for modeling and structural analysis of deteriorated and repaired structures.

4.10. Load testing

4.10.1 Status today

Nondestructive load testing of reinforced concrete building (and other structures) is addressed in three documents published by ACI. A brief summary of each document is provided below.

ACI 318-2011 Building Code Requirements for Structural Concrete and Commentary is a "code" level document that covers the materials, design, and construction of structural concrete used in buildings and other structures. In Chapter 20, this document also addresses the strength evaluation of existing concrete structures. In Chapter 20, the load level, loading methodology, and the acceptance criteria for nondestructive load testing are addressed.

ACI 437R-03 Strength Evaluation of Existing Concrete Buildings is a report prepared by ACI Committee 437. The scope includes recommendations to establish the loads that can be sustained safely by the structural elements of an existing concrete building. The report covers conventionally reinforced cast-in-place concrete, precast-prestressed concrete, and post-tensioned concrete. It also covers several topics related to evaluation of concrete structures, including guidance for the preliminary investigation; methods for materials evaluation, including both concrete and reinforcing steel; assessment of loading conditions and selection of an appropriate evaluation method; and the evaluation itself. The appendix of the report addresses an alternate load testing methodology, referred to as the "cyclic load test," to the 24-hour load test method described in ACI 318, Chapter 20.

ACI 437.1R-07Load Tests of Concrete Structures: Methods, Magnitude, Protocols, and Acceptance Criteria is also a report prepared by ACI Committee 437. The report summarizes the recommendations of the committee with focus on the level of load to be applied to during the load test procedure. The report was prepared in response to the changes that took place in ACI 318 in relation to a generalized reduction in the load factors for design of reinforced concrete building. The committee prepared the report to clarify the origins of the load levels described in ACI 318, Chapter 20 and to recommend revised loading levels during load testing to be more consistent with the revisions to ACI 318 load factors. The report addresses the history of load testing, load factors, the load test protocol, including the 24 hour and cyclic load test methods, and acceptance criteria.

ACI 437-12 *Code Requirements for Load Testing of Existing Concrete Structures and Commentary* The purpose of this Code is to establish the minimum requirements for the test load magnitudes, load test procedures, and acceptance criteria applied to existing concrete structures as part of an evaluation of safety and serviceability, to determine whether an existing structure requires repair and rehabilitation, and to verify the adequacy of repair and rehabilitation measures applied to an existing structure, or to provide for public health and safety.

ACI 562-12, *Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Buildings and Commentary* specifically references ACI 437-12 for the conduct of a load test instead of ACI 318-11. Ultimately, 318 Ch. 20 should cover only new construction, while 437 should cover existing construction.

4.10.2 What needs to be changed?

Considerable disagreement exists between ACI 318-2011, the two ACI 437 reports, and the recent standard in regard to several critical items. The ACI Committee reports and standard address the cyclic load test methodology while the ACI 318 document makes no mention of this approach. The history of the development of the ACI 318 load test methodology and acceptance criteria as described in ACI 437R.1-07 calls into question the applicability of the 24-hour load test method and associated acceptance criteria for modern construction methods. Furthermore, the load levels between the ACI 437 and ACI 318 documents differ. While some of the provisions may be applicable to certain portions of nuclear power plants, other portions of the facility would fall well outside the experience base of the methods described.

4.10.3 Why does it need to be changed?

The load level and the associated acceptance criteria need to be changed. Rational: post-tensioned and prestressed elements would be severely damaged (excessive cracking) if the load test methods and load levels described in the ACI documents were applied. Passively reinforced elements would be similarly affected. This would be of concern in portions of the structure where cracking is to be avoided, such as the external containment and spent fuel pools.

4.11. Guidelines for Assessment of Remaining Service Life

4.11.1 Status today

A review of the state-of-the-art of service life prediction theory and practice for concrete structures is provided in ACI 365.1R-00, "Service-Life Prediction – State-of-the-Art Report," prepared by ACI Committee 365. The document presents a detailed review of service life criteria, factors that affect service life, condition assessment techniques, economic considerations, and service-life prediction methods. Additionally, the report presents six examples of the application of service-life prediction methods to real structures, including four case studies dealing with corrosion of reinforcement, one case in which the combined effects of corrosion and carbonation are considered, and one case that includes corrosion, carbonation, and load effects. An example of reliability analysis of two hypothetical structures is also described.

4.11.2 What needs to be changed?

ACI 365.1R-00 provides end-of-service life criteria for general concrete structures, but it does not address any particular aspects that apply only to nuclear structures. End-of-service criteria for nuclear structures should be established in terms of the types of attack that have more influence on their deterioration. Mathematical modeling of deterioration based on physical principles is often limited to prediction of the time it takes for chlorides to reach a threshold concentration that triggers active corrosion of reinforcement. Other processes must be considered in the models for more reliable predictions and to include damage mechanisms that are more critical. Furthermore, prediction models, whether physics-based or empirical, require onsite measurements at different ages for model parameters to be updated with respect to the current condition of the structure. The literature search unveiled that there are not many comprehensive studies in the area of modeling of deterioration or service life prediction; thus, such a review should be developed. Relations between model parameters and nondestructive evaluation measurements need to be developed. Service life prediction models based on non-destructive evaluation parameters should be developed as well.

4.11.3 Why does it need to be changed?

End-of-service life criterion needs to specialize for nuclear applications. Criteria for conventional concrete structures, such as chloride threshold attainment or cover spalling, are not suitable because chemical attack by agents other than chlorides may be more critical. Moreover, significantly lower levels of cover deterioration can be tolerated in nuclear containments. For the same reason, mathematical models for service life prediction should include not only chloride ingress, but also oxygen diffusion, moisture transport, electrical potential distribution, corrosion kinetics, heat transfer, and carbonation rates, as well as interaction of these processes. Such an approach has been studied by MacDonald et al.[30] in the context of nuclear applications, and by Isgor and Razaqpur[31] for general reinforced concrete applications. Updating service life prediction models requires in-situ data from the structure, which has to be based on destructive or non-destructive testing depending on what parameters are required for the model. Relations between these parameters and non-destructive measurements need to be developed because areas exposed to aggressive agents may be inaccessible for sampling. Furthermore, sample retrieval may cause prohibitive distress to the structure. Empirical models based solely on non-destructive measurements are desirable because they would provide a tool that would be based on actual experimental data with minimum disturbance of the structure.

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[30] MacDonald, D.D., Urquidi-MacDonald, M., Engelhardt, G.R., Azizi, O., Saleh, A., Almazooqi, A., Rosas-Camacho,O., *Some important issues in electrochemistry of carbon steel in simulated concrete pore water Part 1 – theoretical issues,* Corrosion Engineering Science and Technology 46(2), 98-103, 2011

[31] Isgor, O.B., Razaqpur, A.G., *Advanced modeling of concrete deterioration due to reinforcement corrosion,* Can. J. Civ. Eng. 33, 707-718, 2006.

Chapter 5 CONCRETE REPAIR STRATEGY AND DESIGN

5.1. Overview

This chapter section is focused on development of structural concrete repair design. The design of concrete repairs requires good understanding of the root cause problems and the remaining service life of specific concrete elements. The understanding of the protection/repair conditions allows the qualified professional to select repair options that may meet the required structural demands, service life, and first/life cycle costs. Some of these practices are described in codes, standards, specifications, and guides.

5.1.1 Owner expectations and constraints

Desired Life of Repair: The service life of a repair must be established in the program goals that the owner has defined for the nuclear power plant. The nuclear power plants currently in operation in the United States went on-line at different times, are aging, and are at different points in their service life. Many of these plants are nearing the end of their current licensing period. The owners of these power plants are faced with re-licensing, and have to decide whether to petition for a 20-, 40-, or 60-year licensing period.

Schedule Issues of the Repairs: The contractor must be allotted time in the schedule to allow for design, quality control, procurement, and implementation of repairs to the concrete elements. It is desirable for repairs for re-licensing to be planned for well in advance and carried out during times of plant shut-down for maintenance. The case may be that some repairs will have to be performed when the plant is operating, and will have to be completed while causing the least amount of disruption to the plant operations. Contingency time must also be allotted for in the schedule for unforeseen conditions. A process must also be implemented that will allow for unforeseen conditions to be dealt with in the schedule.

Specific Exposure conditions in Service and during Shutdown: Repair materials can be exposed to the following conditions while in service: carbonation, chemical, heat, humidity, moisture, steam impingement, cyclic freezing and thawing, cavitation, abrasion, erosion, leaching, sulfates, phosphate ions, cement-aggregate reaction, fatigue, irradiation, external loads, dead loads, live loads, volume change, and gas or liquid pressure. Prolonged exposure to high levels of radiation can cause a loss of tensile strength, compressive strength, and modulus of elasticity (NUREG/CR – 6927). The radiation is absorbed by the concrete and it is turned into heat.

Repair Economics: The owner is faced with deciding the longevity of the repairs that are made to the concrete in the nuclear power plant. The owner balances the first cost of a repair versus the service life provided by the materials used in the repair. The owner can choose to spend more up front in the repair, which should provide a longer service life, versus spending less on the first cost of the repair, but with the likelihood that the repair will have to be maintained at more frequent intervals in the future. The environment to which a repair is exposed will impact the cost of the repair. The service life design can impact the cost of the repair, as different measures can be used to achieve the same service life for the repair. Therefore, different materials may be used for different repairs depending on the environment to which the repair is exposed and the structural capacity requirements.

5.2. Strategic Design Considerations

5.2.1 Status today

Complete Exposure Conditions and Boundary Conditions of Repair Area: The design professional must understand the exposure conditions (freeze/thaw, sulfates, chlorides, heat, irradiation, etc.) to which a repair is exposed, so that the required service life of the repair can be predicted. The concrete element to be repaired may have different exposure conditions, depending on its location in the nuclear power plant, and, therefore, may require different measures to achieve the required service life. The design professional must also understand the boundary conditions that the concrete element imposes on the repair area, as they can impact the service life and structural design of the repair. For example, the repair may be rigidly locked into the surrounding concrete structure, and, therefore, the repair material is restrained from shrinking during curing.

Reconcile Condition Evaluation/Assessment to Owner Performance Expectations: The design engineer must perform an assessment to determine the magnitude of the degradation that specific concrete elements in the nuclear power plant have experienced (reference Chapter 4). The use of nondestructive testing techniques is desirable in the assessment, but destructive testing may be required to understand the degradation that is manifesting below the surface of the concrete. Assessment will lead to identifying areas where repairs to the concrete will be required in the nuclear power plant. Repair to a concrete element must bring it back to a level of performance/life expectancy required to safely operate the nuclear power plant. The owner will have to balance repairs dictated by the outcome of the assessment versus the first cost of the required repair and the service life of the repair. The degradation discovered in the assessment may dictate a repair that should be performed in a plant shut down for maintenance, but the owner may want to perform the repair while the plant is operating. The design and service life of the repair itself may be dependent on the time frame that the repair to the concrete can be completed.

Structural: Concrete structures in nuclear power plants generally have substantial safety margins. The design professional will have to perform assessments to establish available margins of safety of degraded structures. Repairs must be designed for the loads/service conditions to which they will be exposed, such as dead loads, live loads, wind loads, seismic loads, gas and liquid pressure, heat, and irradiation. There may be different performance expectations for structural concrete elements in the nuclear power plant, depending on whether it is in a primary containment, internal containment, or secondary containment structures. The design professional will have to gain an understanding of the behavior of the concrete structure(s) from a global perspective, before the behavior of the localized area of the structure where a repair is located can be understood.

Loads (dead, live, creep, thermal, wind, seismic), along with the environment that will cause future degradation, will have to be applied to a concrete structure to determine the forces for which a repair will have to be designed. A model of the localized repair area may have to be run in order account for the interaction of the behavior of the original concrete and repair materials, using the forces from the global structural analysis. A refined model using a greater number of finite elements may be required to consider the thickness of walls and/or the complexity of a localized repair area. The model will have to account for the potential degradation of the concrete by irradiation by softening the modulus of elasticity and lowering the compressive and tensile strength of the concrete.

Consideration will also have to be given in the structural models regarding the load path of forces in the repair area and the sequence of loading the repair area when completed. Consideration may have to be given with respect to the structure requiring temporary shoring to remove or redistribute stress from the structure, so that the repair area will resist stress proportional to its stiffness when the shoring is removed and force is re-applied.

Durability: It is critical that the service life of repairs to concrete can be predicted for the licensing effort, as well as for repairs that are required to keep a nuclear power plant safely operating. The design professional will have to work closely with a materials engineer to arrive at a repair with a service life that meets the owner's and/or design professional's expectations.

Service life analysis is a useful tool to assess the remaining useful service life a structure, given the degradation mechanisms to which the concrete has been exposed. Service life analysis, along with nondestructive testing and visual inspection, can be used to determine if repairs are required to extend the service life of concrete elements. It will be necessary to perform testing in order to determine the transport properties (IDC, MTC, and porosity) of the existing concrete and the cover on the reinforcement, so that these properties and concrete cover data can be used in the analysis.

The service life of a repair can also be predicted using service life analysis when repairs to concrete elements are required. The service life design of a repair must consider the degradation mechanisms (carbonation, chemical, heat, humidity, moisture, steam impingement, freeze/thaw, cavitation, abrasion, erosion, leaching, sulfates, phosphate ions, cement-aggregate reaction, and irradiation) imposed by the environment to which it is exposed. It is unclear if irradiation affects the transport properties of concrete repair material, or concrete in general (NUREG/CR – 6927 and C. E. Acevedo and M. G. Serrato[29]). The repair materials must be designed to be compatible with the existing concrete. There may be different performance expectations for concrete elements in the nuclear power plant, depending on whether it is in primary containment, internal containment, or secondary containment structures. Different materials may be used for different repairs, to achieve the desired service life.

5.2.2 What needs to be changed?

Codes and standards need to address the environment to which the concrete in nuclear power plants is exposed and the service life design of repair materials.

Chapter 4 in ACI 318 addresses durability. The chapter lists four classes of exposure: Class F: freeze/thaw, Class S: sulfate, Class P: low permeability, and Class C: corrosion protection. The ACI 365 document targets the prediction of service life for new and existing structures, but does not target repair of concrete. A service life design model is required to be developed for repairs made to concrete in nuclear power plants. It is unclear if the exposure of the concrete to irradiation not only changes the mechanical properties of the concrete, but also changes the transport properties.

5.2.3 Why does it need to be changed?

Standards, such as ACI 318 and ACI 365, do not address if transport properties of concrete are adversely affected by irradiation or temperatures on the order 200 °C to 300 °C (NUREG/CR – 6927 and C. E. Acevedo and M. G. Serrato[29]). The degradation of concrete repair material with respect to irradiation must be understood so that the service life of the repair can be predicted. The service life of cracked concrete may also have to be considered in predicting service life. This is not meant to imply that all concrete structures in a nuclear plant are exposed to high levels of radiation and high temperatures. In fact, the majority of concrete structures experience radiation levels slightly greater than normal background radiation, and temperatures less than 100 °F.

5.3. Repair Design

5.3.1 Status today

Development of Repair Options: The design professional has considered the strategic issues, and must now provide solutions for protection or repair of structural concrete. The strategic issues may be structural, durability-related, or economic. With these strategic targets and an understanding of the structural concrete condition, the professional must design protection and repair plans to evaluate technically, logistically, and economically.

Properties of Available Materials Appropriate for Repair: The products and materials used in concrete repair should be appropriate and compatible for the purposes intended. The materials and products should be thoroughly tested and evaluated by industry standard testing protocols and specific quality and performance tests. The durability of the protection and repair technologies should be matched to the specific service life expectation of the owner and/or the design professional. Some products and materials should be tested for approval for use in nuclear facilities. Identifying suitable concrete repair materials involves comprehensive evaluation of the existing concrete, predicting service conditions and environmental exposure, anticipating the mechanical and durability requirements of the repair, and selecting appropriate construction means and methods. Compatibility between the repair material and existing substrate is a highly critical factor when developing repair systems. Important considerations when selecting compatible concrete repair materials include modulus of elasticity, volume stability over the anticipated range of moisture and temperature changes, creep coefficient, restrained and unrestrained shrinkage, strength, and permeability.

Meeting Scheduling Constraints: Selection of repair systems must include consideration of the facility schedule issues and windows of opportunity for repairs. Some repairs may be very effective; however, the tasks required to properly apply the repair technique may consume too much time. Conversely, if the window of opportunity for repair or protection is large, potentially better and longer-lasting technologies can be considered. Industry guidelines and manufacturer recommendations must be understood to properly apply the technologies in a timely manner. Adequate planning and scheduling of multiple concurrent operations is needed to ensure that an appropriate level of control is maintained throughout the course of the repair project. When establishing scheduling constraints, the size and complexity associated with the project are critical considerations.

Identifying Structural Analysis Needs: The issue of deteriorated concrete that has spalled or delaminated has redirected the existing loads to a new path in the reinforced concrete element. Typically, patching or protecting the structure will not reestablish structural load transfer back into the repair. Some repairs, such as carbon fiber strengthening, will add or replace structural strength performance.

Demolition of deteriorated concrete and reinforcing steel may have significant impact for the service capacity of the structure during repair, or influence the residual structural performance after the planned repair. The design professional should consider these important structural issues.

Most likely, each structure in the nuclear power plant will require a global structural analysis using software that can perform a 3D analysis. The analysis will have to be performed using shell or 3D solid elements. It is likely that 3D solid elements will have to be used, as the walls for the structures are thick. Global analysis can indicate the forces that repairs must resist. Analysis may need to be performed in areas where repairs are proposed, to determine how the repair interacts with the original structural concrete.

Design Repair of Components/Members using Applicable Codes: The repair design professional should use various codes, standards, and guidelines, in descending importance, to develop a sound repair plan for a project. There are many times that these codes and standards are easy to apply to a project. There are times, due to many complex issues (existing conditions, difficult/restrictive exposures, etc.), that the designer must use professional judgment to address the complex repair challenge. The industry has several guidelines by a few organizations, but these lack the authority of a code, and less so with the standards.

Consulting with Repair Contractors for Input on Design and Potential Alternatives (Optional): A contractor may be contacted to obtain pricing for material and labor. This pricing can be used in life cycle cost studies to aid the owner in making decisions regarding the first cost and long-term cost of proposed concrete repair options. Input from a contractor may also be very helpful for incorporating appropriate means and methods into the repair. Repairs that cannot be effectively constructed, or that require unnecessary difficulty, require more time and effort, and are more difficult to implement effectively than are repairs that are more easily implemented.

Conducting Service Life Analysis of Options: A service life analysis can be performed, given the environment or exposure conditions (freeze/thaw, sulfate, chloride, heat, chemical, etc.) in which the repair must perform. Several viable options can be considered and analyzed to determine which materials or combination of materials perform best and are the most economical to provide the required service life.

Conducting Life Cycle Cost Analysis of Options: Viable options can be considered and analyzed to determine which materials or combination of materials perform best. A life cycle cost analysis can be performed for these viable options to determine which repair is most economical when taking the service life into account.

5.3.2 What needs to be changed?

A majority of the ACI and ICRI documents were written targeting general building structures. ACI 546, Concrete Repair Guide presents information that would be applicable to the evaluation and repair of concrete in nuclear power plants, and ACI 365.1R-00, Service-life Prediction presents information that would be applicable to the service life design of components in nuclear power plants. Document ACI 349 deals with design related to thermal issues and safety evaluation of aging nuclear power plants. However, in general, the ACI and ICRI documentation do not speak specifically to the repair of concrete in specific portions of a nuclear power plant environment where high radiation and continuous time periods of elevated temperatures on the order of 200 °C to 300 °C may exist. (NUREG/CR - 6927 and C. E. Acevedo et al.[29]).

5.3.3 Why does it need to be changed?

A document specific to the completion of repairs in a nuclear power plant is required. While the majority of nuclear concrete structures experience nominal radiation levels, the environment in specific areas of a nuclear power plant may be harsher than those that were targeted in existing standards. Existing standards did not target repair materials that will be required to resist irradiation and elevated temperatures. A guide to educate designers on how to model or calculate load transfer through and around repairs of structural concrete is needed.

5.4. Document Review and Recommendations for Design of Concrete Repairs

***ACI 201.2R-08 Guide to Durable Concrete*:** The guide describes specific types of concrete deterioration. Each chapter contains a discussion of the mechanisms involved and the recommended requirements for individual components of concrete, quality considerations for concrete mixtures, construction procedures, and influences of the exposure environment, which are all important considerations to ensure concrete durability.

> ***What needs to be changed?*** ACI 201.2R-08 is completely based on exposure to “normal” ambient conditions. It does not directly deal with high sustained temperatures, pressures or radiation that may be experienced in nuclear plant facilities. However, the mechanisms of deterioration from a variety of other factors are presented and should be considered in design of repairs.
>
> ***Why does it need to be changed?*** ACI 201.2R-08 must deal more completely with the issue of high sustained temperature, pressures and radiation. It may be that a special supplement could be developed to deal directly with the nuclear exposure. It is not clear whether exposure to radiation has detrimental effects on concrete durability, but it should be researched and documented.

***ACI 222.3R-11 Guide to Design and Construction Practices to Mitigate Corrosion of Reinforcement in Concrete Structures*:** Corrosion of metals in concrete is a significant problem throughout the world. In many instances, corrosion can be avoided if proper attention is given to detailing, concrete materials and mixture proportions, and construction practices. The guide contains information on aspects of each of these. In addition, Chapter 5 of the guide contains recommendations for protecting in-service structures exposed to corrosive conditions. The guide is intended for designers, materials suppliers, contractors, and all others engaged in concrete construction.

> ***What needs to be changed?***The guide does deal with some components of nuclear power plants, such as cooling towers. Also, general guidelines for concrete detailing and mixture design could be applied to repair of nuclear power plant facilities. However, it does not directly address sustained elevated temperature or radiation effects.
>
> ***Why does it need to be changed?*** The guide should be updated with direct information on how sustained temperatures of 200 °C to 300 °C and sustained exposure to high levels of radiation affect corrosion.

ACI 318-11 Building Code Requirements for Structural Concrete and Commentary, ACI 349-06 Code Requirements for Nuclear Safety-Related Concrete Structures (ACI 349-06) and Commentary, and ACI 359-07 Code for Concrete Containments (Joint with ASME): ACI 318 covers the materials, design, and construction of structural concrete used in buildings and where applicable in non-building structures. The Code also covers the strength evaluation of existing concrete structures. ACI 318 Section 1.1.5 states "For unusual structures, such as arches, bins and silos, blast-resistant structures, and chimneys, provisions of this Code shall govern where applicable." The Commentary section R1.1.5 refers directly to ACI 349 for nuclear structures.

ACI 349-06 Code Requirements for Nuclear Safety-Related Concrete Structures (ACI 349-06) and Commentary: This publication covers the design and construction of concrete structures that form part of a nuclear power plant and that have nuclear safety-related functions, but it does not cover concrete reactor vessels and concrete containment structures (as defined by Joint ACI-ASME Committee 359). ACI 349 is formatted as a fully dependent Code based on ACI 318.

ACI 359 (ASME Boiler & Pressure Vessel Code Section III, Division 2, Code for Concrete Containments): This code specifies minimum analysis requirements and definitions of loads for concrete components for concrete reactor vessels and concrete containment structures.

> ***What needs to be changed?*** These three documents and their interactions were extensively reviewed by the original NESCC task group that produced the report "Concrete Codes and Standards for Nuclear Power Plants: Recommendations for Future Development (June 2011)." The recommendations in that report for modifications to design Codes would be applicable to the repair designs that would need to meet current Codes. None of the three directly address design of repairs with consideration of changing load paths and staged loading that may be experienced in repairs.
>
> ***Why does it need to be changed?*** The same rationale as in the original NESCC report is applicable for the design of the repair to meet Code. Additional information on consideration of load paths and load staging in repairs would be beneficial to the design community planning repairs to nuclear facilities.

ACI 355.2-07 Qualification of Post-Installed Mechanical Anchors in Concrete (ACI 355.2-07) and Commentary and ACI 355.4-10 Qualification of Post-Installed Adhesive Anchors in Concrete (ACI 355.4) and Commentary**:** ACI 355.2 prescribes testing programs and evaluation requirements for post-installed mechanical anchors intended for use in concrete under the design provisions of ACI 318. Criteria are prescribed for determining whether anchors are acceptable for use in uncracked concrete only, or in cracked as well as uncracked concrete. Performance categories for anchors are established, as are the criteria for assigning anchors to each category. The anchor performance categories are used by ACI 318 to assign capacity reduction factors and other design parameters.

ACI 355.4-11 Qualification of Post-Installed Adhesive Anchors in Concrete and Commentary: This publication prescribes testing programs and evaluation requirements for post-installed adhesive anchors intended for use in concrete under the design provisions of ACI 318. Testing and assessment criteria are provided for various conditions of use, including seismic loading; sustained loading; aggressive environments; reduced and elevated temperatures; and for determining whether anchors are acceptable for use in uncracked concrete only, or acceptable for service both in cracked and uncracked concrete. Criteria are provided for establishing the characteristic bond strength, reductions for adverse conditions, and the anchor category and associated job-site quality control requirements.

> ***What needs to be changed?*** Since the documents are based on use of ACI 318, they likely will have a similar impact on ACI 349. The use of anchors in nuclear facilities with very high temperatures, pressures and radiation are not directly addressed. Temperature exposure is not addressed at all in ACI 355.2-07. ACI 355.4 addresses acceptance criteria at elevated temperatures, but not likely the levels anticipated in specific areas of nuclear facilities. Thus, evaluation of existing testing or future research should evaluate and confirm the performance of the anchors at exposure conditions expected in a nuclear facility. The effect of concrete deterioration on post-installed anchorage is also not directly addressed in the design guidelines. Little work has been done on the effect of deterioration of concrete after the installation of post-installed anchors, so little exists to guide the evaluator.
>
> ***Why does it need to be changed?*** Before utilizing them in repair, post-installed anchors should be determined capable of performing throughout the desired service life in a nuclear facility.

ACI 369R-11 Guide for Seismic Rehabilitation of Existing Concrete Frame Buildings and Commentary**:** This guide was developed based on the format and content of ASCE/SEI 41-06, Chapter 6.0, “Concrete,” describes methods for estimating the seismic performance of both existing and new concrete components in an existing building. The guide is intended to be used with the analysis procedures and Rehabilitation Objectives established in ASCE/SEI 41-06 for the Systematic Rehabilitation Method. The guide provides recommendations for modeling parameters and acceptance criteria for linear and nonlinear analysis of beams, columns, joints, and slab-column connections of concrete buildings and the procedures for obtaining material properties necessary for seismic rehabilitation design.

> ***What needs to be changed?*** The document has general application to concrete frames structures. Where portions of the nuclear facility are concrete frames the document has direct application. For non-frame structures portions of the document may be applicable using engineering judgment. The committee should consider and document what portions of the document are applicable, if any, to non-frame nuclear facilities.
>
> ***Why does it need to be changed?*** The committee needs to confirm the applicability of portions of the document to non-frame portions of a nuclear facility.

ACI 437.1R-07 Load Tests of Concrete Structures: Methods, Magnitude, Protocols, and Acceptance Criteria: ACI 437.1R has recommendations regarding selection of test load magnitudes, protocol, and acceptance criteria to be used when performing load testing as a means of evaluating safety and serviceability of concrete structural members and systems. The history of load factors and acceptance criteria as found in the ACI 318 building code is provided along with a review of other load test practice. Recommended revisions to load factors to be used at this time, additions to load testing protocol, and revisions to acceptance criteria used to evaluate the findings of load testing are provided.

> ***What needs to be changed?*** The document is generally applicable in evaluation of an existing structure or capacity of a repaired structure. However, it has a broad generalized statement "The value of the test load should be increased if: the use of the building requires an unusually high safety factor; a decrease in load-bearing capacity with time is anticipated due to such factors as corrosion or deterioration of material properties; the effects of shrinkage, creep and relaxation are important and should be considered; the structure will be exposed to extreme environmental factors such as large temperature variations; the effects of dynamic loads are important; the service live load exceeds twice the dead load." No quantitative guidance is provided in the document, however, on what additional increase is appropriate. Thus, the committee should provide guidance on what additional increase is applicable in environments with very high temperature exposure, and pressure.
>
> ***Why does it need to be changed?*** The input of the committee would be valuable to the repair design community to have consensus opinion on appropriate load increases.

ACI 440.2R-08 Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures: This document offers general information on the history and use of FRP strengthening systems; a description of the unique material properties of FRP; and committee recommendations on the engineering, construction, and inspection of FRP systems used to strengthen concrete structures. The proposed guidelines are based on the knowledge gained from experimental research, analytical work, and field applications of FRP systems used to strengthen concrete structures.

> ***What needs to be changed?*** The committee needs to review the effect of high temperature exposure in nuclear power facilities on FRP systems. The document addresses fire endurance, and has a general statement that maximum temperatures are

typically 60 to 82 C. It needs to clarify maximum limits and whether these are long-term or short term exposure limits.

Why does it need to be changed? It needs to be changed in order to provide the consensus opinion of the FRP design community on applicable limits for use in nuclear power plants.

ACI 562-12 Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Structures and Commentary and ACI 563-XX Specification for Concrete Removal and Preparation for Repair: The ACI 562 Code has a goal to develop and maintain code requirements for evaluation, repair, and rehabilitation of existing concrete buildings. ACI 563 mission is to develop and maintain specifications for repair of existing structural concrete. The documents are still being developed in committee.

What needs to be changed? It is expected that these two new ACI documents will directly address the repair of building structures. Repair of facilities with elevated temperatures, pressures or radiation were likely not fully considered by the committees. The committees should review the exposure conditions typical in nuclear power plants and confirm whether all or portions of their documents are relevant. In general, ACI 562 will be very difficult to implement in the nuclear arena. Although a design code for repairs, it delegates substantial latitude to the register design professional and does not provide prescriptive requirements for the repair. Statements in the code such as “the license design professional shall consider the effects of creep on the repair” do not provide sufficient guidance for application in the NPP arena, and will require substantial investigation in validation and review prior to their imitation. This will require a case-by-case approach to repairs, negating the entire purpose of this unified approach document.

Why does it need to be changed? It must give the repair designer a consensus opinion on applicability of the provisions of the ACI 562 Code and ACI 563 Specification to situations expected in a nuclear plant repair.

***ACI Concrete Repair Manual*:** The Concrete Repair Manual is a compilation of technical documents and papers from a wide variety of international concrete repair sources. The Third Edition is a large 2-volume set. Topics include condition evaluation, materials for repair, surface preparation, application methods, corrosion management, structural strengthening, and protection methods. There is also contractual guidance for measuring concrete repair work.

Sources of the more than 2,000 pages of guides, specifications, and other information include:

- American Concrete Institute
- BRE (formerly the British Research Establishment)
- The Concrete Society
- International Concrete Repair Institute (ICRI)
- NACE International (formerly National Association of Corrosion Engineers)
- SSPC: Society for Protective Coatings
- United States Army Corps of Engineers

What needs to be changed? This document contains a wealth of information, but may have conflicting opinions on particular aspects of a repair between different documents included in the manual. There are some special cases evaluated (e.g., fire damage), but the only mention of nuclear is a single reference to ACI 349. It would be helpful if the committee preparing the manual could evaluate and make a separate compilation of technical papers, reports, and case studies on the repair of nuclear facilities.

Why does it need to be changed? The suggested compilation would provide the repair designer input on research efforts and past successful repair work accomplished on nuclear power facilities.

***ICRI No. 320.1R, 1996 Guide for Selecting Application Methods for the Repair of Concrete Surfaces*:** This publication illustrates and describes the methods currently available for placement of concrete repair materials, along with material requirements and the best applications for each. In addition, engineering considerations, constructability, and quality control are addressed.

ICRI 320.2R, 2009**, **Guide for Selecting and Specifying Materials for Repair of Concrete Surfaces: This guide is a tool to help designers, specifiers, contractors, and manufacturers make the best possible decisions in selecting materials for the repair of concrete surfaces. It fully describes a process used to develop sound selection criteria that will ensure that, for each project, the material properties needed to produce durable repairs are specified.

ICRI 330.1, 2006 Guideline for the Selection of Strengthening Systems for Concrete Structures: This publication describes several methods of strengthening structures including externally bonded systems, post-tensioning, section enlargement and supplemental supports.

ICRI 340.1, 2006, Guide for Selecting Grouts to Control Leakage in Concrete Structures: This guide provides information on the properties and characteristics of grout materials for selection of a proper grout material to control water leakage through cracks and other discontinuities in concrete structures.

What needs to be changed? The documents listed above provide guidance for the design and specification of high-quality and durable repairs to concrete structures. The practices recommended are applicable to most structures in the nuclear power plant, but likely do not directly consider potential high temperature, pressures or radiation exposures common in nuclear facilities. It would be of benefit for ICRI to review the documents and ascertain what portions are applicable to exposures typical in the nuclear industry.

Why does it need to be changed? The ICRI documents give good general guidance, but would be more valuable to the repair designer of a nuclear facility, if the consensus opinions of the committee experts directly addresses applicability to portions of a nuclear facility.

***NACE RP0290, 2000, Standard Recommended Practice - Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures*:** NACE RP0290, 2000 presents guidelines for cathodic protection of reinforcing steel in concrete structures. The guidelines are limited to impressed current cathodic protection systems for new or existing atmospherically exposed reinforced concrete and are not intended for application to prestressed concrete. This standard includes sections that address criteria for achieving cathodic protection; design of cathodic protection systems; installation practices; energizing and system adjustment; operation and maintenance of cathodic protection systems; and records.

> ***What needs to be changed?*** It is not clear whether the cathodic protection strategies presented in the document would be directly applicable to a nuclear power plant exposure. The committee should review the applicability in nuclear facility exposure and provide a consensus opinion on what limits may be required for application of cathodic protection.
>
> ***Why does it need to be changed?*** This would give the repair designer a consensus expert opinion on the applicability of the provisions of the cathodic protection covered in the document to situations expected in a nuclear plant repair.

***NUREG/CR-6424/1996 Report on Aging of Nuclear Power Plant Reinforced Concrete Structures*:** The Structural Aging Program provides the United States Nuclear Regulatory Commission with potential structural safety issues and acceptance criteria for use in continued service assessments of nuclear power plant safety-related concrete structures. The program was organized under four task areas: Program Management, Materials Property Data Base, Structural Component Assessment/Repair Technology, and Quantitative Methodology for Continued Service Determinations. Under these tasks, over 90 papers and reports were prepared addressing pertinent aspects associated with aging management of nuclear power plant reinforced concrete structures. Contained in this report is a summary of program results in the form of information related to longevity of nuclear power plant reinforced concrete structures, a Structural Materials Information Center presenting data and information on the time variation of concrete materials under the influence of environmental stressors and aging factors, in-service inspection and condition assessments techniques, repair materials and methods, evaluation of nuclear power plant reinforced concrete structures, and a reliability-based methodology for current and future condition assessments. Recommendations for future activities are also provided.

> ***What needs to be changed?*** It would be beneficial to extract those portions of the report that deal exclusively with the potential repair of nuclear power plants. See a more detailed discussion of this document in section 3.3
>
> ***Why does it need to be changed?*** The repair designer would be better able to fully review a compilation of information from the report specific to repair.

5.5. Document/Contract Documents

5.5.1 Reinforced concrete repair design.

5.5.1.1 Status today

Concrete repair design of reinforced concrete buildings (and other structures) is addressed in several documents published by ACI. In addition, the International Concrete Repair Institute (ICRI) offers several guideline reports for several components of concrete repair.

The most widely recognized documents are the mandatory code provisions cited in ACI 318 and ACI 349 while the other documents pertaining to repair are guideline reports generated by various ACI Committees. ACI Committee Reports provide guidance in planning, designing, executing, and inspecting construction. The majority of the repair guidelines are combined into a large ACI document entitled The Manual of Concrete Practice. Reports are intended to be used by individuals that are competent to evaluate the significance and limitations of the contents and recommendations within the report. Reports, therefore, are not written in mandatory language. A brief summary of each document is provided below.

ACI 318-2011 Building Code Requirements for Structural Concrete and Commentary: This is a code level document that includes general requirements for the design of reinforced concrete buildings structures. This code does not address concrete repair details or service life extensions:, however, the document does discuss serviceability in general detail in Chapter 7.

ACI 349-06 Code Requirements for Nuclear Safety-Related Concrete Structures and Commentary: This publication is a code level document that includes general requirements for concrete structures in nuclear facilities. Similar to the ACI 318 document, this document provides direction for new construction of nuclear structures and may be applicable in large-scale rehabilitation.

ACI Concrete Repair Manual, Third Edition, 2008 : This guide, developed by ACI and various industry groups, presents procedures for remediation of concrete with various deficiencies. Each repair procedure is specific. When appropriate, sections giving general requirements for repair specifications and drawings are included. However, the contents are guidelines and lack mandatory language, and thus may be subject to interpretation.

ACI 546-04 Concrete Repair Guide: This document provides guidance on the selection and application of materials and methods for the repair, protection, and strengthening of concrete structures. An overview of materials and methods is presented as a guide for making a selection for a particular application. References are provided for obtaining in-depth information on the selected materials or methods.

ICRI Technical Guidelines: Similar to the ACI Concrete Repair Manual, the ICRI document provides guidelines for several aspects of repair, including but not limited to surface repairs, coatings, material selection, overlays, and evaluations. In general, the information is a primer for contractors and professionals with elementary knowledge on the subject. As with the other guidelines referenced within, the guidelines are subject to interpretation and are not written in mandatory language.

ACI 546.3R-06 Guide for the Selection of Materials for the Repair of Concrete**:** This guide developed by ACI recommends that appropriate data be made available in a standardized manner. Despite this, material suppliers do little to provide this information.

ACI 364.6T-02(11) Concrete Removal in Repairs Involving Corroded Reinforcing Steel b (Tech Notes): This is one of several ACI documents generated by ACI Committee 364 that provides technical guidelines for practitioners and contractors based upon empirical experience and data. As with the majority of ACI documents dealing with concrete repair, the technical notes are general guidelines for specific aspects of concrete repair. They are not a design document with load factors, resistance factors and other prescriptive design methodology.

ACI 364.3R-09 Guide for Cementitious Repair Material Data Sheet - The purpose of this document is to provide a guide to the protocol for testing and reporting of data for cementitious repair materials. It does not address all of the issues associated with material selection, and assumes that the user will be responsible for ascertaining the suitability of the repair material for its intended application before use.

5.5.1.2 What needs to be changed?

The provisions of ACI 318-20 II, ACI 349-06, and the Concrete Repair Manual provide a suitable start for the condition for production of detailed drawings for repairs. In addition, ACI 364.3R-06 and ACI 546.3R-06 provide useful information for specifications. The provisions may apply to nuclear power plants, but only in a general sense. Overall, a comprehensive document that combines the relevant portions of each of the above listed documents should be developed and tailored to nuclear power plant facilities.

5.5.1.3 Why does it need to be changed?

A comprehensive document in mandatory language for the development of repair drawings for nuclear power plant facilities is required to address concrete repair design for safety related structures. This document could incorporate much of the research and applicable guideline language by reference.

Rationale: Analogous to the current reinforced concrete design codes, a concrete repair code should be developed for the nuclear industry's safety-related structures.

Chapter 6 REPAIR IMPLEMENTATION

6.1. Introduction

The durability and service life of concrete repairs is highly dependent on the quality of the implementation practices utilized during construction. Proper demolition surface preparation and application of compatible repair materials or protective products are paramount in creating quality repairs. Proper placement and curing practices are as critical during repair as they are in new construction. This chapter addresses standards that apply to repair materials and construction best practices. Reference is made to several widely utilized standards and guide documents. In many cases, the brief descriptions of these documents are taken verbatim from their published abstracts.

The concrete industry has identified a need for a code-level document that applies to the repair of concrete structures. ACI Committee 562 is in the process of developing a code document for concrete repair: "Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Structures." Similarly, ACI Committee 563 is developing a corresponding set of standard specifications for the repair of existing structural concrete. When finalized and published, "Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Structures" should be reviewed for suitability to NPP repair applications. This standard should be applicable to most concrete NPP structures.

The remainder of this chapter is divided into 4 parts:

1. Concrete removal, preparation and repair techniques
2. Repair materials
3. Protective systems
4. Strengthening techniques

The documents listed below are presented outside of these subheadings, due to their broad scope or general applicability to concrete repair.

ACI 546R-04 Concrete Repair Guide: This document, created by ACI committee 546, provides guidance on the selection and application of materials and methods for the repair, protection, and strengthening of concrete structures. An overview of materials and methods is presented as a guide for making a selection for a particular application. References are provided for obtaining in-depth information on the selected materials or methods. The major headings of this document are used to organize and subdivide the remaining sections of Chapter 6.

ACI 318-2011, "Building Code Requirements for Structural Concrete and Commentary": This is a 'code' level document that covers the materials, design, and construction of structural concrete used in buildings and other structures. Many chapters are applicable to repair implementation, including Chapter 5, which addresses concrete quality, mixing, and placing requirements and Chapter 6, which addresses formwork considerations. Appendix D also covers anchoring to existing concrete.

ACI 301-2010, "Specifications for Structural Concrete": This document covers general construction requirements for cast-in-place structural concrete and slabs-on-ground. Many of the specifications are applicable to repair practices. Provisions governing testing, evaluation, and acceptance of concrete as well as acceptance of the structures are included.

ICRI No. 120.1, 2009 "Guidelines and Recommendations for Safety in the Concrete Repair Industry": This guideline can be used be used to educate supervisors, craft workers, owners, and engineers in safe work practices for the concrete repair industry. The guideline has been developed to be a visual tool that depicts the safe performance of specific tasks and the hazards associated with those tasks. The requirements described are based on the most recent OSHA standards and are intended to provide guidance and training in the planning and execution of restoration projects.

ACI and ICRI, 2008, "Concrete Repair Manual – 3rd Edition": This document is an extensive collection of papers guides, specifications and reports all dedicated to concrete repair. The scope of these documents covers the entire repair process, including implementation. Many of the included guides are referenced separately in this chapter, but they contain additional useful papers and reports that are not otherwise specifically noted. This includes a series of repair application procedure documents published by ACI Committee E706.

6.2. Concrete Removal, Preparation and Repair Techniques

6.2.1 Status today

Proper implementation practices are critical for a durable concrete repair. Improper concrete removal or poor surface preparation reduces the quality of repairs, resulting in costly rework.

A number of useful guides exist that detail appropriate strategies for removing damaged concrete, surface preparation, and anchoring into existing concrete, as well as specialized repair techniques like injection grouting.

ICRI No. 210.1, 1998 (under revision),Guide for Verifying the Field Performance of Epoxy Injection of Concrete Cracks: This document to provide the contractor, engineer, owner, and specifier with guidelines to assist in the development of performance specifications for epoxy adhesive injection work. It describes methods used for quality assurance, including visual observation of the injection process, core testing and non-destructive testing.

ICRI No. 310.1R, 2008, Guide for Surface Preparation for the Repair of Deteriorated Concrete Resulting from Reinforcing Steel Corrosion: This document outlines the steps in preparing concrete for replacement material in areas where corroded reinforcing steel has caused cracking, spalling, delamination, or other types of deterioration. Topics covered include exposing and undercutting reinforcing steel, edge and surface conditioning, repair of reinforcing steel, and removal geometry.

ICRI No. 310.2, 1997, Guideline for Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays: This document summarizes the capabilities, operating requirements, and limitations of the various methods used to prepare concrete surfaces for the application of protective sealers, coatings, and polymer overlays.

ICRI No. 310.3, 2004, Guide for the Preparation of Concrete Surfaces for Repair Using Hydrodemolition Methods: This guideline is intended to provide an introduction to hydrodemolition for concrete removal and surface preparation, the benefits and limitations of using hydrodemolition, and an understanding of other aspects to be addressed when incorporating hydrodemolition into a repair project. This guideline provides a description of the equipment, applications, safety procedures, and methods of water control and cleanup.

ICRI 320.1R, 1996, Guide for Selecting Application Methods for the Repair of Concrete Surfaces: This document illustrates and describes the methods currently available for placement of concrete repair materials, along with material requirements and the best applications for each. In addition, engineering considerations, constructability, and quality control are addressed.

ICRI No. 340.1, 2006, "Guide for Selecting Grouts to Control Leakage in Concrete Structures". This guideline provides information on the properties and characteristics of grout materials for selection of a proper grout material to control water leakage through cracks and other discontinuities in concrete structures.

ACI 224.1R-07, Causes, Evaluation, and Repair of Cracks in Concrete Structures: This report developed by ACI Committee 224 summarizes the causes of cracks in concrete structures. The procedures used to evaluate cracking in concrete and the principal techniques for the repair of cracks are presented. In Chapter 3, the key methods of crack repair are discussed, and guidance is provided for their proper application.

ACI 355.2-07, Qualification of Post-Installed Mechanical Anchors in Concrete and Commentary: ACI 355.2 prescribes testing programs and evaluation requirements for post-installed mechanical anchors intended for use in concrete under the design provisions of ACI 318. Criteria are prescribed for determining whether anchors are acceptable for use in uncracked concrete only, or in cracked as well as uncracked concrete. Performance categories for anchors are established, as are the criteria for assigning anchors to each category. The anchor performance categories are used by ACI 318 to assign capacity reduction factors and other design parameters.

ACI 355.4-10, Acceptance Criteria for Qualification of Post-Installed Adhesive Anchors in Concrete and Commentary (Provisional Standard): This standard prescribes testing programs and evaluation requirements for post-installed adhesive anchors intended for use in concrete under the design provisions of ACI 318. Testing and assessment criteria are provided for various conditions of use, including seismic loading, sustained loading, aggressive environments, reduced and elevated temperatures, and for determining whether anchors are acceptable for use in uncracked concrete only, or acceptable for service both in cracked and uncracked concrete. Criteria are provided for establishing the characteristic bond strength, reductions for adverse conditions, as well as the anchor category and associated jobsite quality-control requirements.

6.2.2 What needs to be changed?

The documents listed above provide guidance for the execution of high-quality and durable repairs to concrete structures. The practices recommended are applicable to most structures in the NPP. It would be of benefit to develop a comprehensive document that established best practices for the nuclear industry, or references existing standards.

6.2.3 Why does it need to be changed?

A uniform standard will create consistency of practice between the various NPPs for most common concrete repairs.

6.3. Repair Materials

6.3.1 Status today

A wide variety of pre-packaged repair materials are commercially available for practically all conceivable concrete repair applications. In the case of large repairs, ready-mixed concrete is also frequently utilized. In every case, selecting a suitable repair material that is compatible with the parent concrete is critical in creating a lasting repair.

The Commercial Grade Dedication process is typically used by the NRC to qualify products proposed for use in a safety-related function. This involves consideration of the failure modes of the product in the operating environment and the effect of failures on the safety of the structure. NPPs are frequently hesitant to use new products, even those that have been used successfully in industry for many years.

In a commercial environment, depending on the intended use of repair products, they are typically put through a series of standardized tests to demonstrate their performance properties. Exactly what tests are performed and any potential modifications to these tests are generally at the discretion of the manufacturer. It is frequently up to the engineer and contractor to verify that the product is acceptable for the intended purpose.

In order to create consistency for the comparison of repair mortar products and to ensure that standardized testing simulates the unique demands on these products, ICRI published the document 320.3R, 2007 “Guide for Inorganic Repair Material Data Sheet Protocol.” Products that are evaluated and reported according to this standard can be easily compared on the basis of performance.

In addition to conventional repair materials, self-consolidating concrete is frequently utilized in repair and strengthening applications like section enlargements, where proper placement of traditional concrete is challenging or not possible. formwork restricts access the application of vibration. Self-consolidating concrete (SCC) is a highly flowable concrete that remains stable and uniformly distributed during placement and does not require vibration in order to consolidate properly.

The documents below provide guidance for the selection of concrete repair materials:

ACI 364.3R-09, Guide for Cementitious Repair Material Data Sheet: Similar to the previously mentioned ICRI 320.3R, this ACI document provides a guide to the protocol for testing and reporting of data for cementitious repair materials.

ACI 546.3R-06, Guide to the Selection of Materials for the Repair of Concrete: This document provides guidance on the selection of materials for the repair of concrete. An overview of the important properties of repair materials is presented as a guide for making an informed selection of repair materials that are appropriate for specific applications and service conditions.

ICRI No. 320.2R, 2009, Guide for Selecting and Specifying Materials for Repair of Concrete Surfaces:. A tool to help designers, specifiers, contractors, and manufacturers make the best possible decisions in selecting materials for the repair of concrete surfaces. It fully describes a process used to develop sound selection criteria that will ensure that, for each project, the material properties needed to produce durable repairs are specified.

ICRI No. 320.3R, 2007, Guide for Inorganic Repair Material Data Sheet Protocol: This guide provides a consistent, logical, and systematic methodology for testing and reporting information for cement-based repair materials. The data sheet protocol allows the specifier to choose verifiable properties optimized for selected requirements of a particular repair situation. The applicator can obtain useful information about yield, working time, surface preparation, application temperature range, curing, and compatibility, as well as verify the material performance. The material producer can optimize products based on market needs and technology improvements, rather than concentrating on closely passing acceptance levels of an existing specification in a commodity-based market.

ACI 237.R-07, Self-Consolidating Concrete: This report contains the current state of knowledge with respect to SCC. The information in this document is expected to inform concrete producers, users, and specifiers of SCC of known practices and processes. Because SCC is a viable solution to various concrete placement problems, ASTM has established Subcommittee C09.47, Self-Consolidating Concrete, to develop standard test methods for SCC.

6.3.2 What needs to be changed?

A clear process should be established for manufacturers of repair materials to follow in order to gain acceptance for use in NPP for safety-related and non -safety-related applications. A list of standardized tests that measure performance should be compiled. Manufacturers can submit independently verified test results. A set of minimum acceptance criteria should be established, depending on the intended application.

The documents listed above primarily focus on cementitious repair materials: however, ACI 546R-04 lists a range of materials related to repair. An established process for approval of all materials based on their specific application would be of benefit to the industry. A database capturing how and where different products are used would be of additional benefit.

If existing standardized tests do not appropriately consider the demands and exposure conditions of an NPP environment, then tests should be developed or modified to do so. This may require additional research into accelerated test methods and deterioration models, as well as tests for performance characteristics of materials subject to high temperature and radiation.

6.3.3 Why does it need to be changed?

The process for acceptance and approval of repair mortar products for use in NPP is not clear. In some cases specified repair materials or components may no longer be commercially available. Many quality repair mortar products exist and should be available to engineers and contractors for repair NPPs. The process should be standardized so that approved products can be used in all NPPs without having to go through the expense of obtaining a site-specific approval for each one. Standardizing the process will save money for the NPPs and the manufacturers that would otherwise be spent on recertification of materials.

6.4. Protective Systems

6.4.1 Status today

As described in ACI 564R-04, "Protective systems consist of materials and methods that reduce corrosion of metals embedded in concrete, which reduces the deterioration of the concrete. Protective systems limit the intrusion of moisture, chloride ions, and other contaminants into the concrete by using surface treatments, applying electrical-chemical principles, or by modifying the PCC overlay."

As NPPs continue to age, sound strategies for mitigating the effects of corrosion will become more important. These strategies include the application of galvanic and impressed current cathodic protection systems.

There are many documents that address materials and strategies used to address corrosion in reinforced concrete structures:

ACI 222R-01, Protection of Metals in Concrete against Corrosion: This report reflects the state-of-the-art of corrosion of metals, and especially reinforcing steel, in concrete. Separate chapters are devoted to the mechanisms of the corrosion of metals in concrete, protective measures for new concrete construction, procedures for identifying corrosive environments and active corrosion in concrete, and remedial measures.

ACI 222.3R-03, Design and Construction Practices to Mitigate Corrosion of Reinforcement in Concrete Structures: This guide contains information on aspects of detailing, concrete materials and mixture proportions, and construction practices used to mitigate corrosion. In addition, the guide contains recommendations for protecting in-service structures exposed to corrosive conditions. The guide is intended for designers, materials suppliers, contractors, and all others engaged in concrete construction.

NACE RP0390, 2006, Standard Recommended Practice - Maintenance and Rehabilitation Considerations for Corrosion Control of Atmospherically Exposed Existing Steel-Reinforced Concrete Structures: This standard presents corrosion control guidelines that are applicable to existing atmospherically exposed structures made of conventionally reinforced concrete. They may be used to develop specifications involving repair and rehabilitation of steel-reinforced concrete structures. These guidelines should be used primarily when repair or rehabilitation is being implemented because of deterioration resulting from the corrosion of steel reinforcement.

NACE RP0290, 2000, Standard Recommended Practice - Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures: Presents guidelines for cathodic protection of reinforcing steel in concrete structures. The guidelines are limited to impressed current cathodic protection systems for new or existing atmospherically exposed reinforced concrete and are not intended for application to prestressed concrete. Criteria described include 100 mV polarization development/decay, statistical distribution analysis, and E log I analysis. This standard includes sections that address criteria for achieving cathodic protection, design of cathodic protection systems, installation practices, energizing and system adjustment, operation and maintenance of cathodic protection systems, and records.

6.4.2 What needs to be changed?

Similar to the recommendations for repair materials, clear standards should be established for the acceptance of protective systems used in NPPs. Standardized tests for qualification of protective systems and products should be established or developed through research if current standards are not suitable for the industry. A database capturing how protective systems and products are used and how they perform would allow the industry to track the efficacy of these systems. More specifically, the acceptability of cathodic protection strategies in NPPs should be established with standards developed specifically for the industry.

6.4.3 Why does it need to be changed?

A standardized process for acceptance and approval of protective systems will save money and create consistency within the industry, improving the overall quality of protective strategies through certification and capturing the performance of best practices.

6.5. Strengthening Techniques

6.5.1 Status today

As described in ACI 564R-04, "Strengthening concrete is the process of restoring the capacity of damaged components of structural concrete to its original design capacity, or increasing the strength of structural concrete." Strengthening techniques are typically utilized when the function of a structure or the loading on that structure is changing, or the structure has been weakened due to degradation. It is expected that most structures in an NPP will not go through a significant change of use, but as they continue to age, strengthening techniques will be valuable in extending the useful service life of structures.

There are many different strategies for strengthening concrete structures. The documents below address some of these:

ICRI 330.1, 2006, Guideline for the Selection of Strengthening Systems for Concrete Structures: An aid for the selection process, this guideline describes several methods of strengthening structures including externally bonded systems, post-tensioning, section enlargement and supplemental supports.

ACI 440.2R-08, Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures: Fiber-reinforced polymer (FRP) systems for strengthening concrete structures are an alternative to traditional strengthening techniques, such as steel plate bonding, section enlargement, and external post-tensioning. FRP strengthening systems use FRP composite materials as supplemental externally bonded reinforcement. FRP systems offer advantages over traditional strengthening techniques: they are lightweight, relatively easy to install, and are noncorrosive. Due to the characteristics of FRP materials as well as the behavior of members strengthened with FRP, specific guidance on the use of these systems is needed. This document offers general information on the history and use of FRP strengthening systems; a description of the unique material properties of FRP; and committee recommendations on the engineering, construction, and inspection of FRP systems used to strengthen concrete structures. The proposed guidelines are based on the knowledge gained from experimental research, analytical work, and field applications of FRP systems used to strengthen concrete structures.

ACI 440.3R-04, Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures: This document provides model test methods for the short-term and long-term mechanical, thermo-mechanical, and durability testing of FRP bars and laminates. It is anticipated that these model test methods may be considered, modified, and adopted, either in whole or in part, by a U.S.national standards-writing agency such as ASTM International or AASHTO. The publication of these test methods by ACI Committee 440 is an effort to aid in this adoption.

6.5.2 What needs to be changed?

Acceptable strategies for strengthening structures in NPPs should be established and specified.
In particular the use of composites for strengthening should be analyzed and any limitations established based on the type of structure to which they are applied. Acceptance standards for systems should be established. Additional research may be required to understand how composite strengthening systems will behave and age in an NPP environment.

6.5.3 Why does it need to be changed?

FRP systems have proven to be a cost-effective and widely utilized strengthening strategy in the building and transportation industries. A process should be established so the benefits of these systems can be safely achieved in the nuclear industry as well.

Chapter 7 MONITORING QUALITY CONTROL

7.1. Introduction

This chapter is intended to provide basic guidance to the NRC and nuclear owners, engineers and contractors in regard to quality assurance/quality control (QA/QC) of concrete repairs (see also Chapters 4 and 7).

7.1.1 Review of existing nuclear industry QA of repairs

Appendix A to 10 CFR Part 50 requires licensees to establish a quality assurance (QA) program, whereas ***Appendix B to 10 CFR Part 50*** defines the requirements of that program. The QA plan is structured to follow the requirements of Appendix B to 10 CFR Part 50, and it provides a general description of the established measures with which licensees need to comply with Appendix B requirements, including *Criterion III, "Design Control."*

ANSI N45.2 Quality Assurance Requirements for Nuclear Power Plants, 1977: This publication describes the requirements of Appendix B in greater detail. Industry standards, such as ANSI N45.2 and daughter standards (e.g., ANSI N45.2.11, "Quality Assurance Requirements for the Design of Nuclear Power Plants"), serve as "how to" documents for the nuclear industry to meet NRC requirements, including Criterion III. The NRC endorsed this standard in RG 1.28, "Quality Assurance Program Requirements (Design and Construction)."

US Nuclear Regulatory Commission, Regulatory Guide 1.28, Quality Assurance Program Requirements (Design and Construction), 2009: In RG 1.28, Revision 4, the NRC endorsed industry standard ASME NQA-1-2008, "Quality Assurance Program Requirements for Nuclear Facilities."

ANSI/ASME NQA-1-1983 Quality Assurance Program Requirements for Nuclear Power Plants: This publication has three main sections: (1) Basic Requirements, (2) Supplements, and (3) Appendices. The Basic Requirements section provides the basic requirements for establishing and executing QA programs. The Supplements section amplifies the individual requirements of the Basic Requirements section. The Appendices section provides non-mandatory guidance for meeting the Basic Requirements and Supplements sections.

ANSI N45.2.11, 1974 Quality Assurance Requirements for the Design of Nuclear Power Plant: This publication describes the minimum QA requirements that licensees must implement during the design of nuclear power plant SSCs. The SSCs are those that are required to prevent accidents that could cause undue risk to the health and safety of the public or those that are required to mitigate the consequences of an accident. During the licensing phase of nuclear plants, most licensees commit to following the guidance contained in the standard. As is the case with all licensing actions, inspectors should verify actual licensee commitments through a review of the facility's UFSAR and other licensing-basis documents. Licensees structure their QA program regarding design control to incorporate the guidance contained in the standard and to meet the requirements of Criterion III of Appendix B to 10 CFR Part 50. The standard itself covers various elements of an effective design control program.

Criterion III of Appendix B to 10 CFR Part 50 of ANSI N45.2.11, 1974: This publication requires, in part, the following: "Design changes, including field changes, shall be subject to design control measures commensurate with those applied to the original design and be approved by the organization that performed the original design unless the applicant designates another responsible organization."

Section 8 of ANSI N45.2.11, 1974: This section provides guidance on "design changes": "Documented procedures shall be provided for design changes to approved design documents, including field changes. The changes shall be justified and subjected to design control measures commensurate with those applied to the original design[32]."

***Amendment to 10 CFR 50.55a of ANSI N45.2.11, 1974*:** USNRC published a proposed rule in the Federal Register on May 4, 2010 (75 FR 24324). There is a proposed rule amendment that would allow the use of 1994 Edition of NQA-1, "Quality Assurance Requirements for Nuclear Facility Applications," when using the 2006 Addenda of Section III of the ASME B&PV Code and later editions and addenda.

7.2. Qualifications of Personnel/Labs- Long Term Monitoring

7.2.1 Introduction

Initially the overarching standard for personnel and equipment involved in nuclear facility construction and maintenance was ANSI/ASME N45.2.6 -73 which followed the criteria of 10 CFR 50 Appendix B. That standard morphed over time to ASME NQA-1 Quality Assurance Requirements for Nuclear Facilities. Requirement 2 declares that a QA Program be established which provides trained personnel using appropriate equipment in suitable environmental conditions. Requirement 12 sets forth calibration and control of measuring and test equipment. Depending on the date of the licensing agreement of the specific facility, either ANSI/ASME or NQA-1 will set personnel and equipment requirements for monitoring repairs. The owner of the plant is responsible for establishing and performing QA. ASME Boiler and Pressure Vessel Code, Section XI, Subsection IWL governs operation and maintenance of nuclear facilities so it would be applicable to repairs at an operating plant. 10CFR50.55a Issuance, Limitations, and Conditions of Licenses and Construction Permits- Codes and Standards is the portion of the law which establishes criteria for relicensing

7.2.2 Status today

ANSI/ASME N45.2.6 -1978, Qualifications of Inspection, Examination and Testing Personnel for Nuclear Power Plants: This publication is an update of ANSI/ASME N45.2.6-1973 which expands the 1973 document to include personnel involved during start up and operational phases. It contains educational and experience requirements for Level I, II and III personnel. This reference does not apply to new licenses.

ASME NQA-1, 2008, Quality Assurance Requirements for Nuclear Facilities: This Standard provides requirements and guidelines for the establishment and execution of quality assurance programs during siting, design, construction, operation and decommissioning of nuclear

[32] USNRC NUREG-1913, *Design Control: A Quick Reference Guide for NRC Inspectors*, August 2009

facilities. This Standard reflects industry experience and current understanding of the quality assurance requirements necessary to achieve safe, reliable, and efficient utilization of nuclear energy, and management and processing of radioactive materials.

ASME Boiler and Pressure Vessel Code, Section XI, Subsection IWL-1992
ASME Boiler and Pressure Vessel Code, Section XI, Subsection IWL-2011: ***ASME Section XI, Subsection IWE, Requirements for Class MC and Metallic Liners of Class CC Components of Light-Water Cooled Plants***: This publication specifies requirements for pre-service and in-service examination/inspection, repair/replacement activities, and testing of Class MC (metal containment) pressure-retaining components and their integral attachments and repair/replacement activities and testing of Class CC (concrete containment) pressure-retaining components and their integral attachments for BWRs and PWRs. Similarly, Subsection IWL, *Requirements for Class CC Concrete Components of Light-Water Cooled Plants*, specifies requirements for pre-service and in-service examination/inspection, repair/replacement activities, and testing of the reinforced concrete and the post-tensioning systems of Class CC (concrete containment) components for BWRs and PWRs.

ACI 349.03R-02 (reapproved 2010), Evaluation of Nuclear Safety Related Concrete Structures: This report supplements the ACI 349 code by recommending an evaluation procedure for nuclear safety-related concrete structures. As the nuclear facilities in the United States remain in service and become susceptible to the adverse effects of aging, periodic inspection and proper evaluation have become important issues.

NUREG 1611- 1997 Aging Management of Nuclear Power Plants Containments for License Renewal, ***Aging Management of Nuclear Power Plant Containments for License Renewal***: This publication reconciles the technical information and agreements resulting from NUMARC/NRC industry report reviews and the in-service inspection requirements of Subsection IWE and IWL as promulgated in 10 CFR 5.55a for license renewal.

10CFR50.55a Issuance, Limitations, and Conditions of Licenses and Construction Permits-Codes and Standards: The NRC endorses Sections III and XI of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code and the Institute and the Institute of Electrical and Electronics Engineers (IEEE) Standards 279, *Criteria for Protection Systems for Nuclear Power Generating Stations*, and 603, *Criteria for Safety Systems for Nuclear Power Generating Stations*.

7.2.3 What needs to be changed?

- ANSI/ASME and ASME documents cannot be changed due to legalities of licensing. The current edition (2011) of ASME *Section XI, Subsection IWL* has very specific personnel requirements (See below for more information).
- ACI349.03R-02 (reapproved in 2010) should be updated to be in sync with ASME *Section XI, Subsection IWL-2011, and 10CRF50.55a*. This is discussed in greater detail below in the "*Nuclear Safety Related Structures*" paragraph.

7.2.4 Why does it need to be changed?

The update to ACI 349.03R should have personnel requirements that are consistent with ASME XI, subsection IWL-2011

Containment: ASME Boiler and Pressure Vessel Code, Section XI, Subsection IWL provides rules and requirements for preservice examination, inservice inspection and repair of concrete Class CC components. The 1992 edition of Subsection IWL has no specific requirements for personnel or labs but assigns responsibility to a Responsible Engineer. This is the code year referenced by NUREG 1611, *Aging Management of Nuclear Power Plants Containments for License Renewal, September 1997*. The 2011 update of Section XI, Subsection IWL has specific personnel requirements which include experience, training, passing written and practical tests and vision. 10CFR50.55a, *Issuance, Limitations, and Conditions of Licenses and Construction Permits- Codes and Standards,* which was amended in 1996 and was updated in April, 2012, dictates criteria to be followed as a function of which edition of Section XI, Subsection IWL is being used. When the 1998 or subsequent edition are being used, there are specific requirements for those doing inspections of post tension tendons.

The ASME XI, IWL 2011 is current however the licensing agreements for most, if not all, plants will refer to earlier versions of the code or ANSI N 45.2. Although these earlier documents do not have specific reference to certifications or training programs they do require that a QA program be implemented using personnel with documented training and calibrated equipment.

Nuclear Safety Related Structures: ACI 349.03R-02 (reapproved 2010) , *Evaluation of Nuclear Safety Related Concrete Structures* provides qualifications for the responsible in-charge engineer and his/her personnel. The requirements are different from those in ASME XI, IWL 2011. ACI 349 should consider adopting the ASME qualifications when ACI 349 is updated. The document recommends that laboratories meet the requirements of ASTM E 329 and C 1077. It further recommends that those performing the repair be experienced with repair materials and methods, plant procedures, operations of equipment, in-process behavior and health concerns. ACI 349 should be updated to reflect current ICRI guides for NDE and ASTM standards for testing. ACI 349.03R does not address monitoring of repairs. Monitoring should be added during updates to be in sync with NRC regulation and ASME requirements.

Non-Safety Related Structures: The building codes of the state in which the facility is located or the Owner's requirements would have jurisdiction over repairs. The personnel and calibration requirements would potentially vary from facility to facility, in the manner that occurs in normal commercial construction.

Currently, the ASME Committee, ANDE, is developing a training, testing and certification program for personnel who will perform NDE and Quality Control at nuclear facilities. The NDE module is nearing completion, while the QC effort is in early development. The certifications will be applicable to both new construction and maintenance. In the future this program may be required for personnel involved in repairs to nuclear facilities.

7.3. Nondestructive Testing and Evaluation Methods for QA/QC

7.3.1 Visual observation of repair process

Useful information about the repair quality is attained from visual observation of the work. For example per the International Concrete Repair Guide[33], if epoxy injection repairs of cracks are the repair procedure and if the crack is visible on both sides of the member, then reasonable assurance that the crack is full can be realized by observation of the material exiting the ports along the crack when the injection sequence described below is followed. However, if only one side of the member is visible or accessible it is more difficult to determine if adequate filling has been achieved. In either case, small diameter cores can be taken through the crack repair section to check the depth of penetration of the epoxy resin. Such cores should be at locations where there is no risk of cutting through existing reinforcing bars. Suitable NDE procedures should be used to confirm such locations in consultation with the structural engineer retained for the repair design. Cores extracted can also be used to check whether the epoxy has provided the necessary bond to the cracked section. Thus, the NRC, owners and engineers need to specify observation of repairs by experienced and qualified engineers and technicians who are independent of the repair contractor for quality assurance of concrete repairs. Repair contractors in turn should conduct their own quality control program during repair operations. Visual observations are a key component of effective QA/QC of concrete repairs.

7.3.2 NDT&E methods for quality assurance of repairs

Nondestructive testing and evaluation (NDT&E) with sonic and ultrasonic methods may be used in some circumstances for testing epoxy adhesive injection repairs as discussed in the International Concrete Repair Guideline No. 210.1-1998[34] by the Evaluation Committee of ICRI and by Promboon et al (2002)[35]. Presently there are three sonic NDT methods applicable to epoxy adhesive injection quality assurance: Ultrasonic Pulse Velocity (UPV), Impact Echo (IE), and Spectral Analysis of Surface Waves (SASW).

Of these methods, UPV has an approved standard (ASTM C597-09) for basic ultrasonic pulse velocity measurements and IE has an approved thickness of plates testing standard (ASTM C1383 - 04(2010)) *Standard Test Method for Measuring the P-Wave Speed* and the *Thickness of Concrete Plates Using the Impact-Echo Method*. However, the UPV ASTM test standard was approved for general flaw detection and does not specifically address its use for epoxy injection quality assurance purposes.

Similarly, the IE ASTM test standard was approved for determination of plate thicknesses and does not address its use for injection quality assurance purposes. The SASW method is documented and discussed in ACI 228.2R-98 *Nondestructive Test Methods for Evaluation of Concrete in Structures* (see Chapter 4).

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[33] Guideline No. 210.1-1998 (formerly 03734 and under revision*): Guide for Verifying Field Performance of Epoxy Injection of Concrete Cracks*

[34] *Guide for Verifying Field Performance of Epoxy Injection of Concrete Cracks*, International Concrete Repair Institute Guideline No.201.1-1998 (formerly 03734, and currently being updated – anticipated December 2012).

[35] Promboon, Yajai, Larry D. Olson and John Lund (2002), *Nondestructive Evaluation (NDE) Methods for Quality Assurance of Epoxy Injection Crack Repairs*, ICRI Concrete Repair Bulletin, January/February 2002.

Recent research and work involving cross medium-medium (direct and angled tests above, below and across an injection zone) to analyze ultrasonic or sonic compressional wave pulse arrival times can produce two-dimensional and three-dimensional images of the wave velocity in concrete, termed a velocity tomogram, and can identify cracks and poor quality concrete (Sack and Olson, 2007[36]). Such ultrasonic and sonic velocity tomograms can be used to reveal slow velocity zones of the cracking damage before injecting and an improved, faster velocity tomogram after successful injection. Sonic NDT methods give an indication of the relative degree of fill of open cracks. They do not measure cure or bond strength of epoxy injection.

7.4. Performance Monitoring of Repairs

As discussed in Chapter 4, ICRI Guideline No. 210.4-2009[37] also discusses not only NDT and NDE for condition assessment of existing concrete and QA/QC of repairs, but also discusses performance monitoring of concrete repairs. In addition to the methods discussed above, Impulse Response testing as discussed in the above document and in ACI 228.2R-98 may also be useful for global comparisons of the dynamic stiffness/response of repaired materials by impacting the surface with an instrumented impulse force hammer and recording the response with a velocity transducer. Poorly bonded patches will behave more flexible and be less stiff than well bonded patches in Impulse Response tests (also see ASTM C1740 - 10 *Standard Practice for Evaluating the Condition of Concrete Plates Using the Impulse-Response Method*).

7.4.1 Long-term degradation monitoring of structural concrete conditions

An effective long-term degradation monitoring system for repaired concrete elements can be established up using dynamic structural monitoring. The procedure involves measuring the frequency response of the element using triaxial accelerometers prior to repair, and getting a baseline response soon after the repairs are executed. Since the frequency depends on mass and stiffness, and the mass is not expected to change, any changes in the frequency response would indicate a change in stiffness related to degradation. Degradation can be in the form of cracking and spalling of concrete. However, minor to moderate degradation can be difficult to quantify and it is suggested that baseline measurements should be conducted before and after repairs to determine whether the measurements are sensitive to the repairs. Such comparisons should also be done with similar thermal conditions so temperature effects are minimized. Localized NDE such as impact echo, SASW and/or ultrasonic pulse echo scanning may be required to check repairs in specific locations over the long-term.

The system can be established to get real time information at a remote location using wireless technology. Thresholds of changes in frequency can be set up and alert messages can be sent via the wireless system to the pertinent personnel such that immediate steps can be taken to remedy the situation as warranted. In case real time monitoring is not considered to be economically feasible, the baseline measurement can be stored digitally and new readings taken at intervals or

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[36] Sack, Dennis A., Larry D. Olson, and Hunter A. Yarbrough (2006), *Concrete Spillway and Dam Inspection using Nondestructive Techniques*, published in HydroVision 2006 Conference Proceedings and in HydroVision Magazine in 2007.

[37] *Guide for Nondestructive Evaluation Methods for Condition Assessment, Repair, and Performance Monitoring of Concrete Structures*, ICRI Guideline No. 210.4-2009

after an extreme event such as high winds or earthquakes to check whether there has been any distress to the repaired structure that may not be quite visible.

7.4.2 Long-term repair inspection considerations

It is imperative for any long-term repair inspection plan that accurate baseline documents be prepared. As a minimum, the documents should accurately indicate what repairs were done, when the repairs were executed, what materials were used and what specifications were followed in making the repairs.

Different repairs may require different periodicity of inspection. Certain repairs like spall repairs and crack injection repairs may require inspection at more frequent intervals especially if the elements repaired are subjected to dynamic loads. Other repairs like corrosion mitigation by cathodic protection, fixing distress caused by alkali silica reaction (ASR) or augmentation of structural elements using fiber reinforced polymer (FRP) or traditional concrete jacketing methods may not need frequent inspections. The structural engineer of record for the repair is the best judge for preparing the inspection program and specifying what type of inspection needs to be done. Generally, visual inspections may be required at more frequent intervals and NDE at greater intervals.

Chapter 8 CONCLUSION AND SUMMARY

The scope of this report was intended to be an overall snapshot on what should be done to improve the repair of NPP concrete. This report is neither a code nor a standard, but only a set of coordinated recommendations to the SDOs involved with concrete repair of nuclear power plants in hopes of “harmonizing” commonly cited concrete codes and standards. These recommendations only identify gaps, overlaps, or conflicts in existing codes and standards. As the stated objectives were to identify relevant standards and make recommendation for the concrete repair of nuclear power plants, the task group (TG) has succeeded. It is clear that this report is not all-inclusive, and other gaps could be identified, but it is the hope of the TG that it provides a good starting point to investigate how to improve the domain of concrete repair. Chapters 2 to 7 provide a long list of potential gaps in each of the stage of a repair: evaluation, repair strategy and design, repair implementation, and quality control.

The objectives stated in the introduction were addressed in the following fashion:

- *Establish coordination and consistency for safety and non-safety concrete repairs in existing nuclear power plants: evaluate the concrete structure, assess the repair strategy, design and implement the repair and monitor the repair*. The domain of repair was evaluated in regard to the NPPs in all chapters for each phase of a comprehensive repair strategy (as defined in section 2.2). Research needs that would improve the repair strategy were identified as well.

- *Identify repair requirements for safety related concrete components, and develop a plan to incorporate these new requirements into codes and standards. Collaboration with standard development organizations (SDO) will be required.* All chapters have an extensive list of documents produced by SDOs. These documents were studied, and the following questions were addressed: “What needs to changed?”; “Why it needs to be changed.” This information would constitute guidelines for the SDOs to update documents to address the needs of the nuclear industry that are related to the domain of repair.

- *Identify U.S. Nuclear Regulatory Commission (NRC) regulatory documents related to concrete repair for existing nuclear power plants and identify any needs.* This was covered mainly in Chapter 3, but NRC documents were also discussed in various other chapters as relevant.

Some recommendations were identified as touching upon all parts of the document and they are repeated here:

- It was identified that NRC documents often make references to obsolete versions of the SDOs documents. Thus, it is advised here that NRC should have a mechanism to evaluate any new version of an SDO document and determine its adoption or clearly state the reason for rejection
- There is no repair code specific for nuclear structures, such as the document prepared by ACI 562, and it is recommended that such code should be prepared.
- To establish a repair code specific for a nuclear structure, it is important to establish unique characteristics of the nuclear structures as compared to typical highway/building structures, such as safety, risks, and design aspects.

- Research on the effects of radiation on concrete is lacking, especially if combined with the effect of temperature exposure over a long period of time.
- Materials and techniques to be used in an NPP are often approved in a case-by-case basis (each plant needs to approve them). This prevents new technology and materials from being used, as it is costly to obtain approval at each NPP. Thus, a standardized process from NRC should be implemented to pre-approve new technology and materials as it is often done by DOT.
- Models for prediction of service life or repairs, especially taking into account the interaction with the concrete substrate, are non-existent. Also, there is a need for models for evaluation of remaining service life of a damaged structure. This would allow a better evaluation of the type of repair needed and its schedule.
- Standard test methods to evaluate a structure for repair, quality control and quality assurance are few or nonexistent. Thus, more research and development on this topic should be fostered.

This report should be used by SDOs and researchers to improve the knowledge related to concrete repair in nuclear power plants

Chapter 9 INDEX of SDOs' DOCUMENTS

9.1. AASHTO, ANSI, ASCE, ASME, FHWA, NACE, RILEM

SDO	Document number and title	Section	
AASHTO	PP65-11 Standard Practice for Determining the Reactivity of Concrete Aggregate and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction	4.7.1.1	
ANSI	N45.2 Quality Assurance Requirements for Nuclear Power Plants	7.1.1	
ANSI	N45.2.11 Quality Assurance. Requirements for the Design of Nuclear Power Plants	7.1.1	
ANSI/ASME	N45.2.6 -1978 Qualifications of Inspection, Examination and Testing Personnel for Nuclear Power	7.2.2	
ANSI/ASME	NQA-1-1983 , "Quality Assurance Program Requirements for Nuclear Power Plants	7.1.1	
ASCE	11-90 (1991) Guideline for Structural Condition Assessment of 37 Existing Buildings"	3.3.3	
ASCE	11-99 Guideline for Structural Condition Assessment of Existing Buildings	4.2.1	
ASCE	41-2006 Seismic Rehabilitation of Existing Structures" and ASCE 31-200 Seismic Evaluation of Existing Structures	4.2.1	
ASME	Boiler and Pressure Vessel Code, Section XI, Subsection IWL-1992	7.2.2	
ASME	Boiler and Pressure Vessel Code, Section XI, Subsection IWL-2011	7.2.2	
ASME	NQA-1 Quality Assurance Requirements for Nuclear Facilities	7.2.2	
FHWA	RD-03-047-2003 Guidelines for the Use of Lithium to Mitigate or Prevent Alkali- Silica Reaction	4.7.1.1	
NACE	RP0290, 2000, "Standard Recommended Practice - Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures"	5.4	6.4.1
NACE	RP0390, 2006, "Standard Recommended Practice - Maintenance and Rehabilitation Considerations for Corrosion Control of Atmospherically Exposed Existing Steel-Reinforced Concrete Structures"	6.4.1	
RILEM	RILEM Technical Committee 219-ACS, Alkali Aggregate Reaction in concrete structures: performance testing and appraisal	4.7.1.1	

9.2. ACI documents

Document number and title	Section					
116, Cement and Concrete Terminology	3.4					
201, or 201.2R Guide to Durable Concrete	3.4	4.3.1	5.4			
201-68, Guide for Making a Condition Survey of Concrete in Service	3.4	4.2.1	4.3.1			
207, Practices for Evaluation of Concrete in Existing Massive Structures for Service Conditions	3.4					
209R-02 Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures	4.6					
210/207, Erosion of Concrete Hydraulic Structures	3.4					
215, Considerations for Design of Concrete Structures Subjected to Fatigue	3.4					
216, Guide for Determining the Fire Resistance of Concrete Elements	3.4					
222.3R-03 Design and Construction Practices to Mitigate Corrosion of Reinforcement in Concrete Structures”	6.4.1					
222.3R-11 Guide to Design and Construction Practices to Mitigate Corrosion of Reinforcement in Concrete Structures	5.4					
222-89, Corrosion of Metals in Concrete	3.4					
222R-01, “Protection of Metals in Concrete against Corrosion”	6.4.1					
224, Control of Cracking in Concrete Structures	3.4					
224-80 & 224.1R-07, Causes, Evaluation, and Repair of Cracks in Concrete Structures	3.4	4.2.1	6.2.1			
228.1R-03 In-Place Methods to Estimate Concrete Strength	4.2.1	4.4				
228.2R-98 "Nondestructive Test Methods for Evaluation of Concrete in Structures	7.3.2	4.2.1	7.4			
237.R-07 “Self Consolidating Concrete”	6.3.1					
301-10, “Specifications for Structural Concrete”	6.1					
311, Guide for Concrete Inspection	3.4					
318 Building Code Requirements for Structural Concrete and Commentary	3.4	4.5.2				
318-11, Building Code Requirements for Structural Concrete and Commentary	4.2.1	4.7.3	4.10.1	5.4	5.5.1	6.1
349.03R-02 (reapproved 2010), Evaluation of Nuclear Safety Related Concrete Structures	4.2.1	4.2.2	4.2.3	7.2.2		
349.1R, Reinforced Concrete Design for Thermal Effects on Nuclear Power Plant Concrete Structures	3.4					
349.3R, Evaluation of Existing Nuclear Safety-Related Concrete Structures	3.4	2.2.2				

Document number and title	Section					
349-96 & 349-06, Code Requirements for Nuclear Safety Related Concrete Structure	3.4	4.2.1	5.4	5.5.1		
355.2-07 Qualification of Post-Installed Mechanical Anchors in Concrete	5.4	6.2.1				
355.4-10 &11 Qualification of Post-Installed Adhesive Anchors in Concrete	5.4	6.2.1				
359 (ASME Boiler & Pressure Vessel Code Section III, Division 2, Code for Concrete Containments)	5.4					
364, Guide for Evaluation of Concrete Structures Prior to Rehabilitation	3.4					
364.1R-07 Guide for Evaluation of Concrete Structures before Rehabilitation	4.2.1					
364.3R-09 “Guide for Cementitious Repair Material Data Sheet”	5.5.1	6.3.1				
364.6T-02(11) Concrete Removal in Repairs Involving Corroded Reinforcing	5.5.1					
365.1R-00, “Service-Life Prediction – State-of-the-Art Report”	4.11.1					
369R-11 Guide for Seismic Rehabilitation of Existing Concrete Frame Buildings and Commentary	4.2.1	5.4				
437.1R-07 Load Tests of Concrete Structures: Methods, Magnitude, Protocols, and Acceptance Criteria	4.10.1	5.4				
437-12 Code Requirements for Load Testing of Existing Concrete Structures (ACI 437) and Commentary	4.2.1	4.10.1				
437-82 & 437R-03, Strength Evaluation of Existing Buildings	3.4	4.2.1	4.4	4.10.1		
440.2R-08 Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures	6.5.1	5.4				
440.3R-04, “Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures”	6.5.1					
515, A Guide for the Use of Waterproofing Damp proofing, Protective, and Decorative Systems for Concrete	3.4					
546.1R, Guide for Repair of Concrete Bridge Superstructures	3.4					
546.3R-06 “Guide to the Selection of Materials for the Repair of Concrete”	5.5.1	6.3.1				
546-04 Concrete Repair Guide	2.2.2	5.5.1	6.1			
562-12 Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Structures and Commentary	2.2.2	4.2.1	4.10.1	5.4		
563-XX Specification for Concrete Removal and Preparation for Repair:	5.4					
Concrete Repair Manual, Third Edition, 2008	2.2.1	5.4	5.5.1			

9.2.1 ACI and other organizations

SDO	**Document number and title**	**Section**
ACI/ASME	359, ASME Boiler and Pressure Vessel Code	3.4
ACI/ASME	359-07 Code for Concrete Containments	5.4
ACI/ICRI	Concrete Repair Manual – 3rd Edition”	6.1

9.3. ASTM

Document number and title	Section
C1383 - 04(2010)) Standard Test Method for Measuring the P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method	7.3.2
C 512-02 Standard Test Method for Creep of Concrete in Compression	4.6
C 856-11 Standard Practice for Petrographic Examination of Hardened Concrete	4.5.1
C1152 Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete	4.5.2
C1202 Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration	4.5.2
C1218 Standard Test Method for Water-Soluble Chloride in Mortar and Concrete	4.5.2
C1260 Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)	4.7.1.1
C1293 Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction	4.7.1.1
C1543 Standard Test Method for Determining the Penetration of Chloride Ion into 17 Concrete by Ponding	4.5.2
C1567 Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate	4.7.1.1
C1583 / C1583M - 04e1 Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull off Method)	4.2.1
C1740 - 10 Standard Practice for Evaluating the Condition of Concrete Plates Using the Impulse-Response Method	7.4
C227-10 Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar Bar Method)	4.7.1.1
C289 Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method)	4.7.1.1
C295 Standard Guide for Petrographic Examination of Aggregates for Concrete	4.7.1.1
C42-12 Standard Test Method for Obtaining and Testing Drilled Cores and Sawed 9 Beams of Concrete	4.4
C441 Standard Test Method for Effectiveness of Pozzolans or Ground Blast Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction	4.7.1.1
C597-09, Standard Test Method for Pulse Velocity Through Concrete	7.3.2
C876 Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete	4.5.2

9.5. ICRI

Document number and title	Sections	
120.1, 2009 “Guidelines and Recommendations for Safety in the Concrete Repair Industry”	6.1	
210.1, 1998 (under revision) “Guide for Verifying the Field Performance of Epoxy Injection of Concrete Cracks”	6.2.1	
310.1R, 2008, “Guide for Surface Preparation for the Repair of Deteriorated Concrete Resulting from Reinforcing Steel Corrosion”	6.2.1	
310.2, 1997, “Guideline for Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays,”	6.2.1	
310.3, 2004, “Guide for the Preparation of Concrete Surfaces for Repair Using Hydrodemolition Methods,”	6.2.1	
320.1R, 1996 “Guide for Selecting Application Methods for the Repair of Concrete Surfaces”	5.4	6.2.1
320.2R, 2009 ”Guide for Selecting and Specifying Materials for Repair of Concrete Surfaces”	5.4	6.3.1
320.3R, 2007 “Guide for Inorganic Repair Material Data Sheet Protocol”	6.3.1	
330.1, 2006 Guideline for the Selection of Strengthening Systems for Concrete Structures	5.4	6.5.1
340.1, 2006, “Guide for Selecting Grouts to Control Leakage in Concrete Structures”	5.4	6.2.1
201.1-1998, Guide for Verifying Field Performance of Epoxy Injection of Concrete Cracks,” International Concrete Repair Institute Guideline No.201.1-1998 (formerly 03734, and currently being updated – anticipated December 2012)	7.3.1	7.3.2
210.3-2004, Guideline No. 210.3-2004 (formerly 03739): Guide to Using In-Situ Tensile Pull-Off Tests to Evaluate Bond of Concrete Surface Materials	4.2.1	7.3.2
210.4-2009 Guide for Nondestructive Evaluation Methods for Condition Assessment, Repair, and Performance Monitoring of Concrete Structures	7.4	

Appendix A: Request for CRTG

Nuclear Energy Standards Coordination Collaborative

Application for NESCC Task Group

ANSI American National Standards Institute

NIST National Institute of Standards and Technology U.S. Department of Commerce

1.) **Submitter Contact Information:**

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2.) **Task Group Name:** *Repair of Reinforced concrete of Existing Nuclear Power Plants (CRTG)*

3.) **Scope and Objectives of Task Group:**

Scope: Establish coordination and consistency for safety and non-safety concrete repairs in existing nuclear power plants.: evaluate the concrete structure, assess the repair strategy, design and implement the repair and monitor the repair.

Identify repair requirements for safety related concrete components, and develop a plan to incorporate these new requirements into codes and standards. Collaboration with standard development organizations (SDO) will be required.

Identify U.S. Nuclear Regulatory Commission (NRC) Regulatory documents related to concrete repair for existing nuclear power plants and identify any needs.

Objectives: The process will be carried out in a series of sequential steps:

1) Categorize all codes and standards related to concrete repair that are referenced in NRC-regulatory documents:

- Up-To-Date: The reference is the most relevant
- Outdated but Appropriate for Application: An updated version exists
- Reference Needs Revision: The reference is obsolete, or a different code or standard takes precedence

2) Identify relevant repair concrete codes and standards missing from the NRC-regulatory documents
3) Identify technologies and new research that could translated in to new standards and codes to be adopted by an SDO, for instance seismic retrofitting of structures, waterproofing, corrosion repair, pre-stressing tendons and related system repair …
4) Identify new technology and research needs to fill knowledge gaps in existing repair concrete codes and standards

4.) **Expected Results of Task Group:** Inventory of relevant standards with gaps and overlaps analysis. Recommendations for revision or new development of repair concrete standards, review of current citation of concrete codes and standards in NRC regulatory documents.

5.) Name and Contact Information of Task Group Convener:

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6.) Identified Participants:

Participants should be recruited from

- relevant SDOs: e.g. ACI, ASME and AISC
- nuclear power plant industry (NSSS vendors, Engineering Design & Construction (EDC) firms, utilities)
- NRC staff (licensing and inspection)
- accredited/certifying concrete inspectors
- Other experts in specific fields as needed

7.) **Date, Time and Location of Meetings:** TBA in coordination with participants. It is anticipated, that virtual meeting and electronic communication would be utilized as much as possible. Meetings to be held coincident with scheduled relevant technical committee meetings.