CONCRETE DETERIORATION INSPECTION SYSTEM FOR EXTENDING THE OPERATING LIFE OF NUCLEAR POWER PLANTS

by

Daniel Lee Staron

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APPROVED:

Dr. Richard M. Barker, Chairman

Dr. Richard E. Weyers

Dr. Siegfried M. Holzer

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(ABSTRACT)

This study has evaluated the degradation processes which will potentially affect the reinforced concrete structures of a nuclear power generation facility during and beyond its original design life. This task was undertaken in consideration of the feasibility of extending the life of nuclear power plants beyond their current license expiration dates. Following the identification of deterioration mechanisms which are expected to occur, an inspection system was developed to correctly assess and document the condition of the reinforced concrete components during their service life.

Twenty-eight out of thirty-nine possible degradation modes are deemed likely to affect Surry's reinforced concrete structures. The majority of these modes are visually evident in their incipient stages. Currently available nondestructive testing methods were assessed to determine their applicability to detect modes which are not visually evident or to determine the extent of deterioration due to other modes. It was found that many nondestructive testing methods are currently lacking in reliability, portability, or ease of application. Consequently, the developed inspection program is based primarily on visual inspections performed by qualified inspectors.

This report was prepared under the authority of Virginia Power Company in conjunction with the Surry Unit One life extension study.

It is the conclusion of this report that reinforced concrete degradation will in no way impair the usefulness or safety of the concrete structures of a nuclear facility during the 40 year design life provided actions are taken to implement a concrete inspection program similar to that which is described within. This program will allow the detection of potentially critical situations thereby directing the maintenance and repair activities necessary to insure the feasibility of extended life.

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Table of Contents

1 INTRODUCTION 1

1.1 Background 1

1.2 Objective and Scope 2

1.3 Synopsis of Interim Report 5

2 INSPECTION PROGRAM 8

2.1 Establishment of an Inspection Reference System 8

2.2 Inspection Methodology 9

2.2.1 Visual Inspection 9

2.2.1.1 Borehole Techniques 11

2.2.1.2 Underwater Inspection 12

2.2.1.3 Voice-Activated Inspection 13

2.2.2 Physical Testing Methods for Concrete Structures 14

2.2.2.1 Stress Wave Methods 15

2.2.2.2 Surface Hardness Methods 20

2.2.2.3 Penetration Resistance Methods 22

2.2.2.4 Dynamic Deflection Method 23

2.2.2.5 Borehole Logging and Televiewing 23
2.2.2.6 Electrical Methods 24
2.2.2.7 Infrared Thermography 26
2.2.2.8 In-Situ Stress Determinations 27
2.2.2.9 Nuclear Methods 28
2.2.2.10 Pull-out, Break-off, and Pull-off Techniques 28
2.2.2.11 Radar 29
2.2.2.12 Magnetic Methods 30
2.2.2.13 Radioactive Methods 31
2.2.2.14 Microwave Absorption 32
2.2.2.15 Permeability and Absorption Tests 33
2.2.2.16 Coring 33
2.2.2.17 Laboratory Procedures 34
2.2.2.18 Supplemental Instrumentation 37
2.3 Identification of Concrete Degradation at Surry 39
2.3.1 Material Interaction Related Degradation Modes 39
2.3.2 Short-Term Extreme Operating or Load Exposures 40
2.3.2.1 Fire Damage 40
2.3.2.2 Temperature Shock 42
2.3.2.3 Chemical Spills or Leaks 42
2.3.2.4 Short-Term Load Exposures 44
2.3.3 Aggressive Environmental Degradation Modes 46
2.3.3.1 Freezing and Thawing 46
2.3.3.2 Wetting and Drying 47
2.3.3.3 Corrosion of the Reinforcing Steel 48
2.3.3.4 Abrasion 49
2.3.3.5 Erosion of Concrete 50
2.3.3.6 Cavitation 50

2.3.3.7 Acid Rain 51
2.3.3.8 Temperature Changes 51
2.3.3.9 Irradiation 52
2.3.3.10 Seepage 53
2.3.3.11 Fatigue 53
2.3.4 Environment-Stress Interactions 54
2.4 Frequency of Inspections 54
2.4.1 Baseline Inspection of Surry 55
2.4.2 Recurring Inspections 58
2.4.2.1 Routine Inspections 59
2.4.2.2 Periodic Inspections 59
2.5 Inspection Procedures by Plant Component 60
2.5.1 Intake and Discharge Structures 61
2.5.1.1 Intake Structures at River and Station 63
2.5.1.2 Intake and Discharge Canals 65
2.5.1.3 Discharge Tunnels 68
2.5.1.4 Seal Pits and Weirs 68
2.5.2 Containment 69
2.5.3 Remaining Components 71
2.6 Uniformity in Concrete Inspections 74
2.6.1 Rating System 75
2.6.2 Communication 75
2.6.3 Documentation 77
2.6.3.1 Reports 78
2.6.3.2 Records 80
2.6.4 Quality Control 81
2.6.4.1 Quality Control in Documentation 81
2.6.4.2 Quality Control in the Selection of Inspection Personnel 82

3 ADDITIONAL RESEARCH 85

References 88

Appendix A. Interim Report 91

List of Illustrations

Figure 1. Research Approach Taken 4
Figure 2. Degradation Modes Considered 7
Figure 3. Inspection Methodology 10
Figure 4. Applicability of Physical Testing Methods 38
Figure 5. Types of Inspections 56
Figure 6. Suggested Frequency 57
Figure 7. Components of Surry Unit One 62
Figure 8. Achieving Uniformity in Concrete Inspections 76

1 INTRODUCTION

1.1 Background

The Atomic Energy Act of 1954 set the duration of a nuclear power plant operating license at a maximum of 40 years [1]. At the end of this 40 year period a plant may either be granted an extension of its operating license or be decommissioned. Since many existing nuclear facilities are near or beyond the mid-point of their licensed operation period, the decision whether to decommission an aging plant or opt for relicensing has been a recent concern.

Since the mid-1970's several life extension studies have been undertaken and have concluded that major portions of nuclear plants could last much longer than the original license duration [1,2,3]. This is not surprising if one considers the apparent lack of technical basis for the 40 year duration. The selection of this duration was perhaps based on plant depreciation and anticipated improvements in nuclear engineering technology [1].

More-recent studies have concluded that refurbishing plants - even with costs as high as $500 million - would be economically beneficial [1,3]. This conclusion is mainly a result of the relatively high construction and start-up costs associated with nuclear facilities combined with the relatively low cost of nuclear fuel.

A number of contractors have begun studies on Virginia Power's Surry Unit 1 Pressurized Water Reactor (PWR) and Northern States Power's Monticello Boiling Water Reactor (BWR). The goal of these studies is to provide models for life extension practices for other utilities [1,3].

Surry Unit 1 was found to be a good candidate for a life extension pilot study for several reasons. It is considered a good prototype PWR plant; it is in the middle of its operating license (which will expire in 2008); and it was built in the late 1960's, prior to todays more stringent quality assurance documentation and data retention requirements [1,3].

1.2 Objective and Scope

The objective of this research is to investigate the reinforced concrete degradation of Surry Unit 1 in view of the possibility of life extension. For a plant to be granted a renewal of its operating license, the utility must show that the integrity of the plant's components will be maintained throughout the extended life.

Precise calculation of the service life of reinforced concrete is difficult due to the complex interaction between the concrete structure and its environment. However, the life of the reinforced concrete components is expected to be greater than any likely period of plant

life extension, provided neither environmental factors, applied load, nor a combination of load and environmental factors compromise the structural integrity of the reinforced concrete.

The research approach which was taken to achieve the above mentioned objective is depicted in Figure 1 on page 4 and includes four tasks: a site visit to Surry Unit One, a review of pertinent plant records, the conceptual development of the program, and the development of the inspection program itself.

The site visit and review of plant records (Tasks 1 & 2) provided the necessary information to determine the environmental exposure conditions of the reinforced concrete components of Surry, and thus, the susceptibility to the various degradation modes. Upon completion of Tasks 1 & 2, the inspection system concept was developed and an Interim Report was written and submitted to Virginia Power. A synopsis of the Interim Report is included in the following section, and the complete report is included as Appendix A.

The Final Report describes the results of the fourth task: development of inspection procedures to be used in the evaluation of concrete components of Surry Unit 1. The inspection system covers inspection methods, frequency of inspections, preparation of reports and records, and qualifications of the inspection team. The inspection methods employed will consist of any applicable, currently used concrete inspection procedures.

This report presents the basis for the development of a "Concrete Inspection Manual for Nuclear Power Plants." However, the development of such a manual is not included in the scope of this research project.

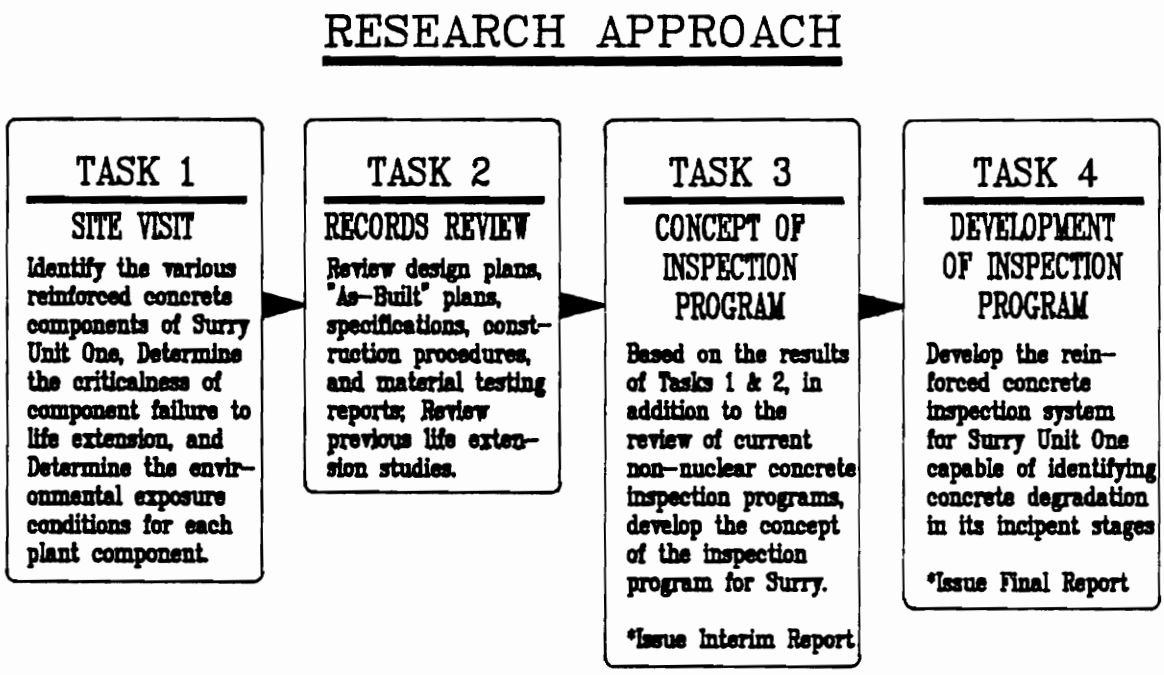


Figure 1. Research Approach Taken

1.3 Synopsis of Interim Report

The two main objectives of the Interim Report were to select the type of inspection system to be developed, and to isolate all possible modes of concrete degradation which might occur over the design life of the plant. The second objective is far more extensive, and it forms the basis for the developed concrete inspection system for Surry Unit 1. The conclusions of the Interim Report, with regard to type of inspection system selected and modes of degradation that were identified, are summarized below.

A Reliability Centered Detection System (RCDS) format was chosen as the basis for the development of this inspection system. This type of inspection system was selected since it possesses three important features. Firstly, decisions are based on failure modes and actual case histories of failures; secondly, all failures are classified as either safety, operational, or consequence related; and finally, the system is oriented towards practical decision making. Once this type of inspection system was selected, all possible modes of concrete degradation were identified and investigated.

Thirty-nine modes of concrete degradation were identified as being applicable to reinforced concrete. These possible modes of degradation are categorized as either: material interaction related mechanisms, aggressive environmental exposures, short-term operating or load exposures, or environment-stress interactions. The probability of occurrence of each mode for each plant component was assessed and assigned a number (1-4) indicating the probability of that component experiencing the specified mode. Only the modes which carry a probable occurrence value of 2 or greater (28 out of 39) are in-

cluded in the developed concrete inspection program for Surry Unit 1. The included degradation modes are displayed in Figure 2 on page 7.

The mechanics of each mode, as well as a description of the plant components, are included in the Interim Report and will not be repeated here. Also included in the Interim Report are the component versus degradation matrices which indicate the possibility of the tabulated modes occurring at the various plant components.

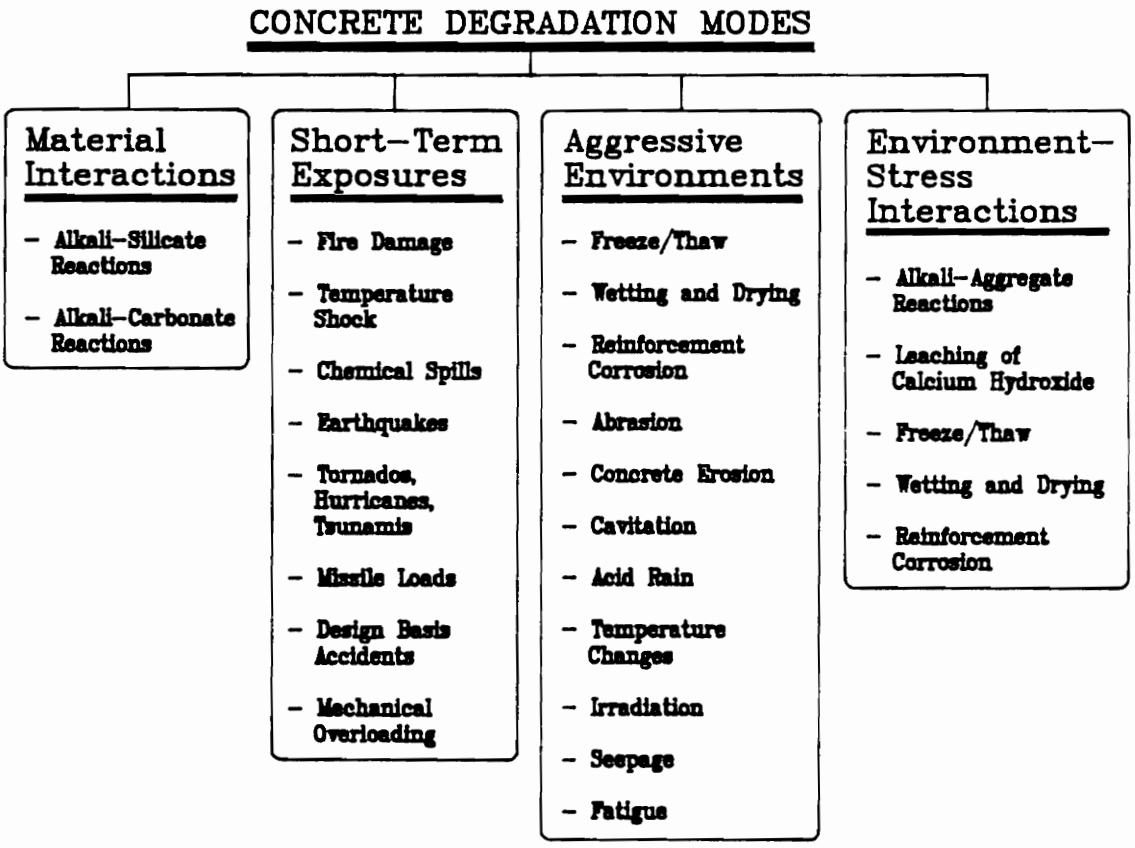


Figure 2. Degradation Modes Considered

2 INSPECTION PROGRAM

2.1 Establishment of an Inspection Reference System

Since many of the concrete components at Surry are large and complex structures, a reference system is required in order to specifically identify locations in the plant for reference in future inspections. Therefore, prior to the initial inspection of the concrete components at Surry, an inspection reference system must be established. Two possible reference systems are suggested.

One possible reference system would consist of locations being identified by a plant-wide three-dimensional system of coordinates. The control point for the system would be the nearest established survey marker at which the elevation and horizontal coordinates are known.

Another possible reference system for inspections would be one which is local to each plant component. In the vicinity of each component a control point would be established. Quite possibly such bench marks currently exist throughout the plant. The lo-

cations of anomalies found during an inspection would be referenced to these control points in the reports and records compiled during, and following an inspection.

The second of these two alternative reference systems is recommended for Surry's concrete inspection program since its implementation would be easier to accomplish, thus resulting in lower cost.

2.2 Inspection Methodology

The basic feature of current concrete inspection programs is that of visual inspection followed by a sequence of physical tests selected according to cost, convenience, and suitability [4]. The inspection system developed for Surry Unit 1 retains this basic feature since it represents the most logical approach to concrete inspection system development [5]. Figure 3 on page 10 indicates the basic characteristics of visual inspection and physical testing.

2.2.1 Visual Inspection

The type of reinforced concrete evaluation most widely used is that of visual inspection. Visual inspection conforms quite well to concrete structures since many of the modes of concrete degradation exhibit visual signs in their incipient stages.

Concrete deterioration may be related to workmanship, structural serviceability, or material deterioration and is often indicated by surface cracking and spalling [4]. Because

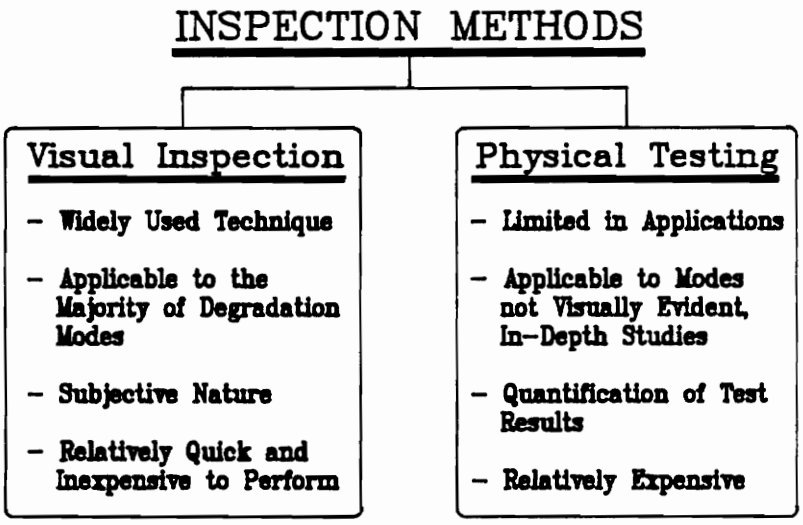


Figure 3. Inspection Methodology

of similarities, it will often be impossible to determine the cause of deterioration by visual inspection alone. However, an examination of the crack patterns by trained personnel will provide an indication of the cause and will enable the most worthwhile application of physical testing.

The most severe drawback of visual inspection is its subjective nature. Each inspector is likely to view or evaluate this type of qualitative data in a slightly different manner. Section 2.6 addresses the aspects of achieving uniformity in concrete inspections, including reducing the subjectiveness of visual inspections.

Because they are closely related to visual inspection, borehole photography and televiewing, underwater inspection, and voice-activated inspection will also be discussed herein.

2.2.1.1 Borehole Techniques

Borehole techniques involve the drilling of a borehole which is then inspected by various methods which include borehole photography, television, logging, and televiewing [6]. The first two techniques, borehole photography and television, are visually supplemented methods and thus will be discussed herein. Borehole logging and televiewing are not visual in nature and therefore are discussed in Section 2.2.2, Currently Used Physical Test Methods.

The visually related borehole techniques are either used to inspect inaccessible regions, such as the interior of box-beams or thick, voided slabs, or to examine the interior concrete of a structure. The first application is not required at Surry due to the absence of

these structural types. In addition, although the second application may provide valuable evidence during concrete inspections, it too is deemed undesirable since holes with a minimum 3-inch-diameter must be drilled [6].

2.2.1.2 Underwater Inspection

Many states now require underwater inspection in their bridge maintenance and inspection programs [7]. The application of underwater inspection to Surry's concrete inspection program would involve inspection of the portions of the intake and discharge structures and the intake canal which are below the waterline. Underwater inspections would reveal concrete deterioration, the occurrence of silting, cavitation, concrete erosion, and the water-tightness of the joints.

Underwater inspections may be conducted with sonar, trained divers, or remotely operated vehicles. Sonar inspection involves directing generated sound waves into the water and receiving an echo response to detect bottom surface irregularities. The output from sonar devices usually consists of a chart of the surveyed bottom surface.

Divers trained as concrete inspectors are also currently used to inspect underwater concrete surfaces. The divers usually visually inspect concrete and record observations with photographs or video cameras. In addition to visual observation, divers may be outfitted to remove cores for petrographic or chemical analyses.

Remotely operated vehicles are currently used to inspect regions not accessible to divers or inappropriate for surface sonic inspection. Remotely operated vehicles may perform tasks such as cleaning, sampling, video inspection, or sonic charting. Remote vehicles

are advantageous since they may be operated in environments not desirable for diving (e.g., cold or deep water). Lights may be added to allow for video inspection in dark or low visibility water.

2.2.1.3 Voice-Activated Inspection

Voice-activated inspection systems (VAIS) have recently been developed to increase inspector efficiency and to expedite the documentation of conditions observed during concrete inspections.

A VAIS allows an inspector to verbally record inspection observations into a portable recording device. Following the inspection, the tape is played in a tape deck which is attached to a personal computer which includes a voice recognition card. The VAIS system translates the inspectors comments into a concise, prioritized report omitting further human effort and time. In addition to saving labor in the preparation and processing of reports, the VAIS also has the capability of transporting data for other purposes (e.g., interfacing with spreadsheets or other data management programs). Currently, such a system is being developed by the U. S. Army Corps of Engineers [8] and is expected to be commercially available in early 1988. The system holds much promise and is suggested for Surry's concrete inspection program pending its successful completion and testing.

2.2.2 Physical Testing Methods for Concrete Structures

Several testing methods exist for the evaluation of concrete in-service. The process of test selection is based on consideration of the most appropriate tests to meet the aims of the investigation and the extent and number of tests required to reflect the true state of the concrete. In addition, cost, speed, degree of nondestructiveness, and the reliability of each method should also be considered.

A large number of nondestructive techniques were developed primarily for quality compliance testing in new construction [5]. These methods are only included where they can be used to assess the serviceability of the existing structures at Surry.

It should be mentioned that there are only a few scientific principles on which nondestructive testing methods are based [5]. As a result, most of the techniques have limitations which must be realized prior to their successful application. In addition, although some standardization of nondestructive techniques exists, standards are still needed in establishing inspection methodologies, aiding in the analysis of the data obtained, and developing pass/fail rules or criteria to assist in decision making [9].

Due to this lack of standardization of several concrete inspection procedures, in addition to the few scientific principles upon which the testing methods are generally based, engineering judgment is inevitability required when interpreting test results. The employment of qualified inspection personnel is of paramount importance and is discussed in detail in Section 2.6.4.2, Quality Control in the Selection of Inspection Personnel.

Although current and future research may allow the successful application of some of the test methods which currently do not appear feasible, the discussion herein is based on the available techniques and applications at the time of this writing.

Each category of physical tests will be discussed including a description of the testing procedure, comments on test advantages and disadvantages, and a description of the equipment and/or access required. In-situ testing methods are discussed first, followed by laboratory techniques and supplemental instrumentation.

2.2.2.1 Stress Wave Methods

Stress wave methods (sometimes referred to as Dynamic or Vibration methods) are one means of detecting defects in reinforced concrete structures. The methods attempt to detect changes in response to mechanically or electronically generated stress waves (or elastic waves) which are transmitted by direct contact between molecules [5]. The boundary between flaws or discontinuities and sound material offers differing resistance to the passage of stress waves. Thus, waves passing through a material will strike either a flaw or a external surface and the reflected vibrations can indicate the location and type of reflecting surface. Stress wave methods include acoustic impact methods, the resonant frequency method, and pulse-velocity methods.

2.2.2.1.1 Acoustic Impact Methods: Acoustic impact or sounding methods are techniques which involve striking the concrete surface in some manner while monitoring the changes in the acoustic response [5]. The changes in acoustic response reflect changes in concrete uniformity or soundness.

The two most common forms of acoustic impact methods are hammer sounding and chain drag surveys. Hammer sounding involves tapping the concrete surface with a hand-held hammer while listening to the response. Although hammer sounding is tedious because only small regions may be checked at a time, the method is a quick and inexpensive technique and when used in conjunction with visual inspection provides an indication of possible regions of distress for further investigation. It is in this context that hammer sounding is included in Surry's concrete inspection program.

Chain drag surveys have long been used to locate regions of delaminations when inspecting bridge decks [5,10]. The method consists of dragging a group of chains across horizontal concrete surfaces while listening to the response. The loss of accuracy in chain drag surveys is offset by the low cost and high efficiency of the method. However, chain drag surveying is not suggested for Surry since the method can only be applied to horizontal surfaces and background noise must be a minimum.

In addition to hammer sounding and chain drag surveys, another method was developed for sonic inspection of bridge decks. The equipment, known as a Delamtect, consists of a tapping device, a sonic receiver, and a signal interpretation system [5]. As the equipment is wheeled across the deck, acoustic signals are generated, propagated through the concrete, received, and electronically interpreted. Although the Delamtect is not influenced by background noise, it is less accurate than a chain drag survey [5]. Thus far, attempts to adapt the Delamtect to vertical surfaces have not been successful [5]. Due to these drawbacks, the Delamtect is not deemed suitable for Surry's concrete inspection program.

2.2.2.1.2 Resonant Frequency Method: The resonant frequency method is a nondestructive technique which involves the determination of the natural frequencies of vibration of concrete specimens which are then related to the velocity of the propagated stress waves [5,10,11]. The method has been standardized by the American Society for Testing and Materials (ASTM).

Although the method has been used for following the degradation of concrete specimens in laboratory durability studies (usually accelerated freeze/thaw and aggressive alkali/acid exposure tests), field application is neither currently feasible, nor desirable [5,6,11].

2.2.2.1.3 Pulse-Velocity Methods: Pulse-velocity methods involve measurement of stress wave velocities in a solid media. Variations in these velocities will indicate delaminations or internal cracking [2,4,5,6,10,11,12]. Pulse-velocity methods may be divided into two distinct categories based on the means of stress wave generation.

2.2.2.1.3.1 Mechanical Sonic Pulse-Velocity Methods: Mechanical sonic pulse-velocity methods involve measurement of travel times of compression waves generated by a single hammer blow or by repetitive blows [5,11]. Sonic pulse-velocity methods include pulse-echo, microseismic refraction, and low-level acoustic emission techniques.

The pulse-echo technique is suited to concrete structures which have only one accessible surface. A single blow is applied to the surface of the concrete by a hammer or falling weight and shock waves are detected as they reflect from the opposite boundary (back surface, crack plane, or deteriorated area) [2,4,6,12]. Although the technique has been used to determine the soundness and continuity of driven concrete piles [4,6], the appli-

cability to concrete structures in general is still under development [4,12] and thus the method is deemed inapplicable to Surry's concrete inspection program.

Microseismic refraction is a miniaturized geophysical technique. A series of receiving transducers are placed along a survey line on the concrete surface. The difference in travel time between the waves travelling near the surface and those refracted from an underlying interface are detected and recorded. Although the procedure is capable of detecting differences between sound and unsound concrete, the method is considered impractical because it is time consuming and the data is difficult to interpret [5,10]. Microseismic refraction is not recommended for Surry's concrete inspection program.

Low-level acoustic emission techniques involve the detection of minute perturbations in stress waves created by localized deformations [4,5,6,11,13]. Piezoelectric sensors are attached to the concrete surface to detect these perturbations. Although the method has been used to assess in-situ strength and detect crack growth, the application to concrete structures is in its infancy and there are still serious difficulties to be overcome [4,5,6,11]. It is not suggested for Surry's concrete inspection program.

2.2.2.1.3.2 Ultrasonic Pulse-Velocity Methods: Ultrasonic pulse-velocity techniques have been in use for over 30 years [2,4,9,11]. These methods involve measurement of travel times of electronically generated mechanical pulses through concrete. The high frequency sound waves travel at a velocity which is related to the density and the elastic properties of the concrete. The sound waves are reflected at interfaces, and thus voids, discontinuities, and flaws may be detected.

The repetitive voltage pulses are generated electrically and transformed into waves of mechanical energy by a transmitting transducer. The transducer is coupled to the con-

crete surface by a suitable acoustic medium such as grease, petroleum jelly, or liquid soap. A similar receiving transducer is also coupled to the concrete at a known distance from the transmitter and the mechanical compression wave is converted back to an electrical pulse. An electrical timing device measures the travel time of the wave and it is displayed on an oscilloscope or digital meter.

Three transducer arrangements may be used when measuring pulse-velocities through concrete: direct transmission, semi-direct transmission, and indirect or surface transmission.

For direct transmission, the transducers are placed on opposite sides of the concrete surface to be inspected. Since the maximum pulse energy is transmitted normal to the surface of the concrete, the direct method provides the most reliable results of the three orientations [4,5,11]. Also, the path length is clearly defined and can be accurately measured. The direct approach should be used whenever possible.

Semi-direct transmission involve placing the transducers on two adjacent concrete surfaces meeting at an angle; usually 90°. This is usually the case when a test path extends across the corner of a large mass of concrete. This arrangement can provide accurate results if the angle between the transducers is not great, and if the path length is not long [4]. Although the path length is not clearly defined, it is generally taken as the center-to-center distance between the transducers [4].

The indirect or surface transmission method is the least desirable arrangement [4,5,11]. Since both the transmitting and receiving transducers are placed on the concrete surface, the received signal is dependent upon scattering by discontinuities and therefore is highly subject to errors [4].

In addition to transducer placement, the presence of reinforcing steel affects the results of pulse-velocity measurements [2,3,4,5,11]. Generally, it is desirable to choose paths that avoid the influence of reinforcement. When this is not possible, the measured values must be corrected. When the axis of the reinforcement is perpendicular to the direction of wave propagation and the quantity of reinforcement is small, the influence of the steel will also be small. When the axis of wave propagation is parallel to the reinforcement, the influence can be substantial. In heavily reinforced structures, the influence of the reinforcing steel may not be avoided and it is mandatory to use direct transmission in order to produce reliable results [5,11].

Despite these drawbacks, pulse-velocity measurements have been found to be a reliable indication of the overall quality of concrete and are deemed applicable to Surry's concrete inspection program. A number of qualitative scales have been published to relate pulse-velocities to the concrete quality.

Currently, ultrasonic pulse-velocity equipment is compact, battery operated, and fully portable [4,5,6,12]. The PUNDIT (Portable Ultrasonic Non-Destructive Digital Indicating Tester) and the V-Meter are probably the best known ultrasonic pulse-velocity devices in North America [5].

2.2.2.2 Surface Hardness Methods

Surface hardness testing of concrete includes indentation and rebound methods. Both of these procedures measure the hardness of the concrete surface which in turn is then empirically related to the concrete strength.

The first indentation tests were performed in the 1930's [4,11]. The concrete surface was impacted by a standardized mass which was activated by a known amount of energy. The size of the indentation was then measured and related to the concrete strength.

Indentation test methods have been used in Germany, the USSR, and the United Kingdom but have not gained acceptance in North America [4,5]. Also, indentation tests are considered semi-destructive and are not very accurate [2,5]. For these reasons, indentation methods are not included in the developed concrete inspection program for Surry.

Rebound methods, on the other hand, have been more widely accepted [4,5,6,11]. The rebound method correlates the rebound of a spring loaded plunger to the strength of the concrete. The only known instrument utilizing this principle is Schmidt Rebound Hammer (or Swiss Hammer) [5,11]. The hammer is inexpensive, rugged, and easy to use, but serious limitations exist [2,4,5,11].

Rebound hammer readings are sensitive to the angle of the test, the type of coarse aggregate, the mix proportions, the surface smoothness, the moisture content, and the presence of surface carbonation [2,4,5,6,11,12]. Since there are numerous factors affecting the results, the rebound hammer is most useful in evaluating the uniformity of the concrete in a structure or in isolating the extent of a deteriorated region. Whatever the application, it should be remembered that the results only reflect the state of the ***surface*** region of the concrete under investigation.

In regard to Surry's concrete inspection program, it is concluded that the rebound hammer will be effective in determining the extent of deteriorated regions caused by the

various degradation modes which reduce the strength of the concrete at and/or near the concrete surface by detecting relative differences in the compressive strength.

2.2.2.3 Penetration Resistance Methods

Penetration resistance methods involve the firing of a projectile into a concrete mass. One such technique is the Windsor Probe test which was developed in the mid-sixties and is the best known example of a penetration resistance procedure [4,5,6]. Use of the Windsor Probe in North America has been extensive and in some cases it is accepted in lieu of control cylinders for compliance testing [4].

The test is performed by firing hardened alloy probes into the concrete in a triangular pattern. The exposed lengths of the individual probes are measured by a calibrated gage and averaged. Since the probes may penetrate the concrete up to 2 inches [4,5], the method is customarily considered a penetration method rather than a surface hardness method.

The Windsor Probe test is affected by the size and distribution of the coarse aggregate in the concrete and less affected by the surface moisture, texture, and carbonation than are Schmidt Hammer results [5]. However, the Windsor Probe's main advantage is in assessing the in-situ strength of the concrete when coring is difficult. Although the Windsor Probe method is semi-destructive, the method may still prove useful in measuring the relative differences in the surface properties of the concrete and thus would be useful on a limited basis. Therefore, the Windsor Probe is included as a feasible testing technique in Surry's concrete inspection program.

2.2.2.4 Dynamic Deflection Method

The dynamic deflection method involves application of a sine wave repetitive force or oscillatory type load to slab-like or continuous concrete systems such as floor slabs or pavements [6]. The deflections of the system are monitored and are related to the condition of the structural system or integrity of the support conditions. The method has been successfully used to locate void areas beneath a concrete-lined river channel [6].

The probable application of dynamic deflection testing at Surry would be to locate regions of undermining beneath the intake canal. This application is not desirable since the canal would have to be dewatered prior to testing [6]. Consequently, the dynamic deflection method is not considered applicable to Surry's concrete inspection system.

2.2.2.5 Borehole Logging and Televiewing

Several drill hole logging techniques often used in the oil industry may be utilized to provide the porosity and density of in-situ concrete [6,12]. Although these parameters may give an indication of the susceptibility of the concrete to deterioration, they will not indicate whether or not a specific degradation mode is occurring. For this reason, in addition to the fact that the method involves the drilling of holes, borehole logging is deemed inapplicable to Surry's concrete inspection program.

Borehole televiewing involves probing a borehole with a continuously rotating piezoelectric transducer which emits bursts of acoustic energy [6]. The amount of energy reflected by the wall is a function of the physical properties of the surface. Voids, cracks, and fractures can be detected from televiewer logs. Although borehole televiewing may

provide valuable information about the concrete, this method of inspection is not suggested for Surry since borehole drilling is required which is undesirable due to its destructive nature.

2.2.2.6 Electrical Methods

Currently, electrical methods are limited to electrical potential and electrical resistivity measurements [5]. Both of these techniques are used to determine the possibility of the occurrence of reinforcement corrosion. High-frequency capacitance measurements for determining moisture content and polarization studies for measuring corrosion rates have been made in the laboratory but equipment suitable for field use has not yet been developed [5].

2.2.2.6.1 Electrical Potential Method: The measurement of half-cell potentials to indicate corrosion is well established [10]. When steel corrodes in concrete, a potential difference exists between the anodic half-cell areas and the cathodic half-cell areas along the bar. The potential of the corrosion half-cells can be measured by comparison with a standard reference cell which has a known, constant value. A copper-copper sulfate half-cell is normally used in the field since it is inexpensive, rugged, and reliable [4,5].

In order to apply the method, access to the reinforcement is required. This can usually be obtained by drilling into the concrete above a reinforcing bar. It is suggested that a check be made to insure that good contact has been made and that the steel is continuous by measuring the resistance of the reinforcing steel at another location.

The test is performed by connecting one lead of a voltmeter to the reinforcing steel. The other lead is connected to the reference cell which is then moved over the concrete surface in an orderly manner. At each location the electrode potential is measured and recorded. Based on the readings, the probability of corrosion occurring may be assessed.

Although the method provides an indication of the potential for corrosion at the time of the measurement, no information about the rate of corrosion can be obtained [4,5,10]. Since corrosion rates are primarily controlled by the resistivity of the concrete and the availability of oxygen at the steel surface, it is possible to have high potential measurements but low corrosion rates [5]. Also, since corrosion is an electrochemical process, it is temperature dependent and thus readings will change with the time of the year.

Although these disadvantages exist, the method is attractive since it is straightforward to carry out, relatively quick, and the only nondestructive test currently available which provides a direct measure of the corrosion activity [5]. For these reasons, electrode potential measurements will be included in Surry's concrete inspection program to detect corrosion in its incipient stages.

2.2.2.6.2 Electrical Resistivity Measurement: The resistivity of concrete is one of the factors which controls the rate of corrosion of steel in concrete [5]. As concrete resistivity increases, corrosion currents decrease thus reducing the possibility of corrosion occurring.

All measurements of concrete resistivity are made with an alternating current meter to eliminate polarization effects. Concrete resistivity measurement is currently performed by employing the four-electrode method common in geophysical testing [4,5,11]. Four contacts are placed on the concrete surface along a survey line. An alternating current

is passed between the outer electrodes and the resulting potential difference between the inner electrodes is measured and the concrete resistivity may be computed.

The major disadvantage of the method is that the surface resistivity dominates the measurements while the resistivity of the concrete in contact with the steel is of primary interest [5]. Also, the presence of surface moisture may result in electrode shorting, and thus, invalid results. In addition, the resistivity associated with corrosive activity is currently somewhat uncertain. Due to these limitations, electrical resistivity measurements are not considered suitable for concrete inspection at Surry and will not be considered in the developed concrete inspection program.

2.2.2.7 Infrared Thermography

The use of infrared thermography, in which infrared photographs are taken during the cooling of a heated structure, has been utilized to detect delaminations in concrete structures (in particular, concrete bridge decks) [2,4,5,10]. The detection of delaminations by infrared thermography is based on differences in surface temperatures between sound and unsound concrete. As concrete heats and cools, a substantial thermal gradient develops within the concrete due to its poor thermal conductivity. As a result, variations in surface temperatures due to the presence of delaminations will be observed. The time and power required to heat concrete to establish the necessary thermal gradients prevent the use of artificial heat sources [5].

The infrared thermography equipment consists of an infrared scanner, a control unit, a battery pack, and a display screen [5]. To provide a hard copy of test results, the images

are usually recorded on photographic plates or videotape. The equipment is readily available on a rental basis [5].

One disadvantage of infrared thermography is the need for the concrete component to be directly exposed to sunlight. Also, the presence of moisture on the concrete surface will affect the results because of its high emissivity [5,10]. Probably the most discouraging disadvantage of the technique is that while a positive result is valid, a negative result may mean that the structure is either free from deterioration or that it contains deterioration which could not be detected during prevailing conditions during testing [4,5,10].

In regard to Surry's concrete inspection program, it is concluded that infrared thermography may be useful in detecting deterioration in concrete which is exposed to sunlight, excluding those structures which will not heat evenly due to geometry or location (i.e., surface curvature or partially shaded regions may contribute to uneven thermal gradients, and thus, unreliable results).

2.2.2.8 In-Situ Stress Determinations

Over-coring and Flatjack methods have been in use for the in-situ stress determination in rock mechanics for some time. The extension of these methods to evaluate the in-situ stress in concrete materials has been performed [6,12]. These methods are valuable in evaluating the effects of observed distress due to materials deterioration and excessive dynamic or static loading.

The determination of existing stress conditions may be necessary to assure the safety of the structure. Observed stress conditions can be compared to design values and existing strength levels. These methods may provide valuable information in the event of a short-term extreme operating or load exposure and thus are included in Surry's concrete inspection program.

2.2.2.9 Nuclear Methods

The main application of nuclear methods is the measurement of moisture content by neutron absorption and scattering techniques [4,5,11]. By determining the moisture content of concrete structures, the probability of corrosion of the steel reinforcement may be assessed. Although these methods have been successfully applied in the laboratory environment, the equipment is expensive, heavy, and not currently commercially available [5,11]. For these reasons, nuclear methods are not included in Surry's concrete inspection program.

2.2.2.10 Pull-out, Break-off, and Pull-off Techniques

Each of these techniques attempts to assess the in-place concrete compressive strength. Pull-out testing involves measuring the force required to pull a bolt or similar device from the concrete surface [2,4,11]. Break-off methods are intended primarily as a quality control test for concrete pavements [4]. Pull-off techniques are similar to pull-out methods but require a steel bracket to be epoxied to the concrete surface as opposed to embedding a bolt or stud [4].

All of these techniques are destructive in nature and require the repair of the concrete surface. In addition, these methods produce an estimate of the concrete compressive strength which can not be directly correlated to the occurrence of any particular degradation mode (although compressive strength is affected by several of the deterioration modes). For these reasons, these methods will not be employed in Surry's concrete inspection program.

2.2.2.11 Radar

Low-power, high-resolution radar has been used since the mid-seventies to detect deterioration in pavements and bridge decks [5,10]. A pulse of low-power radio frequency energy is directed into the concrete and the echo is received and displayed on an oscilloscope. Delaminations and voids will be detected due to their effect on the reflected signal [5,10,13,14].

The equipment consists of a monostatic antenna, a transmitter, a receiver, and an oscilloscope [5,10]. A permanent record of the oscilloscope traces can be stored on film or analog magnetic tape. The equipment is usually mounted on a cart or vehicle. As the vehicle moves slowly across the concrete surface, the antenna usually scans a "footprint" of 1 square foot. The only environmental constraint is that the concrete surface must not be wet [5,10].

Although the technique has been tested in several concrete applications in the laboratory, the difficulty of analyzing the large amount of data that is collected remains a problem [5,10,13]. Lack of experience in interpreting the data has led to a number of false results [10]. Also, there are only a few systems available and most are not portable

enough for field use. Consequently, radar is not currently considered feasible for Surry's concrete inspection program for the detection of deterioration and voids.

In addition to applications to detect deterioration, radar has been used to determine the location of reinforcement in concrete structures. As of 1984, approximately 50% of all U.S. nuclear power plants were using radar to accurately locate reinforcement [15]. Although the data interpretation requires a certain amount of skill, radar is deemed applicable to Surry's concrete inspection program for the detection of rebar as required to perform electrical potential measurements (refer to Section 2.2.2.6.1, Electrical Potential Method).

2.2.2.12 Magnetic Methods

Electromagnetic methods are commonly used to determine the location and cover to steel reinforcement embedded in concrete [4,5,6,11]. Such devices are commonly referred to as pachometers or cover meters. It is generally agreed that these devices can measure cover to within ¼ inch to depths of 3 inches (although the manufacturers state greater capabilities) [5].

These methods operate on the principle that the presence of a magnetic material (such as steel) will affect the field developed by an electromagnet. The degree of distortion of the magnetic field is a function of the bar diameter and the distance from the probe, and can be measured on a calibrated meter. All current versions of the equipment are portable, compact, and battery operated.

Although cover meters and pachometers have been shown to be effective in determining the size or depth of reinforcement in ***lightly reinforced*** structures, their applicability to heavily reinforced structures is limited [4,5,11]. In addition, metal tie wires, if present, will also distort magnetic field readings [4,5]. Also, the performance of these methods is adversely affected by temperatures below freezing [4,5,11].

Despite these drawbacks, magnetic methods may be incorporated into Surry's concrete inspection program for the purpose of rebar location and/or depth in lightly reinforced structures. The determination of reinforcement location is necessary to perform electrical potential measurements.

2.2.2.13 Radioactive Methods

Three radioactive methods of concrete inspection currently in use are: X-Ray Radiography, Gamma-Ray Radiography, and Gamma-Ray Radiometry. Radiography involves essentially taking a "photograph" through a specimen to reveal the interior, while radiometry involves the use of a concentrated radiation source and detector [4,5].

X-ray and gamma-ray radiography have been shown to be useful in detecting concrete deterioration [2,4,5,11]. The only difference in these two methods is the origin of the radiation [5,11]. This difference is significant because x-ray equipment has high initial cost, produces high voltages, and is not currently portable. As a result, x-ray radiography is not deemed applicable to Surry's concrete inspection program.

Gamma-ray radiography involves the detection of gamma radiation by a photographic emulsion. Variations in the density of the exposed film reflect the internal structure of

the material under examination [5]. Standard x-ray film is used and is placed against the back face of the concrete; thus, access to both sides of a member is required [4].

While this technique has gained considerable acceptance as a nondestructive inspection technique for concrete, the main applications have been for detecting defects in prestressed concrete structures, in particular to assess the position or condition of prestressing cables or to detect voids in the grout [4,5,11]. The technique is further limited due to the expense and stringent safety precautions that are required [4,11]. Therefore, gamma radiography is not suggested for concrete inspection at Surry.

Gamma radiometry incorporates a Geiger or scintillation counter to detect variations in gamma radiation produced by a concentrated source [4,5,11]. Current applications include the measurement of in-situ density and thickness. Although the density of a concrete will generally affect its resistance to deterioration, assessing the in-situ density at Surry will not indicate the occurrence or non-occurrence of a degradation mode. For this reason, this method is not considered applicable to Surry's inspection system.

2.2.2.14 Microwave Absorption

Microwave absorption incorporates electromagnetic waves to determine in-situ moisture content of concrete. This is possible since microwaves are absorbed by water at a higher rate than by concrete [4,11]. The method is not included in Surry's concrete inspection system since assessing the in-situ moisture content will not indicate whether or not a particular degradation mode is occurring.

2.2.2.15 Permeability and Absorption Tests

This group of tests includes air permeability tests which can indicate the concrete's resistance to carbonation, penetration of aggressive ions, and the quality of grout in post-tensioning ducts [5]. Permeability tests can also be used to assess the possibility of water penetration in water retaining structures [4]. With the exception of aggressive ion penetration, all of the other above mentioned permeability and absorption techniques are inapplicable to Surry.

Air permeability can be used to indirectly assess the possibility of corrosion activity by assessing the concrete's resistance to aggressive ion penetration. Although the application of the method has been performed in Denmark and Japan, it is still considered experimental in the United States [5]. Thus, it is not included in Surry's concrete inspection program.

2.2.2.16 Coring

Cores taken from selected areas which exhibit distress can provide valuable information about the interior condition of a concrete structure. The examination and testing of cores is well established and it enables visual inspection of interior concrete coupled with strength estimations [4]. Although cores can be taken from concrete structures and the concrete can be repaired rather easily, core drilling is expensive and should only be considered when sampling and testing of the interior concrete is deemed necessary [4,6,12].

Guidelines on drilling and transporting concrete cores can be found in references [4,6,12], as well as, ASTM C42, ASTM C823, and ACI 318-83.

Coring is recommended for Surry if evidence exists which suggests the structural integrity of a plant component may be compromised due to severe deterioration. Laboratory procedures to be performed on these drilled cores or other concrete samples are discussed in the following section.

2.2.2.17 Laboratory Procedures

Laboratory procedures can conveniently be divided into: petrographic techniques, physical tests, and chemical tests [5].

2.2.2.17.1 Petrographic Analyses: Petrographic analyses are detailed examinations of the material, composition, and structure of concrete. The analyses may include identification of material aggregates, examination of paste-aggregate interfaces, and an assessment of the structure and integrity of the paste itself [5]. Specimens are usually prepared by polishing the surface, etching the surface, or grinding thin sections. These analyses should be performed by a person qualified by education and experience in operating the required equipment.

Petrographic analyses are very useful in identifying deterioration mechanisms such as freeze/thaw, sulfate attack, and alkali-aggregate reactions [5]. Guidelines for petrographic analysis are included in ASTM C856 - "Recommended Practice for Petrographic Examination of Hardened Concrete."

2.2.2.17.2 Physical Laboratory Tests: Physical laboratory tests include strength determinations, air-void system measurement, chloride permeability tests, and thermoluminescence measurements.

Strength tests are commonly conducted on cores to determine the compressive strength and elastic moduli. The tensile strength can also be determined using cores. Cores which are obtained for strength tests should preferably have a diameter which is three times the maximum aggregate size and at least twice the maximum nominal size of the coarse aggregate [4,5,12].

Air-void system measurements can be obtained by either the linear-traverse or modified-point-count methods [5]. Both of these methods are currently considered the best tests for assessment of the concrete's resistance to freeze/thaw damage [5].

A relatively new laboratory method is the rapid measurement of chloride permeability. The test consists of passing an electric current through a 2-inch-long core while one end is immersed in sodium chloride solution and a potential of 60 volts is maintained for 6 hours [5]. The total charge which passes through the specimen is recorded and then related to the chloride permeability.

Thermoluminescence testing involves the monitoring of the visible light emission which occurs on heating certain minerals. The test has recently been used to assess the extent of fire damage for concrete. The method requires the heating of sand which has been extracted from concrete which has been exposed to high temperatures. In natural occurring quartz sand, light is emitted between temperatures from 300°C to 500°C [4]. If samples are reheated, there is no emission of light up to the temperature of the previous heating. Thus, by heating the sand in an oven and recording temperature versus radi-

ation detected, the range of temperature to which the concrete was exposed can be estimated.

Although the method offers considerable potential for the detailed investigation of the extent and severity of fire damage, thermoluminescence testing is still in the development stage and thus is not include in Surry's concrete inspection program.

2.2.2.17.3 Chemical Test Methods: Two chemical testing methods of great importance relative to concrete durability are depth of carbonation and chloride ion content tests [5].

The depth of carbonation can be measured by exposing a fresh concrete surface to a 2% solution of phenolphthalein in ethanol. Phenolphthalein is a commonly used indicator which exhibits a color change at about 10 pH. A fresh concrete surface can be obtained by chipping a sample or cracking a core. The magenta areas which appear will represent uncarbonated concrete, while the colorless regions represent carbonated concrete [5].

The chloride ion content of concrete can be determined using a wet chemical method of analysis. The concrete sample is usually taken from a core and then pulverized. The total chloride ion content is determined by dissolving the powdered sample in dilute nitric acid and then performing a titration with silver nitrate [5].

Although the test for chloride ion content is straightforward, interpreting the results may present some problems. The problems arise since the test measures the total chloride ion content (both free and chemically bound ions). Thus, the test results include an unknown quantity of chloride ion that is not available to contribute to corrosion [5].

2.2.2.18 Supplemental Instrumentation

Various techniques exist to monitor the conditions of structures during their service life. These conditions may be related to movement of the structure, joint sealing efficiency, or uplift due to water pressures. Currently used supplemental instrumentation which may be implemented at Surry is mentioned below.

- Strain and Deflection Measurements - Vibrating wire strain gages, mechanical strain gages, extensometer points, borehole extensometers, electronic distance measurement devices, joint meters, electrolevels, inclinometers, tilt measurement instruments, and ball-in-box gages are all instruments which can be installed to monitor strains and deflections between inspections. References 6 and 12 include descriptions of these methods.

- Stress and Pressure Measurements - In addition to the in-situ stress determination methods discussed in Section 2.2.2.8, vibrating wire stress meters and pressure cells can be used to determine stresses in-situ. Open tube piezometers can be used to determine water pressures at various locations [6,12].

Figure 4 on page 38 summarizes the conclusions of the previous section (2.2.2, Physical Testing Methods for Concrete Structures) by tabulation of those methods which are deemed applicable and inapplicable to the concrete inspection system for Surry Unit One.

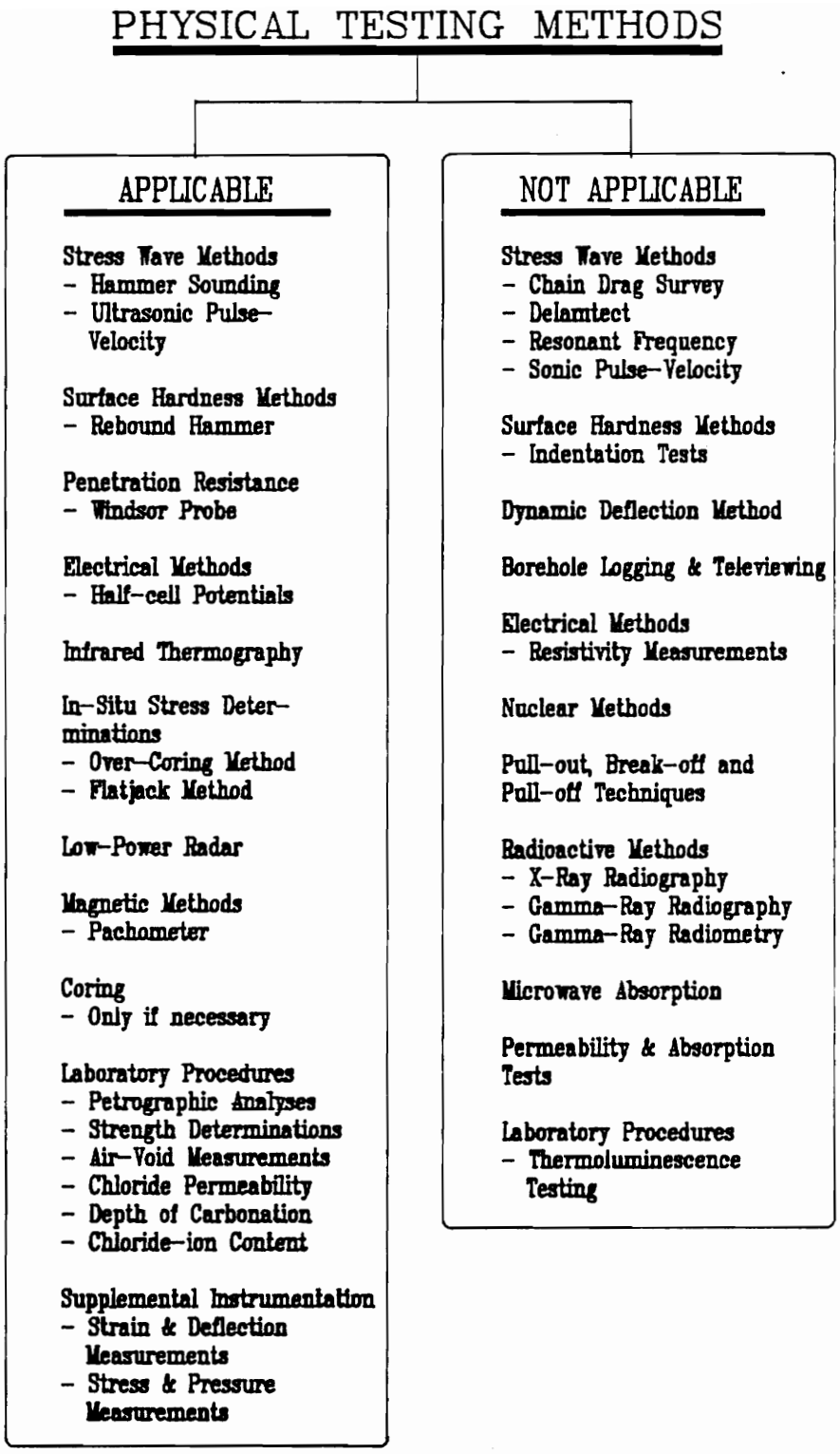


Figure 4. Applicability of Physical Testing Methods

2.3 Identification of Concrete Degradation at Surry

The inspection and testing methods discussed previously are applied to concrete inspection at Surry. Each degradation mode with a probable occurrence value of two or higher will be discussed including signs or symptoms of the mode and suggested inspection techniques. The organization of this section follows that of the Interim Report in that the modes are addressed under four concrete durability categories. The discussion of concrete inspection procedures by plant component is included as Section 2.5.

2.3.1 Material Interaction Related Degradation Modes

Of the eight possible modes of deterioration classified as material interactions in the Interim Report, only 2 modes are likely to occur at Surry. These two modes, alkali-silicate reaction and alkali-carbonate reaction, will be addressed together since the symptoms of these two degradation modes are similar.

Both alkali-silicate and alkali-carbonate reactions are expansive chemical reactions which are generally characterized by star-shaped cracks [4] or extensive map cracking [5,6,16]. Concrete which is affected by alkali-silicate reactions will often display exudation of water-rich silica in a viscous gel-like state [6,16]. This silica gel is not present in alkali-carbonate reactions [6]. Both of the alkali-aggregate reactions yield white reaction product "rims" which generally surround the aggregate particles [6,12] and may eventually totally replace them [6]. Alkali-aggregate reaction deterioration may appear very similar to freeze-thaw induced distress.

Alkali-aggregate reactions are usually most severe in regions where a constant renewable source of water exists [6]. Since the reaction is expansive in nature, another common region of distress is in the vicinity of joints where crushing of the concrete is evident [6].

Visual examination is to be used to determine the occurrence of alkali-aggregate reactions since the reactions generally occur at or near the surface of the concrete [6]. If the inspector believes that the deterioration may be due to freeze-thaw action, a petrographic procedure exists [17] which will differentiate between the two modes. However, coring is required [4].

2.3.2 Short-Term Extreme Operating or Load Exposures

Three short-term extreme operating conditions and five short-term load exposure degradation modes were identified in the Interim Report. They are: Fire Damage; Temperature Shock; Chemical Spills; Earthquake Loads; Tornado, Hurricane, or Tsunami Loads; Missile Loads; Design Basis Accident Loads; and Mechanical Overloading.

2.3.2.1 Fire Damage

The effect of the heat generated by fires which are a result of the ignition of equipment, plant furnishings, or chemicals are discussed herein. The damage due to chemical exposure, but not fire, will be discussed in Section 2.3.2.3, Chemical Spills or Leaks.

Concrete is much more resistant to fire than steel or timber but intense heat may cause damage and reduce the concrete's strength. The effect of the temperatures generated

by a fire on the concrete strength is minimal below 250°C, above 300°C a definite loss of strength takes place [18,19]. However, if the fire is of a relatively short duration (e.g. one hour), a slow recovery of strength may occur [19].

In addition to possible strength loss, fire damage to concrete may include cracking, spalling, and discoloration. The moisture content of the concrete has a bearing on the type of distress which will be evident following a fire. If the concrete has a high moisture content, spalling and separation of the hot surface layers from cooler inner layers is likely to occur [18,19]. If spalling exposes the reinforcement, the heat conducted by the steel will accelerate the damage due to fire [19]. If the concrete has a relatively low moisture content, in particular if the concrete is in hygral equilibrium with the air, spalling will not occur [18]. If temperatures are extreme (about 570°C), the aggregate type will affect the concrete's response. Quartz undergoes inversion at 574°C and suddenly expands by 0.85%, damaging the concrete [19].

Concrete which has siliceous or limestone aggregate will show a change in color with temperature, and since the change is permanent, the maximum temperature during a fire may be estimated [18]. From 300°C to 600°C concrete is usually pink or red, from 600°C to 900°C it is grey, and above 900°C a buff color is common. Concrete whose color is beyond pink is suspect and concrete which is grey is usually friable and porous [19].

Applicable inspection techniques to determine the extent of fire damage include ultrasonic pulse-velocity measurements and Schmidt rebound hammer testing. Ultrasonic pulse-velocity has been useful in assessing those parts of a structure with the most severe fire damage [2,4,5,11]. The percent loss in the pulse-velocity through concrete which has been damaged by fire has been shown to very closely follow the percent loss in flexural strength [11]. In addition to estimating the loss of strength, ultrasonic pulse-velocity has

been employed in a method to determine the depth of damage due to fire exposure [4]. The method has been incorporated in a number of fire damage studies and has produced reasonable results [4].

The Schmidt rebound hammer is also a viable inspection technique in assessing fire damage since it is a quick and reliable method to delineate regions of distress in concrete surfaces.

2.3.2.2 Temperature Shock

Accidental spills of hot fluids are capable of affecting the integrity of reinforced concrete. When temperature shock occurs, expansion of the concrete results. Due to the low thermal conductivity of concrete, the layers at the surface expand more rapidly than those further from the surface. As a result, parallel surface cracks usually occur which may eventually lead to spalling.

Visual inspection, hammer sounding, and pulse-velocity measurements may give an indication of the seriousness of the damage. However, coring and petrographic analyses will more definitely define the extent of damage due to temperature shock.

2.3.2.3 Chemical Spills or Leaks

Portland cement concrete can be attacked chemically by a process of dissolution and leaching, or by a chemical transformation (or both) [20]. The intensity of the attack depends on the specific properties of the aggressive agent (e.g., its concentration, etc.).

The resistance of concrete to attack by chemical agents is generally lower than to other forms of attack [18].

At Surry, chemical spills or leaks of demineralized water, sodium hydroxide, lithium hydroxide, ammonium hydroxide, potassium chromate, boric acid, sulfuric acid, and chlorine are possible.

Demineralized water, sometimes termed "soft" or "pure" water, has the capability of attacking the hardened cement paste by the dissolution process. In this process the free (unbonded) calcium hydroxide, which is fairly soluble in water (about 1.7 gm/liter) is leached out [20]. Continuous leaching will cause hydrolysis of the calcium silicates which will eventually leave behind the colloidal hydrates of silica, alumina, and ferric oxide, which are rich in water and possess very little strength [20].

Sodium hydroxide is a white, water soluble solid. Solutions of this alkaline hydroxide have no chemical effect on cement and concrete which has already hardened [21].

Lithium hydroxide, as with most alkaline solutions, has a negligible effect on hardened concrete unless it is present in very high concentrations (i.e., greater than 20%). Since such concentrations are unlikely at Surry, lithium hydroxide is not expected to pose any problems with regard to concrete deterioration.

Ammonium hydroxide is a weak alkaline and has a negligible effect on hardened concrete [22].

Potassium chromate is not expected to affect hardened concrete in any appreciable way. However, deterioration may occur if chromic acid is formed from the potassium

chromate. If porous or cracked concrete is subjected to chromic acid, the reinforcement may be affected and rusting may progress to such an extent that concrete spalling occurs [21].

Boric acid is a white crystalline compound which is sometimes used as an admixture to slow down the setting of cement, it has little or no affect on finished concrete [21].

Sulfuric acid is capable of gradually dissolving cement paste by converting its constituents into readily soluble salts [23]. Damage is expected if the pH of the acidic solution is lower than six [23].

Tests have proven that chlorine is capable of destroying concrete through its combination with the lime in the cement and by attacking the alumina [21]. Calcium chloride, a easily soluble compound, is formed and the concrete becomes more permeable, thus allowing the ingress of other degrading environments.

Visual inspection will be used to detect concrete deterioration due to chemical exposure since each of the aggressive agents mentioned above will "soften" or deteriorate the surface of the concrete in the vicinity of the spill or leak.

2.3.2.4 Short-Term Load Exposures

Short-term load exposures include earthquake loads; tornado, hurricane, or tsunami loads; missile loads; design basis accident loads; and mechanical overloading. Earthquakes, tornados, hurricanes, and tsunamis are loadings which may produce localized stresses in excess of concrete's fracture strength, thus resulting in structural cracking.

In addition to cracking, these loads may also cause differential settlements. Obviously, an infinite number of variations exist in a plant the size of Surry.

In the event of one of these loads, an assessment of the overall integrity and structural safety of the plant is in order. Such an evaluation would consist of a visual survey by qualified structural and materials engineers. Any anomalous areas should be investigated more thoroughly, incorporating appropriate testing methods selected by the inspector. In addition, supplemental instrumentation may be incorporated at the request of the inspector to monitor any changes in crack widths or settlements following the event.

Missile loads may be a result of external environmental missiles (aircraft parts, tornado generated missiles, etc.) or plant generated missiles. These loads are generally very localized and therefore a through examination of the concrete in the vicinity of a missile impact should be conducted.

Design basis accident (DBA) loads include accident pressure and temperature; jet reaction and impingement; and pipe whip. These loads represent the most severe loading on the plant's structures. Due to their extreme nature, a thorough evaluation is to be performed following DBA load occurrence to assure the continued safe operation of the plant prior to a possible start-up.

Mechanical overloading is primarily of concern to the containment vessel. Although the periodic Integrated Leak Rate Tests (ILRT's) are conducted at design pressure, they will be considered an overload condition since they may cause additional cracking in the containment. Since guidelines exist for the performance of and surveillance during a ILRT, the concrete inspector should request testing reports to verify the extent and se-

riousness of any new cracking. Further investigations should follow as directed by the engineer.

2.3.3 Aggressive Environmental Degradation Modes

Eighteen aggressive environmental modes of degradation were investigated as indicated in the Interim Report. Thirteen of these modes were deemed likely to occur at Surry.

The two freeze-thaw modes (paste and aggregate) will be discussed together as will the two temperature change modes of degradation. The stray current and acid rain modes of degradation may accelerate steel corrosion and therefore will be combined with the corrosion mode of degradation and will be addressed in Section 2.3.3.3, Corrosion of Reinforcing Steel.

2.3.3.1 Freezing and Thawing

Successive cycles of freezing and thawing will deteriorate concrete and will be indicated by cracking, scaling, and pop-outs. Regions where near saturated conditions occur or deicing salts are used are likely locations for freeze-thaw damage [5,16].

Closely spaced, fine, parallel cracks (sometimes called "D-cracking") occurring near edges or joints are the most common type of cracks characteristic of freeze-thaw damage [5,10]. As the deterioration progresses, the cracks occur further from the joints. Soon after, spalling occurs in the weakened, cracked concrete. "D-cracking" is commonly limited to slabs on grade.

"Pop-outs" are a special form of freeze-thaw deterioration and are generally a surface related problem. Pop-outs are small, conical-shaped spalls which result from excessive expansion of surface aggregate [5,16]. Although pop-outs are considered to be of minor consequence in terms of concrete degradation [16], they may occur in conjunction with general freeze-thaw action and thus would indicate the occurrence of freeze-thaw deterioration to the inspection personnel.

Visual inspection is required for the detection of the freeze-thaw mode of concrete degradation. In addition to visual inspection, a laboratory method described by Power and Hammersley [17] is the only reliable method of distinguishing between freeze-thaw attack and alkali-aggregate reactions [4].

2.3.3.2 Wetting and Drying

Cycles of wetting and drying may cause deterioration by recrystalization of certain salts, or by development of differential stresses due to the different volume change characteristics of the concrete constituents. As indicated in the Interim Report, the second of these deterioration mechanisms is not likely at Surry and therefore, only the first mechanism will be addressed.

The only sign of deterioration due to cycles of wetting and drying is the leaching of salts from cracks in the concrete. In time the leaching may significantly impair the concrete's soundness. Visual inspection by qualified inspectors will detect this mode of concrete deterioration.

2.3.3.3 Corrosion of the Reinforcing Steel

Sources of steel corrosion at Surry include corrosion due to diffused chloride ions, stray current induced corrosion, and corrosion due to acid rain exposure. Stray current induced corrosion is only of concern at Surry where direct current equipment or the neutral lead of transformers or generators are grounded by attachment to the reinforcement. Acid rain may also deteriorate concrete by reacting with the highly hydrated cement and thus may corrode the cement matrix. This mode of acid rain deterioration will be discussed in Section 2.3.3.7, Acid Rain.

In the normally alkaline environment of concrete, the steel reinforcement does not corrode. A passive oxide layer initially forms on the steel which prevents corrosion from occurring. Chlorides will break down this oxide layer, and if moisture and oxygen are present, the steel will corrode [24]. If the rebar is used as a ground connection, or if acid rain occurs, the rate of corrosion may be accelerated. Cracking is not necessary for corrosion to occur because chloride ions may penetrate uncracked, high quality concrete [5]. If left unchecked, steel corrosion will severely weaken a structure by reducing the concrete/rebar bond and thus, the behavior as a composite material.

Corrosion will not be visually evident in its incipient stage. In later stages, depending on the reinforcement depth, corrosion induced cracks or delaminations will occur. With shallow cover, corrosion induced cracks will occur directly above and parallel to the reinforcement and will usually exhibit rust staining. At greater depths, delaminations will occur prior to the above mentioned parallel cracks and spalling of large sections of concrete may occur.

The only direct way to determine the existence of corrosion in its incipient stages is by electrical potential measurements. Therefore, this method is suggested for detection of corrosion at Surry. Once corrosion has started, hammer sounding, ultrasonics, and infrared thermography may be used to detect the presence of delaminations and separation due to the volume change associated with the products of corrosive activity. Visual inspection may detect rusting if the reinforcement is shallow and the corrosive activity is not detected in its incipient stage.

2.3.3.4 Abrasion

For the purpose of this discussion, abrasion is defined as the dry attrition of concrete caused by wear. The resistance of concrete to abrasion is difficult to assess since the damaging action varies depending on the exact cause of wear [19]. Unfortunately, there is no simple, generally accepted in-situ test for measuring the abrasion resistance of concrete [4].

Although abrasion occurs on all concrete surfaces which are subjected to wear, generally the mechanism will not significantly affect the durability of the concrete except in that the surface roughness will increase. Visual inspection would detect any regions where severe abrasion is occurring and thus procedures could be modified or protective layers could be placed to reduce the damage to the concrete surface.

2.3.3.5 Erosion of Concrete

Erosion of concrete is defined as wear due to abrasion of solid particles carried by water [18]. The mechanism of forming cavities by water flowing at high velocities and resulting in high pressures is usually termed cavitation and is addressed in the following section.

The rate of erosion depends on the quantity, size, shape, and hardness of the transported particles, as well as the transport velocity [18,19]. In all cases, of course, the quality of the concrete at or near the surface is affected. Even the best concrete will rarely withstand severe erosion. Visual or underwater inspections will detect any regions where severe erosion is occurring and thus procedures could be modified or protective layers could be placed to reduce the damage to the concrete surface.

2.3.3.6 Cavitation

Cavitation is defined as the formation of vapor bubbles when the local absolute pressure drops to the value of the ambient vapor pressure of water at the ambient temperature [18,19]. The small vapor bubbles travel downstream and, upon entering an area of high pressure (usually at changes in channel alignment or at obstructions), collapse with great impact [18,19].

The surface of concrete which has been affected by cavitation is irregular, jagged, and pitted, in contrast to the smoothly worn surface of concrete which has been eroded by water-borne solids [19]. The damage does not progress steadily: usually, after a small period of minor damage, rapid deterioration occurs, followed by damage at a slower rate

[18,19]. As with erosion, visual or underwater examinations are the only applicable inspection techniques.

2.3.3.7 Acid Rain

The effect of acid rain discussed herein is the corrosion of the cement matrix. The effect of acid rain on steel corrosion is discussed in Section 2.3.3.3. The deterioration of concrete induced by acid rain is primarily the result of a reaction between the acid and the calcium hydroxide of the hydrated portland cement [6].

The results of acid rain attack on concrete may include discoloration, efflorescence, cracking, spalling, and general surface disintegration [6]. In addition, acid rain exposure may cause expansion and swelling of concrete components [6].

Visual inspection is recommended for detection of acid rain damage since the deterioration is always visual and surface related.

2.3.3.8 Temperature Changes

As indicated in the Interim Report, temperature changes may affect both the cement paste and cement/aggregate bond. Since the paste mode of deterioration is not a concern at Surry, only the inspection procedures used to detect the cement/aggregate bond mode of deterioration are discussed herein.

Bond is usually lost since a difference in thermal expansion coefficients of cement and aggregates exists. A large change in temperature will cause expansion or contraction at different rates.

The loss of bond due to temperature changes will not be evident in early stages unless petrographic analyses are performed. In later stages, visual inspection of the concrete surface will detect the loss of aggregate/cement bond.

2.3.3.9 Irradiation

Irradiation may affect concrete by reducing the concrete strength or by reducing its effectiveness as a radiation shield. Tests have shown that irradiation will lower the tensile strength of concrete, however the effects of irradiation were not separated from those of high temperature [18,19]. Tests on oven stored concrete lost approximately the same amount of tensile strength as was lost in irradiation tests, thus it is possible that irradiation is not in itself an important factor with respect to concrete durability [18,19]. Visual inspections should be conducted in regions of irradiation to detect excessive cracking which may be a result of a reduction in the concrete's tensile strength.

Concrete has traditionally been used in nuclear structures as a radiation shield since it possesses excellent attenuation properties with reasonable thicknesses. Although considerable research needs to be conducted to fully assess the long-term effects of radiation on concrete, in general irradiation seems to have little effect on the shielding properties of concrete beyond that of moisture loss due to the associated temperature increase [2]. A program of irradiation monitoring should detect any changes in the effectiveness of the concrete to act as a radiation shield.

2.3.3.10 Seepage

Seepage through joints at Surry may affect the performance of the plant components and thus joint efficiency should be evaluated during inspections. Seepage may occur through unbonded horizontal or vertical construction joints; around waterstops or sealants in expansion, contraction, or control joints; along cracks; along the interface between the concrete and other materials, form bolts, or tie holes; or through areas of porous low quality concrete [12]. Polyvinyl chloride water-stops are used extensively throughout the plant and are subject to oxidation which may result in the loss of the mechanical properties which insure their correct function. These locations should be visually checked to assure they are functioning as designed (such procedures should be conducted as "good housekeeping" rather than as part of a developed concrete inspection program). If excessive leakage is evident, the region should be further examined to determine the cause of joint failure, to evaluate the possibility of damage, and to determine appropriate repair procedures.

2.3.3.11 Fatigue

The various sources of fatigue possible at Surry are discussed in detail in Section 2.2.5.1 of the Interim Report. The conclusion of that section was that the only plausible type of fatigue to the concrete components at Surry would be fatigue due to equipment or machinery vibrations.

Visual inspection of the anchoring systems for the various rotating and reciprocating machinery should be conducted during plant inspections. Naturally, equipment which

is in constant use during the production of power would be more susceptible than that equipment which is intended for emergency or back-up use.

2.3.4 Environment-Stress Interactions

Five modes of concrete deterioration were classified as environment-stress interactions, they are: alkali-aggregate reactions, leaching of calcium hydroxide, freeze-thaw damage, cycles of wetting and drying, and steel corrosion. With the exception of leaching of calcium hydroxide, inspection procedures for all of these interaction modes have been discussed in previous sections.

Leaching of calcium hydroxide will occur if cracked concrete is subjected to flowing or percolating water [19]. Surface dissolution occurs and white deposits, termed efflorescence, are commonly observed. The deposits consist primarily of calcium carbonate formed by atmospheric carbonation of the calcium hydroxide which has leached from the concrete [16]. Visual inspection of susceptible regions in Surry's concrete structures will permit identification of this deterioration mode.

2.4 Frequency of Inspections

The frequency of inspections of concrete in-service is primarily based on the rate of occurrence of the possible degradation modes. At Surry, in addition, the data required to reflect possible changes in the state of the concrete components before a decision must

be made to relicense or decommission the plant would also influence the frequency of inspections in the next decade. The types of inspections to be performed in Surry's concrete inspection program are displayed in Figure 5 on page 56. Figure 6 on page 57 represents a suggested inspection schedule for Surry Unit One.

2.4.1 Baseline Inspection of Surry

A baseline inspection of Surry is recommended to determine the present state of the plant's concrete structures, to delineate potentially critical regions in each plant component, and to establish a basis for comparison in the event of a short-term extreme operating or load occurrence.

The baseline inspection would include a thorough visual survey of the exposed concrete surfaces in addition to a limited cracking survey. Crack mapping and the installation of supplemental instrumentation is suggested only in deteriorated regions. The plant's size and number of concrete components make plant-wide surface crack mapping impractical.

In addition to a thorough visual survey, underwater inspection should be conducted to assess the current condition of the below water portions of the intake and discharge structures. Such an inspection would include a sonar system mounted on a boat which could quickly and thoroughly inspect the bottom of the canal to detect any abnormal heaving, depressions, or excessive silting. A hard copy of the bottom profile could be obtained using a chart recorder.

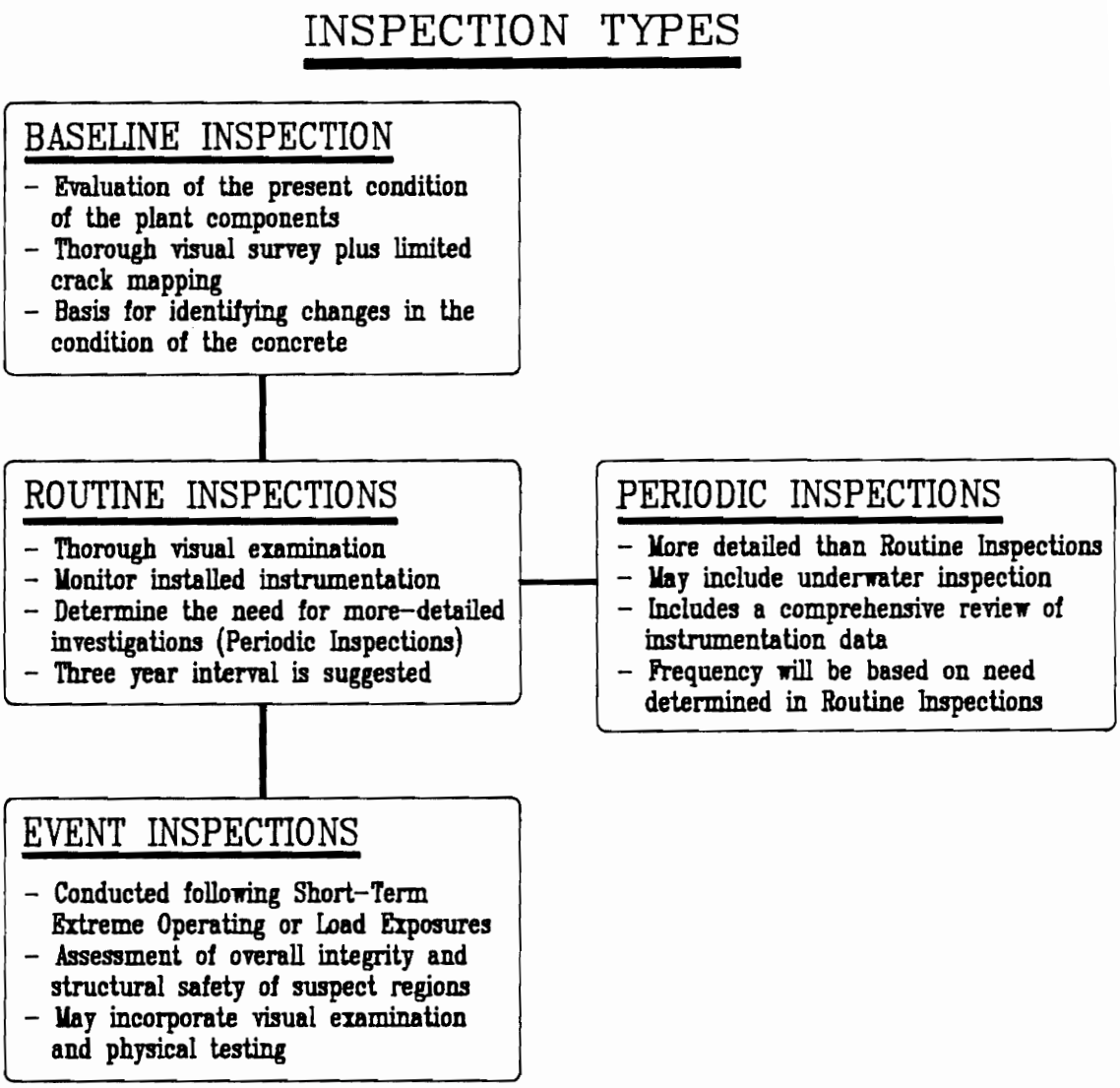
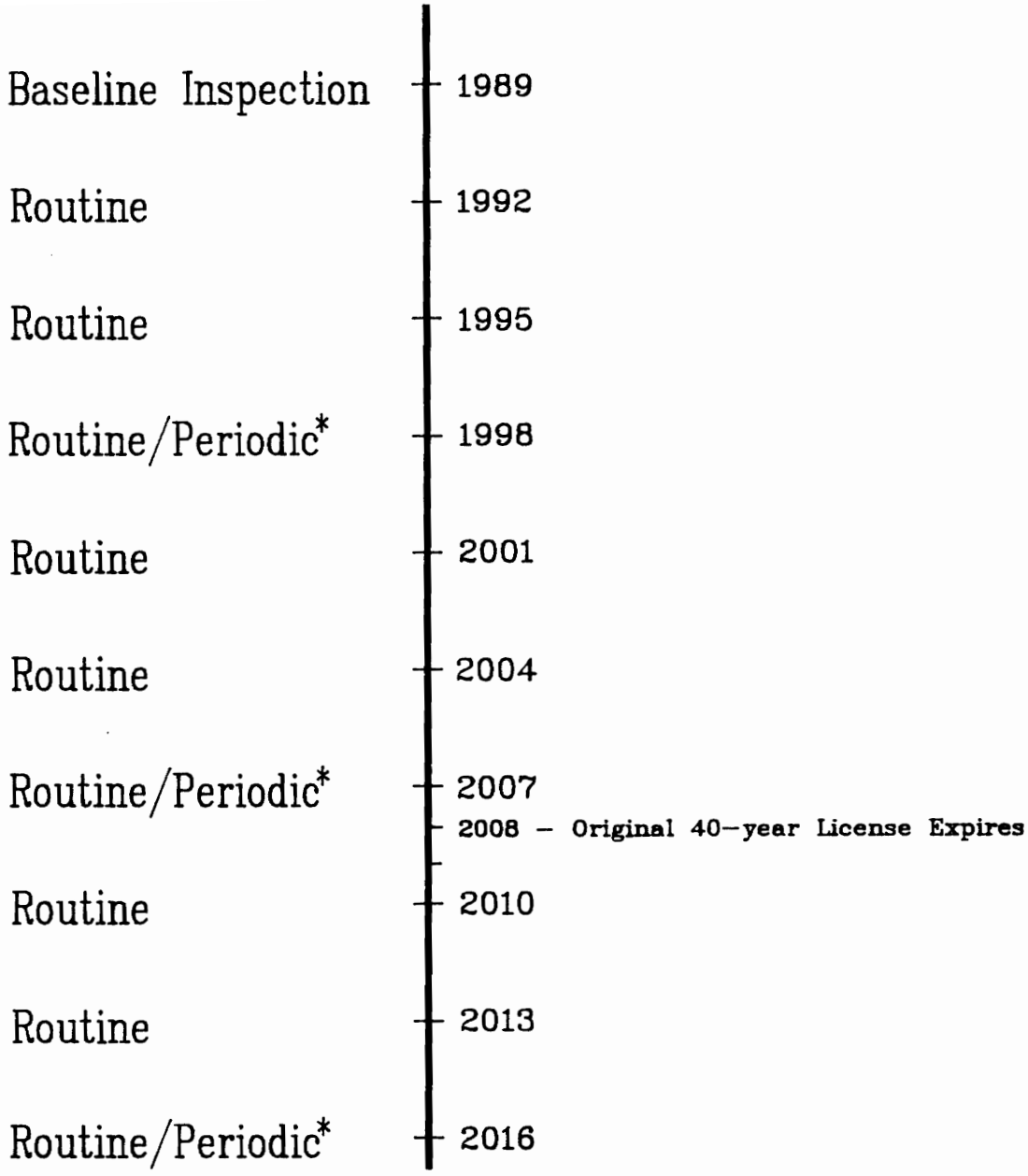


Figure 5. Types of Inspections



*Tentative Schedule, May be Adjusted as Required by Changing Conditions

Figure 6. Suggested Frequency

Following this sonar survey, a small remotely operated submersible with video recording capabilities should be used to examine the entire canal to detect any abnormalities not detected by the sonar inspection.

Following the review of the sonar chart recording and the underwater video, divers could be implemented to further investigate anomalous regions including removing cores if deemed necessary by the inspector.

Inspections performed following the baseline examination are directed at identifying any changes in condition of the concrete which may affect the continued integrity of the plant components.

2.4.2 Recurring Inspections

Routine and periodic inspections are suggested for Surry's concrete inspection program. It is important to note that the frequencies which are suggested for these two inspection types serve only as guidelines. The interval between successive inspections may be increased or decreased based on conditions discovered in previous inspections.

In addition to routine and periodic inspections, inspections should be conducted in the event of a short-term extreme operation or load exposures. Refer to Section 2.3.2, Short-term Extreme Operating or Load Exposures, for further discussion.

2.4.2.1 Routine Inspections

Routine inspections will efficiently provide an overall statement of the concrete condition. These inspections are generally the most frequently conducted form of evaluation. Routine inspections commonly consist of a thorough visual examination of the surface of exposed and accessible concrete. In general, nondestructive inspection techniques are not incorporated in performing routine inspections. In addition to visual inspection, any instrumentation which has been previously installed is usually monitored and recorded during routine inspections.

Routine inspections will dictate whether further, more detailed investigations should be performed at that time or whether such investigations can be postponed to be included in the next periodic inspection. The need for these evaluations is to be determined by the engineer based on the suspected mode of deterioration.

The frequency of routine inspections performed by various state and federal agencies in their bridge inspection programs is usually from 6 months to 2 years. A frequency of three years is suggested for Surry's concrete inspection program. This three year frequency is suggested based on the rates of occurrence of the degradation modes, in addition to the fact that the structures at Surry are more passive in nature than bridge structures and their foundations.

2.4.2.2 Periodic Inspections

Periodic inspections are those inspections which are conducted less frequently than routine inspections and usually are performed in lieu of a routine inspection. Periodic

inspections are generally conduced at a frequency of 2 to 10 years [12]. These inspections are basically the same in nature and objective as routine inspections, but involve a more detailed examination of the structures.

Periodic inspections may involve dewatering or underwater inspection to examine the submerged portions of structures. A comprehensive review of instrumentation data and design and operating criteria may also be included in a periodic inspection. Nondestructive techniques may be incorporated in regions of observed distress as directed by the engineer. The techniques used should yield sufficient data and information to provide guidance in the selection of any required repair or maintenance work.

A nine year frequency is suggested for conducting periodic inspections at Surry. This frequency is tentative in nature and may be adjusted as necessary as dictated by conditions found during routine inspections.

2.5 Inspection Procedures by Plant Component

The inspection of the concrete structures at Surry is discussed herein on a component-by-component basis. The discussion is intended to provide inspection guidelines when conducting concrete evaluations of the various plant components. The emphasis of this section will be to indicate, insofar as possible, critical regions for each component based on the environmental exposure conditions required for the occurrence of specific modes of degradation and on observations made during two previous site visits. It should be mentioned that the locations of such potentially critical regions in several plant compo-

nents are currently not defined due to limited access during site visits, in addition to the complexity of various plant components. It is therefore suggested that the evaluation of potentially critical regions should be made during the baseline inspection and would serve to direct the evaluation of the plant structures in following inspections.

The organization of this section follows that of the Interim Report in that three component categories are used. They are: Intake and Discharge structures, Containment building, and Remaining components. These three distinct subsections were chosen due to the unique exposure conditions of the intake/discharge structures and the containment relative to the other plant components. Figure 7 on page 62 indicates the various plant components which were included in this study.

The eight short-term extreme operating or load exposure degradation modes will not be discussed herein since the occurrence of these modes is assumed to be very localized in nature and will result in an inspection of the suspect region(s) incorporating the methods which are discussed in detail in Section 2.3.2.

2.5.1 Intake and Discharge Structures

The plant cooling water system at Surry consists of a circulating water intake structure at the James River, a reinforced concrete trapezoidal intake canal, a high-level intake structure at the station, reinforced concrete discharge tunnels, seal pits/weirs, and an unreinforced concrete-lined discharge canal.

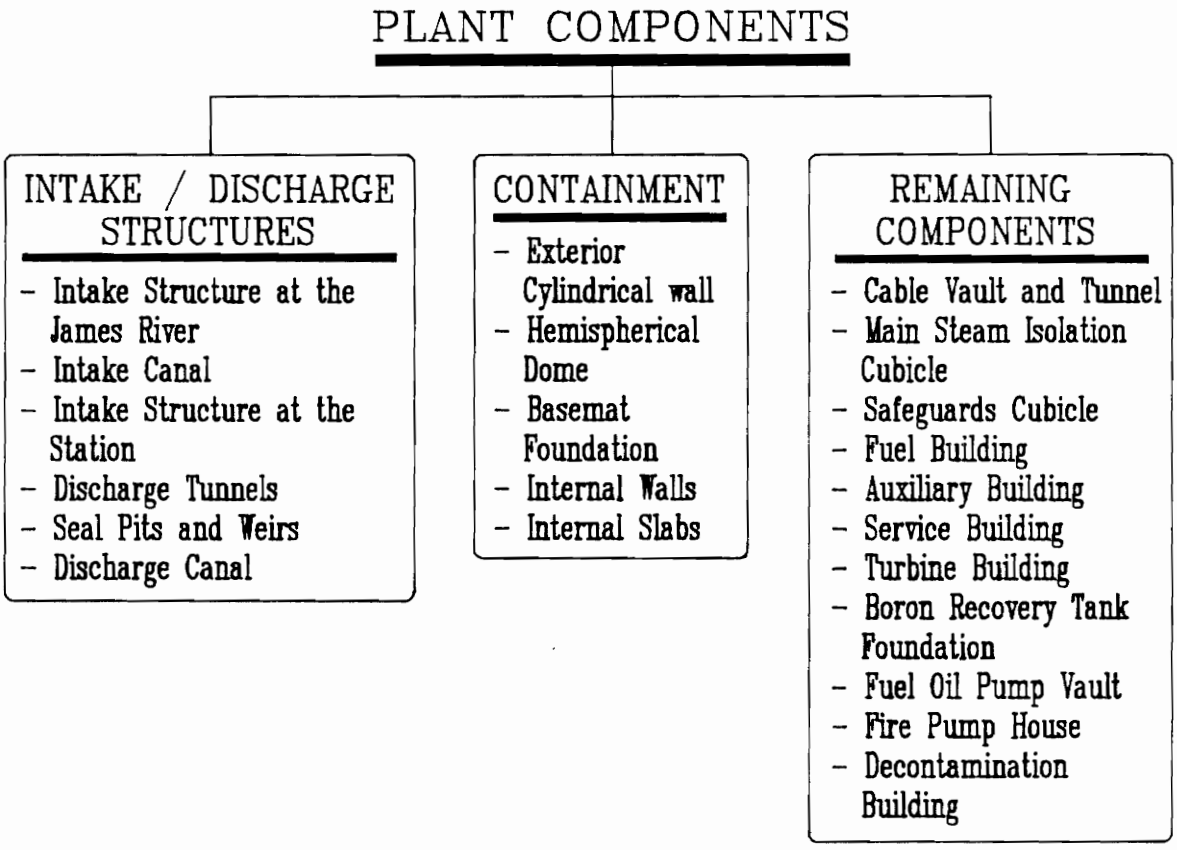


Figure 7. Components of Surry Unit One

2.5.1.1 Intake Structures at River and Station

The circulating water intake consists of a reinforced concrete structure adjacent to the James River and eight 96-inch-diameter pump discharge lines which convey the water over the embankment for the high-level intake canal. Potential modes of concrete degradation for the circulating water intake structure at the James River include alkali-aggregate reactions, freeze-thaw damage, damage due to cycles of wetting and drying, steel corrosion, acid rain, temperature changes, and leaching of calcium hydroxide.

The waterline region and other locations which are commonly wet (such as the trash and sluice flumes on the top exterior portion of the intake structure) should be thoroughly visually inspected. These regions are more susceptible to alkali-aggregate reactions, freeze-thaw damage, damage due to cycles of wetting and drying, and leaching of calcium hydroxide since a constant, renewable source of water exists. Possible damage due to these modes of deterioration includes map cracking, exudation, efflorescence, spalling, and general surface deterioration.

The concrete piers which support the structure at the river are directly exposed to the brackish water. The waterline region should be thoroughly investigated, particularly in the vicinity of the rake slot guides and the associated trash rake and grate embedments for evidence of cracking, spalling, and reinforcing steel corrosion. In addition, although not directly a reinforced concrete deterioration mode, corrosion of the embedments should be noted since this would lead to volume expansions and concrete distress which would allow the ingress of aggressive environments thus further accelerating degradation.

The pedestal for the emergency diesel generator, which is located in the upper level of the intake structure, should be investigated for signs of deterioration due to dripping water, fuel, or oil. Such stains were noticed during a recent site visit and although they presented no immediate problem, the region should be inspected during later investigations. If deterioration occurs, the integrity of the engine's mounting could be compromised and thus may impair proper operation in the event that the back-up engine is needed.

The lower level of the intake structure at the river includes eight massive circulating water pumps which discharge into 96-inch-diameter lines. Although trench sump pumps exist, standing water was evident in the cubicle beneath the circulating water pumps, apparently due to malfunctioning sump pumps. This wet environment will tend to increase the probability of occurrence of several of the degradation modes. In addition, since the slabs appear to be restrained in this structure, the corners are likely locations for cracks and thus should be inspected.

The supports for the 96-inch-diameter intake pipes are founded on pedestals cast with the concrete canal liner. Many of these pedestals exhibited cracking and in several instances large spalls had occurred.

The equipment building located above the intake pipes as they traverse the intake canal embankment should be inspected for corrosion and other modes which are accelerated by the presence of water. During a recent site visit, spalling, rust staining, and exposed reinforcement were noticed at the anchor bolts of an electric motor in this structure.

The settlement monitoring instrumentation and the piezometers which are located along the intake canal liner, beneath the intake pipes, should be monitored and recorded during an inspection.

The modes of deterioration expected at the intake structure at the station are identical to those expected at the river intake. For this reason, the inspection of the intake structure at the station should include an examination of those regions indicated above for the intake at the river. In addition, the region around the screen wash pumps should be checked since a significant amount of standing water is present (which has rusted several of the pump base plates) and may accelerate other modes of degradation.

Acid rain degradation may occur in the above water portions of both of the intake structures and would result in softening of the concrete and general surface disintegration.

2.5.1.2 Intake and Discharge Canals

Potential modes of concrete degradation for the intake and discharge canals include alkali-aggregate reactions, freeze-thaw damage, damage due to cycles of wetting and drying, steel corrosion, erosion, acid rain, temperature changes, seepage, and leaching of calcium hydroxide.

As indicated in the previous section, the waterline region is generally more susceptible to degradation due to the presence of both water and air. Inspection of the waterline region of the intake and discharge canals should be performed from a boat when water levels are low (if possible) to allow the inspection of the largest possible area. Also, the

joints of the canal should be thoroughly inspected for degradation due to thermal expansion, freeze-thaw, or alkali-aggregate reactions. In a recent site visit several joints exhibited cracking, spalling and vegetation growth.

Corrosion of the reinforcing steel is possible in the intake canal but not in the unreinforced discharge canal liner. Inspection for corrosive activity should include visual inspection of the concrete, particularly in crack locations; expansion, contraction, and construction joints; and interfaces of steel/concrete embedments. Such embedments are found along the canal where exposed rebar is used as steps and where steel brackets are used, such as in the attachment of the overflow pipe which enters the intake canal.

Parallel cracks which exhibit rust staining should be further investigated by hammer sounding, ultrasonic techniques, or coring to determine the extent of delamination due to corrosive activity. However, corrosion is not expected to be a major concern for the intake canal since galvanized wire mesh was used in construction and no rusting was evident during a recent site visit (even in the exposed mesh).

Acid rain degradation may occur in the above water portions of the intake and discharge canals and would result in softening of the concrete, and general surface disintegration.

Concrete erosion and cavitation are generally underwater phenomena and thus require underwater inspection for their detection. These underwater inspections are to be conducted in conjunction with periodic inspections. The bends in the canals are regions which are more susceptible to concrete erosion and cavitation. Consultation with Northeastern Underwater Services [25] resulted in the following recommendations relating to underwater inspection procedures applicable to concrete inspection at Surry.

- The underwater portions of the intake and discharge canals should be inspected via divers or remotely operated devices with the observations recorded with still photographs or video cameras. Continuous video coverage has been an economical approach and has been successfully incorporated in several bridge substructure examinations. In particular, regions where high velocities are possible or where steel embedments are used should be checked to insure the integrity of the concrete is not compromised by corrosive activity or concrete erosion and cavitation.

- In addition, as indicated in Section 2.4.1, Baseline Inspection of Surry, a sonar system mounted on a boat could quickly and thoroughly inspect the bottom of the canal to detect any abnormal heaving, depressions, or excessive silting.

- The evaluation of the discharge canal would be similar in nature to the inspection of the intake canal with the exception of the sonar survey. The sonar survey is not recommended since the discharge canal is constructed of layers of concrete filled fabric which by its very nature will not provide as clear a sonic profile as that of the trapezoidal intake canal liner.

Seepage into or out of the canals can be detected by the underwater inspection procedures indicated above and if detected should be thoroughly investigated due to the severe impact that seepage could have on the canals, and consequently, plant operations. In addition to underwater surveys, the soil adjacent to the intake and discharge canals should be visually inspected for subsidence which may indicate the occurrence of seepage into or out of the canals. Such subsidence previously occurred at Surry in mid-1985. In addition, any pipes or conduits which outfall into the intake or discharge canals should also be inspected to detect any soil erosion caused by leakage which may poten-

tially impair the function of the canal. Such damage occurred in December, 1984 and resulted in the collapse of a portion of the discharge canal liner.

2.5.1.3 Discharge Tunnels

The discharge tunnels include the reinforced concrete pipes running between the high-level intake at the station and the condensers, and the square reinforced concrete tunnels which terminate at the seal pits/weirs at the outfall to the discharge canal. These pipes and tunnels are located completely below ground and thus signs of deterioration are not readily observable. In a recent site visit, several design drawings were checked to ascertain the possibility of visual or remote video inspection of the tunnels. No manholes allowing access to the discharge tunnels were found in the plant records. Consequently, it may only be possible to inspect the tunnels by incorporating divers or remotely operated vehicles during plant shutdowns. Access to the tunnels may be possible from the seal pit and weir regions.

It should be mentioned that the discharge tunnels are enveloped in a polyvinyl chloride (PVC) membrane which is expected to provide good resistance to alkalis, acids, salts, and other potentially degrading agents.

2.5.1.4 Seal Pits and Weirs

Possible modes of concrete degradation at the seal pits and weirs include alkali-aggregate reactions, freeze-thaw damage, damage due to cycles of wetting and drying, steel corrosion, erosion, cavitation, seepage, and leaching of calcium hydroxide.

At the outlet of the discharge tunnels, where the seal pits and weirs are located, the region in the vicinity of the waterline should be thoroughly inspected to determine if alkali-aggregate reactions, freeze-thaw, cycles of wetting and drying, steel corrosion, or leaching are impairing the concrete. It may be possible to inspect the seal pits and weirs at low water level (i.e. plant shutdown). In conjunction with this visual inspection, an underwater inspection should be conducted to detect surface erosion or cavitation in vicinity of the outlets. Divers with continuous video coverage could be incorporated. If it is not possible to inspect the seal pits and weirs due to high velocities, turbulence, or turbidity, dewatering may be required.

2.5.2 Containment

The reactor containment structures include the exterior cylindrical wall and hemispherical dome, a basemat foundation, internal walls, and internal slabs. Possible modes of concrete degradation include freeze-thaw damage, steel corrosion, damage due to temperature changes, acid rain, irradiation, fatigue, and leaching of calcium hydroxide.

The exterior of the containment vessel, including the cylindrical wall and hemispherical dome, has numerous vertical hairline cracks which were probably caused during the initial Structural Acceptance Test or subsequent Integrated Leak Rate Tests. A visual surface condition survey should determine if any efflorescence is evident indicating the occurrence of leaching of calcium hydroxide. Such stains were noticed at the horizontal junction between the first and second construction lifts and around the construction opening enclosure. The concrete around the equipment and personnel hatches should

be checked for deterioration since these are locations of stress concentrations and therefore are more susceptible to cracking. In addition, in regions were moisture is more likely, such as at the base of the containment, an examination should be conducted to identify evidence of surface deterioration due to freeze-thaw, acid rain, or cycles of temperature change. Electrical potential measurements should be taken during periodic inspections to detect the occurrence of reinforcement corrosion. The locations of these measurements are to be determined by the inspector based on critical regions delineated during the baseline inspection.

On the interior of the containment structure, 2 to 4½ ft thick walls and slabs are present which are heavily reinforced and contain substantial embedments. In the vicinity of these embedments, such as base plates, hangers, or brackets, the concrete condition may be compromised. Not only are these regions more susceptible to fatigue, but they also represent locations were cracking may be initiated which would allow access of aggressive environments and tend to accelerate several of the other modes of deterioration.

The interior concrete walls and supporting members in the containment are painted. The flaking or discoloration of these painted surfaces may indicate potential regions of deterioration. In addition, the hardened floor coating may also indicate potentially degrading regions due to excessive wear or delamination from the concrete. Also, the floor slab covering the basemat exhibited cracking during a site visit and should be inspected routinely to determine if the presence of these cracks is accelerating the degradation processes.

Floor slabs which are restrained commonly exhibit cracking in corners which may accelerate concrete deterioration. In addition, several regions in the lower levels of the containment structure seemed to have defective sump pumps resulting in standing water

or other fluids. These conditions will also tend to increase the probability of concrete deterioration.

As indicated previously, following the baseline inspection of the containment, the location of critical regions will be better defined thus directing the inspection during later evaluations.

2.5.3 Remaining Components

The remaining plant components include the cable vault and tunnel, the main steam isolation cubicle, the safeguards cubicle, the fuel building, the auxiliary building, the service building, the turbine building, the foundation of the boron recovery tanks, the fuel oil pump vault, the fire pump house, and the decontamination building. Each of these components, with the exception of the fuel building and boron recovery enclosure, were visited during a recent site visit. These two components were not visited due to safety considerations.

The cable vault and tunnel region, located beneath the turbine and auxiliary buildings and leading into the motor control center, is a rather narrow region filled with cable trays and associated equipment. The walls of the containment in the motor control room exhibited some horizontal cracks with white efflorescence possibly indicating leaching of calcium hydroxide.

The main steam isolation cubicle is located adjacent to the containment and houses the piping systems, pumps, and the main steam and feedwater systems. The basement level appeared flooded during a recent site visit and should be inspected for evidence of

alkali-aggregate reactions and leaching of calcium hydroxide. High temperatures were observed in the upper-most level of the structure and this region should be inspected for evidence of temperature change induced distress.

The safeguards cubicle, which is also adjacent to the containment, contains recirculation spray and low head safety injection pumps and its associated pipe tunnel. Since a majority of the piping, pumps, and HVAC ducts are supported by the concrete mat and walls (both interior and exterior), the embedments should be checked to insure that the concrete in the vicinity is not excessively cracked. During a site visit, water was also observed running down the exterior south wall. Steam plumes were also observed blowing against the containment, exposing the concrete to moist, warm air. Both of these regions should be checked during concrete inspections as they represent locations which may be more susceptible to degradation.

The auxiliary building is a four-story structure comprised of reinforced concrete and structural steel. The two lowest levels contain components of the reactor chemical and volume control systems and are therefore high-radiation regions. The floors are well coated, thereby reducing the concrete's exposure. On the third floor, in the vicinity of the mechanical equipment room, moisture was noticed on the floor which may possibly accelerate concrete deterioration.

The service building is located adjacent to the turbine building and contains the emergency switchgear and relay rooms, battery control rooms, air conditioning equipment room, reactor trip breaker cubicle, and the auxiliary diesel generator cubicles. The emergency diesel generator cubicles have thick, shiny protective layers on the floors. Along one wall is a bank of several batteries used for cranking the engine. The floor slab

in this region should be inspected for signs of surface deterioration resulting from possible acid exposure.

The turbine building is a large corrugated metal building with a concrete foundation. The pedestals for the two turbines are located within the building. For the purpose of this report, the condensate polishing facility is considered a subcomponent of the turbine building, being located at the east-end of the turbine building enclosure.

All of the bases for the equipment on the lower level of the turbine building need to be inspected for deterioration. Several of these, such as the heater drain pump base, were severely deteriorated. In the valve pit below the first level there was approximately 4 inches of standing water on the floor and white leachate on some of the walls. Future inspections should detect whether any excessive leaching or alkali-aggregate reactions are occurring in the valve pit.

In one region, around a column on the south wall on the lower level of the turbine building, apparently a highly corrosive material had washed all of the cement from the concrete surface and had resulted in loose debris on the floor. The cause of the deterioration needs to be further investigated and the region should be inspected during subsequent concrete examinations.

The floors of the condensate polishing room exhibited severe surface deterioration in the vicinity of the caton resin bed tank. Also, tanks of sodium hydroxide, caustic acid, and sulfuric acid are present. The entire floor surface should be inspected for signs of deterioration and corroding of the cement paste due to these aggressive chemical agents.

The boron recovery tank enclosure consists of a concrete slab foundation and a lower concrete wall rising about 15 ft above the slab. The exterior portion of the structure looked to be in good condition during a recent site visit. Access to the interior regions was restricted during our visit.

The fuel oil pump vaults consist of two below-grade reinforced concrete buildings which house the diesel generator supply pumps. The top slabs are at grade and exposed to the environment and should be inspected for evidence of freeze-thaw attack, alkali-aggregate reactions, steel corrosion, acid rain attack, and damage due to thermal cycling. The pumps are located below and evidence of fuel oil spilling was noticed. In addition, there was a substantial amount of standing water in the cubicles.

The fire pump house is located near the intake structures at the station and is a single-level, reinforced concrete structure with an exterior brick veneer. A chlorine storage area is located in the building and the door to the storage area was severely corroded. The concrete surface in this vicinity should be inspected to detect abnormal surface wear which may be due to chlorine exposure. Minimal amounts of dripping water, oil, and fuel were also noticed at the base of fire pump #2. These agents could, over some time, deteriorate the concrete pedestal.

2.6 Uniformity in Concrete Inspections

Achieving uniformity in evaluation and reporting procedures between different inspection teams is imperative to insure the success of a concrete inspection system.

A well planned sequence of inspection will lead to more efficient time utilization by the inspector. Inspection planning will assist the inspector in making both a systematic, and more importantly, a more thorough investigation.

In addition to inspection planning, Whittemore [26] suggests that uniformity in an inspection system can be obtained if there is uniformity in the rating system, communications, documentation, and quality control. Figure 8 on page 76 depicts the aspects of achieving uniformity in concrete inspections.

2.6.1 Rating System

A uniform rating system including standardized visual responses (which are correlated to specific deterioration descriptions) is an essential part of any concrete inspection program. This standardized rating system should include a classification system for surface deterioration such as that given by Lehtinen [27]. In addition, a scale for quantifying the extent of cracking, such as the classification by ACI Committee 207 [12], is also recommended.

2.6.2 Communication

Two means of promoting good communication as related to a concrete inspection system are the development of an inspection manual and required inspector training courses.

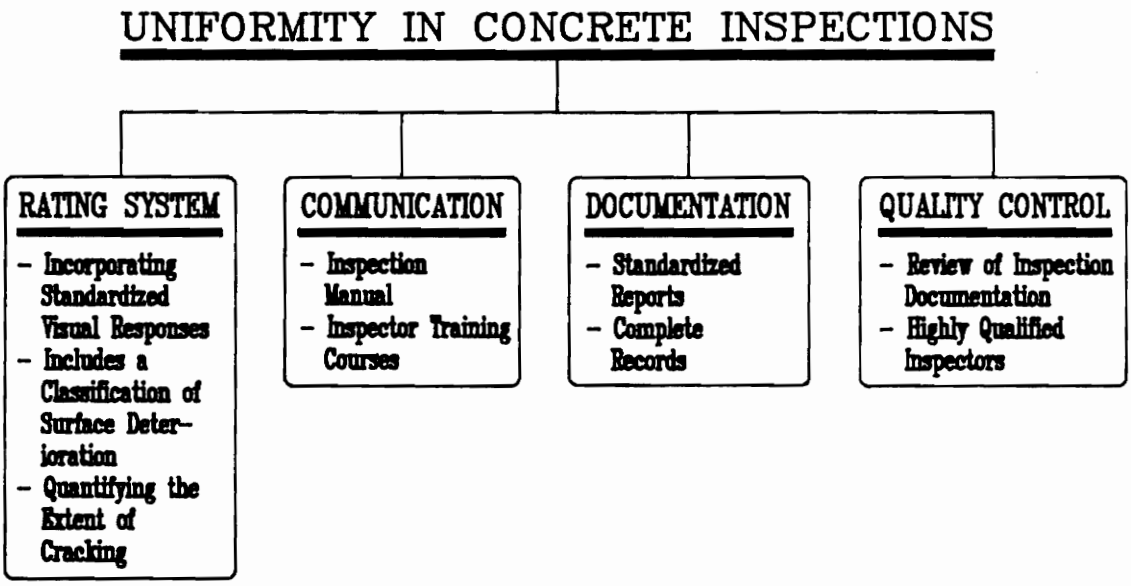


Figure 8. Achieving Uniformity in Concrete Inspections

A well developed inspection manual, similar in nature to FHWA's "Bridge Inspector's Training Manual" [28], would provide a uniform, comprehensive document for the inspection of nuclear power plants. Such a manual would serve both as a instructional document as well as a field reference. As indicated previously, the development of a "Concrete Inspection Manual for Nuclear Power Plants" is outside of this project's scope. However, the development of such a manual is recommended prior to the implementation of the inspection system for Surry Unit One.

Although inspector training courses are one aspect of important communication in an inspection system, inspector training also represents a facet of quality control, and thus will be discussed in Section 2.6.4, Quality Control.

2.6.3 Documentation

The preparation of standardized documentation is most important in assuring the uniformity of concrete inspection evaluations. A well defined documentation scheme which is adhered to by all inspectors will prove to be invaluable when concrete condition comparisons are made between current and past inspections. The documentation reports and records need to be well organized, clear, concise, and readable. In the interest of uniformity, the same nomenclature and terminology should be used to avoid any ambiguous interpretations. Only when the condition evaluations are uniformly documented can valid decisions be made concerning the rate of occurrence of degradation modes, and thus the need for repair or maintenance activities.

2.6.3.1 Reports

Reporting procedures to be used in the field investigation of Surry's concrete components are discussed herein as well as the suggested content of inspection reports prepared following the field investigations. These reports are to be included in the plant's concrete inspection records as discussed in Section 2.6.3.2, Records.

The concrete condition, as determined by the inspection team, is usually recorded in an inspection notebook or on standard forms. A notebook is usually desirable when inspecting complex structures with special construction details and features.

Standardized forms are desirable since a listing of all critical regions in each plant component would serve as a checklist and should preclude any oversight on the part of the inspection team. Standardized forms are suggested for the inspection system at Surry and should be included in the development of the suggested inspection practices manual mentioned previously in Section 2.6.2, Communication.

During field inspections the following information should be obtained and recorded:

- General Information - Includes the dates of the inspection, the inspection team members, and the type of inspection performed (routine, periodic, or event).

- Component Inspection - Includes the component being inspected, the designated subregion of the component, ties to the component local reference point (see Section 2.1), the surface deterioration evident (based on a standardized scale), the inspector's analysis of possible causes, a statement indicating the urgency of required action, the inspector's recommendation for further investigation (i.e. implementing

nondestructive/destructive techniques), the monitoring and recording of supplemental instrumentation data, and any additional comments.

Sketches and photographs can be included in the documentation of inspection evaluations and should amplify the narrative descriptions of conditions. Sketches and photographs will assist in the understanding of the report at a later date.

Polaroid photographs are particularly desirable in documenting conditions since they can immediately be checked to insure that they depict the condition of the concrete in its true state. In addition, it is desirable to take 35mm photos for records since polaroid photos may fade and discolor with age. A tape measure or recognizable object should be included in each photo to convey scale. The use of artificial light and any camera filters should be indicated in the field notes.

The preparation of a formal report is suggested following each inspection and should describe the condition of the concrete components and include recommendations for further investigation, urgency of action, and maintenance/repair activities. Such recommendations should indicate the severity of the deterioration and the priority of each repair. The assessment should include all signs of deterioration, failure, or defects, and an evaluation of the adequacy of the concrete structures in sufficient detail so that other inspectors can easily make comparisons at a later date.

Potentially unsafe conditions found during an inspection should be reported to the appropriate officials, without delay, prior to the preparation of the formal inspection report.

2.6.3.2 Records

The usefulness of the information obtained during an inspection depends upon its availability in a complete, organized, and concise recording system. White, et al. [29], recommend that inspection records be coded for incorporation into a computer data base to increase record availability and access.

Recommended records to be maintained on the condition of the plant's concrete structures should be included in an Inventory Report prepared for each component and consist of the following:

- A general description of the component including design and "As-Built" plans and a statement on the operating impact involved in the event of structural failure.
- The dates of completed inspections and those planned in the future.
- The type of wearing surface and its thickness, as applicable.
- The date of construction.
- Comments on unusual loadings or conditions to be expected.
- Completed formal inspection reports, as discussed in Section 2.6.3.1.

In the event of rehabilitation or maintenance, an addendum should be attached to the respective component Inventory Report detailing changes and the date(s) of work performed.

Well prepared concrete component inventory records will also be valuable in familiarizing new inspection personnel with the plant's components.

2.6.4 Quality Control

Quality control measures and procedures are required in Surry's concrete inspection program to assure that:

- The level of quality and completeness of inspection reports and records is maintained to assure substantiation of the plant's integrity in the event of relicensing.

- Uniformity in the selection and qualifications of inspection personnel is maintained to insure that thorough, subjective examinations are being performed by those qualified to perform such evaluations.

2.6.4.1 Quality Control in Documentation

As far as documentation is concerned, each report or record should be reviewed at the inspectors level for clarification and correctness prior to submission. In addition, a "Quality Control Engineer", who meets the same qualifications as an inspection team leader, should review the inspection documents to further insure that uniformity in the inspection system documentation is being adhered to.

2.6.4.2 Quality Control in the Selection of Inspection Personnel

The importance of qualified concrete inspection personnel to the success of a concrete inspection program can not be overstressed.

Several agencies have developed inspector qualifications for the examination of concrete structures in service (most are related to bridges). Some examples are found in the Federal Highway Administration's (FHWA) "Bridge Inspection Training Manual-70" [28] and the American Association of Highway and Transportation Officials'(AASHTO) "Manual for Maintenance Inspection of Bridges" [30].

AASHTO recommends that the individual in charge of an inspection be either a registered professional engineer, or be qualified for registration, or have 10 years of experience in bridge inspection. FHWA recommends graduation from a standard or vocational high school plus two years of engineering or technical courses. In addition, but not mandatory, are five years experience in either structural maintenance, structural inspection, steel construction, or surveying.

For Surry's concrete inspection personnel, higher qualifications are recommended due to the importance of concrete soundness to the continued integrity and safety of nuclear facilities. Recommended qualifications would include the following:

- Personnel must be practical and dedicated diagnosticians who thoroughly investigate each and every clue as related to the behavior of the structures.

- The evaluation team must possess a good understanding of the modes and causes of failure in large concrete structures.

- Expertise in civil and mechanical engineering, engineering geology, concrete material deterioration, and petrography.

- Experience in design, construction, and operation of large concrete structures.

- Physical agility to inspect, record, and photograph deteriorated regions while in difficult positions or at great heights.

- Ability to interpret design and construction plans, visualize details, and be aware of potential hazards and safety considerations.

- Possess proficiency in the selection of nondestructive testing methods and knowledge of their applications and limitations. However, it is strongly recommended that these types of evaluations be performed by consultants who have displayed expertise in their application and are more familiar with possible drawbacks, limitations, and the interpretation of test results.

Seldom will one individual have sufficient experience to be qualified as an expert in all fields of engineering comprising the design, construction, and surveillance of large structures. Therefore, the inspection team should be chosen with each individual's experience and limitations in mind in order to assure a qualified team consisting of members capable of complimenting the others' knowledge.

Several references exist which address certification, training, and evaluation of concrete inspectors. However, these publications, such as "Guide for Certification of Nuclear Concrete Inspection and Testing Personnel" [31] and "Qualifications of Concrete In-

spection Personnel" [32] are oriented towards practices during construction rather than the evaluation of hardened concrete in-service.

It is highly recommended that certification, training, and evaluation procedures be developed for the inspection of hardened concrete as related to nuclear power plant structures. Such procedures would further insure that qualified inspection personnel are performing accurate concrete inspections.

3 ADDITIONAL RESEARCH

During the development of a concrete deterioration inspection system for Surry Unit 1, it was recognized that further research is necessary to insure the realization of the inspection program objectives. The research needed can conveniently be divided into: material degradation studies, development of standardization, and improvement of testing methods.

The long-term effects of the service environment on concrete structures is in general not well defined. Studies on the effects of the environment on concrete as a material, and as related to the structure as a whole would help, not only in providing a better understanding of the processes involved, but also help to substantiate the life of concrete structures in general. More specifically, the effects of long-term exposure to irradiation need to be clarified to properly assess the useful life of those structural components which will be subject to irradiation in excess of 40 years.

Standardization still appears to be inadequate in the area of testing methodologies and procedures. Further work is required by appropriate agencies (e.g. ACI, ASTM, ASCE, etc.) to develop standard practices which are specifically related to nuclear power plants.

Several of the existing criteria could be evaluated and modified to be more relative to nuclear facilities. In addition to the standardization of methods and procedures, inspector qualification, certification, and evaluation as related to nuclear power facilities need standardization to insure that the quality of concrete inspection personnel is being maintained.

Improvement of existing test methods and the development of new methods currently represents the most important task to be addressed in future research. In order to determine where the most energy should be directed, it is perhaps most desirable to not develop new techniques, but rather thoroughly and objectively assess each of the existing techniques. Included in this evaluation would be numerous field trials conducted by various agencies which would indicate which methods are more applicable to various structural systems.

In general, many of the methods are capable of obtaining fairly reasonable results but are lacking in portability. As electronic circuitry and related technological developments become more advanced, the associated test equipment should become portable, rugged, and less costly. In addition to portability considerations, some of the methods are discussed below in the context of additional refinements.

- Thermography is currently being applied successfully to detect delaminations or voids in bridge decks due to their exposure and generally uniform heating. However, the method is still lacking in its application to structures in general. Also, the development of a recording system to videotape the oscilloscope traces; including software to permit a scaled, hard copy of the testing results is desirable.

- Nondestructive test methods to determine the probable time to corrosion initiation as well as the rate of corrosion are desirable. Included in such studies would be developments related to the susceptibility of a concrete component to corrosion and determination of the chloride ion penetration depth.

- Development of a viable system which would increase the speed and accuracy of radar inspection by automating data collection and analysis.

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Appendix A. Interim Report

CONCRETE DETERIORATION INSPECTION SYSTEM FOR EXTENDING THE OPERATING LIFE OF NUCLEAR POWER PLANTS APPLIED TO SURRY UNIT ONE

INTERIM REPORT

Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

July 1987

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Table of Contents

1 INTRODUCTION **A-5**

1.1 Background A-5

1.2 Objectives and Scope A-6

1.3 Inspection Systems A-6

2 CONCRETE DEGRADATION AT SURRY UNIT ONE **A-8**

2.1 Concrete Degradation Categories A-8

2.2 Structural Considerations A-9

2.3 Surry Unit One Plant Components A-20

2.4 Concrete Deterioration Matrices A-23

3 CONCEPT OF INSPECTION SYSTEM **A-55**

3.1 Concept of Surry Concrete Inspection System A-55

REFERENCES **A-57**

List of Tables

Table **Page**

1. Matrix of Aggressive (Long-Term) Environmental Modes of Degradation A-53

2. Matrix of Environment-Stress Interaction Modes of Concrete Degradation A-54

1 INTRODUCTION

1.1 Background

All engineered structures are designed for a specific life span. For example, bridges are designed for a service life of 50 years, pavements for 25 years, and nuclear power plants for 40 years. However, many bridges and pavements continue to remain in service long after their design life and continue to economically operate at an acceptable safety level for the motoring public. Inspection programs for bridges and pavements determine their physical condition thereby ensuring public safety and protect the public's investment so that maintenance, rehabilitation, and replacement activities can be properly programmed.

Current and projected circumstances now appear to make it economically feasible to continue to operate nuclear power plants beyond the original 40 year licensing period. For a plant to be granted a renewal of its operating license, the utility must show that the integrity of the plant's components will be maintained throughout the extended life. The life of the reinforced concrete components of a nuclear power plant is expected to be greater than any likely period of plant life extension, provided that neither environ-

mental factors, applied load, nor a combination of load and environmental factors compromise the structural integrity of the reinforced concrete.

1.2 Objective and Scope

The objective of the research project is to develop a reinforced concrete inspection program for nuclear power plants which would identify concrete degradation in its incipient stages and thus provide a basis for the continued renewal of the operating life of the plant with respect to the soundness of its reinforced concrete components. To accomplish the project objective the researchers visited the Virginia Power Surry nuclear power generating facilities; reviewed the literature on the mechanisms of concrete deterioration, inspection procedures, and nondestructive testing; reviewed Surry's concrete construction quality control inspection records; and reviewed Surry Unit No. 1 Life Extension Project Topical Reports [1,2,3,4].

1.3 Inspection Systems

In the development of an inspection system to detect the onset of degradation, there are three possible paths that may be taken to achieve the specific goal.

1. A mathematical modelling approach defines the critical points and thus the approach to an optimum system. This approach requires that mathematical relationships be known for all material degradation interactions between environmental exposure conditions, stress level, and loading history. The knowledge base of all

known concrete deterioration mechanisms has yet to be developed to a point where this approach may be used.

2. The checklist approach assumes that degradations occur at fixed-time intervals and thus incipient degradation may be visually detected before failure occurs. Since significant changes may take place between inspections periods, the checklist approach does not appear to be an acceptable solution to the detection of incipient failures for all concrete components of nuclear power plants.

3. A Reliability Centered Detection System (RCDS) is a decision based approach which attempts to bridge the gap between theory and practice [5]. The important features of this approach are:

   - decisions are based on failure modes and actual case histories of failures.
   - all failures are classified into either safety related, operational related, or hidden consequences of failures. Further, the consequences of failure establish priority.
   - the system is based explicitly on whatever information is available; the availability of information for decision making is a critical factor.

The RCDS is oriented towards practical decision making, yet it retains a strong theoretical base by combining design theory with probability of failure determined from actual case histories of failures. Thus, the RCDS system is selected for the basis for the development of an incipient concrete inspection system for the reinforced concrete components of Surry Unit One.

2 CONCRETE DEGRADATION AT SURRY UNIT ONE

2.1 Concrete Degradation Categories

Concrete is usually a manufactured mixture of portland cement, stone, sand, water, and admixtures. The outward simplicity is contradicted by the extreme complex physiochemical factors which influence the durability of the material. Some 116 factors which could adversely affect the durability of concrete have been identified under the following five major categories [6].

1. Constituent materials

2. Construction practices

3. Physical properties of hardened concrete

4. Loading conditions

5. Environmental exposure conditions

Predominant environmental concrete degradation mechanisms which safety-related components in light-water reactor plants could be subjected to include [7]: freezing and thawing, aggressive chemical exposure, abrasion, corrosion of steel and other metals in concrete, chemical reactions of aggregates, unsound cement, shrinkage cracking, elevated temperature, and irradiation.

For Surry Unit One, a pressurized-water reactor, the above five concrete durability categories were combined into four categories. The four concrete durability categories are:

1. Material Interactions - concrete degradation mechanisms related to chemical or physical properties of concrete constituent materials.

2. Extreme Operating or Load Exposures - concrete degradation caused by short-term exposure to extreme environmentally degrading conditions.

3. Aggressive Environments - concrete degradation caused by long-term exposure to an adverse environment or mechanical or thermal load.

4. Environment-Stress Interactions - concrete degradation mechanisms which are related to the interaction of two or more factors which would not occur if each acted independently.

2.2 Structural Considerations

As indicated above, the development of a concrete inspection program for nuclear power plants requires the identification of all possible modes of concrete deterioration. This

section of the report addresses the possible structural or structurally related modes of concrete degradation as opposed to material or material interaction related mechanisms.

Structurally related modes of degradation are those modes which are a result of loads being imposed on the concrete structures during the service life of the plant. This includes the design loads as well as other loads such as the Structural Acceptance Test and the Integrated Leak Rate Tests.

The design loads are usually subdivided into Service Loads, Severe Environmental Loads, and Extreme Loads [8]. Service Loads are those loads which are expected to occur during the normal operation of the plant. Severe Environmental Loads are those loads which are expected to occur less frequently and are generally more severe than Service Loads. Extreme Loads consist of loadings which are generally very short-term in nature and cause stresses exceeding those associated with Service or Severe Environmental Loads.

It should be noted that engineering judgment was used to evaluate the probable effects of these loads on the service life of the structures. Although detailed loading-response analyses for each of the loads could have been performed, the correlation of the results of these analyses to the durability of the concrete over the service life of the plant would be difficult to establish. For this reason, these analyses were not included in the scope of this project.

Below is a discussion of the design loads which may be imposed on the reinforced concrete structures at Surry followed by some comments on the Structural Acceptance Test and the Integrated Leak Rate Tests.

2.2.1 Normal or Service Loads

1. Dead Load

Dead Load is the vertical load due to the weight of all permanent structural and nonstructural components of a building. Dead load is generally a small fraction of the total possible load which may be imposed on a component. For this reason, dead loads are not expected to degrade the plant's concrete components in any way.

2. Operating Live Load

Live Load is the load that is superimposed by the use and occupancy of the building. The following types of live load are possible:

- Uniformly Distributed live load
- Concentrated live load
- Railway support loads
- Truck support loads
- Ordinary Impact loads
  - Machinery (including vibration)
  - Craneways

Live loads may cause cracking in the concrete components where tensile stresses are present. Although this, in itself, poses no problems, the cracking may allow moisture to penetrate the concrete thereby accelerating some of the other modes of deterioration. Refer to Section 2.4.4, Interactions, for further discussion.

Live loads may also induce vibration which may in turn cause fatigue. The possibility of fatigue due to machinery vibration is discussed further in Section 2.2.5.1.2.

3. Construction Loads

Construction loads generally include temporary large, heavy loads due to construction and erection of equipment and the temporary storage of major mechanical and electrical components. Construction loads occur over a relatively short construction period and therefore will not affect the life length of the structures.

4. Snow Loads

Snow loading on the structures is distributed over the horizontal projections and is a function of the geographical region under consideration. Although snow loads are not expected to directly cause deterioration of the concrete, degradation modes which require the presence of moisture could be accelerated.

5. Soil, Hydrostatic Pressure and Buoyancy Loads

In the design of buildings which are partly or totally below grade, provisions shall be included in the design to account for soil and water pressures including the uplift from buoyancy. These soil, hydrostatic, and buoyancy loads are not expected to effect the life of the reinforced concrete in any way.

6. Piping Equipment Reaction Loads

Piping systems are attached to the building structures by various types of anchors and hangers. Piping equipment reaction loads are those loads which will be transferred to the structures by these anchors and hangers. These loads may cause local

distress in the concrete supporting structures if the reactive forces are varying, or more importantly reversible. Refer to Section 2.2.5.1.2 for further discussion.

7. Operating Pressure

In several cases compartments and subcompartments within the plant are exposed to pressures lower than the atmospheric pressure. One example is the containment structure. In some instances pressure variations may also be possible. Fatigue may occur if pressure fluctuations are relatively large and frequent. Refer to Section 2.2.5.1.1 for further discussion on the possibility of fatigue due to cycles of operating pressure.

In addition, subatmospheric operating pressure is the principle design load imposed on the Nelson stud anchors which attach the steel liner to the concrete containment. The possibility of the studs being overstressed and damaging the concrete is discussed below in Section 2.2.5.2.

8. Operating Temperature

Operating temperatures in the plant vary. Thermal gradients may develop as a result of temperature variations. The effect of high temperatures on the plant's concrete components will be addressed in Section 2.4.3, Aggressive Environments. Also, cycles of operating temperature may cause fatigue if they are severe. Refer to Section 2.2.5.1.1 for further discussion on the possibility of fatigue due to variations in temperature.

2.2.2 Severe Environmental Loads

1. Wind Loads (excluding tornado and hurricane winds)

   Wind loads are based on a mean recurrence interval, a basic wind speed for a given geographic location and an effective velocity pressure for a specific structure. Wind loads are not expected to cause any degradation to the concrete structures over the service life of the plant.

2. Operating Basis Earthquake

   The occurrence of an Operating Basis Earthquake may cause cracking of the concrete and differential settlements. Refer to Section 2.4.2 for further discussion. As of this writing, the Operating Basis Earthquake has not occurred at the site.

2.2.3 Extreme Loads

Extreme loads include the following:

1. Design Basis or Safe Shutdown Earthquake

2. Tornado Loads (due to wind and pressure)

3. Hurricane Loads (wind distributions and atmospheric pressure changes)

4. Tsunami Loads (hydrodynamic and hydrostatic forces)

5. Missile Loads

- Plant generated missiles
- Extreme environmental missiles

6. Design Basis Accident Loads

- Accident pressure
- Accident temperature
- Jet reaction and impingement
- Pipe whip

Each of these Extreme Environmental Loads are short-term in nature and their occurrence will be evident. These loads are discussed further in Section 2.4.2.

2.2.4 Testing of the Containment Structure

In April, 1972, a Structural Acceptance Test (SAT) was performed as required by the Nuclear Regulatory Commission at a pressure of 115% of the design pressure [1]. The deformation of the containment was within the values predicted by the analysis [1]. A significant amount of cracking occurred as a result of the test. Although the containment was depressurized following the SAT, cracks which apparently formed during this test were visible to the unaided eye during recent site visits.

In addition to the SAT, Integrated Leak Rate Tests (ILRT's) are also performed on the containment. These tests are conducted at the design pressure and will open the existing cracks in the containment and possibly create new cracks [1]. Although cracking is expected in concrete structures and generally is accounted for in design, this cracking creates avenues which will allow the penetration of water and may accelerate other modes of concrete degradation.

2.2.5 Structural Modes of Concrete Degradation

Based on the previous discussion, three modes of structurally related degradation have been identified: Fatigue of concrete due to Normal or Service Loads, structural cracking of concrete resulting from containment testing or live loads, and concrete damage due to overstressed studs on the containment's steel liner. As discussed above in Section 2.2.4, cracking, in itself, poses no threat to structural soundness and therefore will be addressed in Section 2.4.4, Interactions. Possible damage due to fatigue and stud pull-out will be addressed below.

2.2.5.1 Fatigue

Fatigue failure can be defined as failure under a repeated number of loads with each load causing stresses which are less than the strength of the material [9]. These repeated cycles of stress cause permanent internal structural changes. These changes may be damaging and result in crack growth and concrete failure if the repetitions of stress are sufficiently large [10].

Fatigue may be a result of cycles of operating pressure and temperature or vibration induced by rotating and reciprocating machinery. In addition, the possibility of fatigue occurring in the vicinity of the main steam penetrations may be possible. Each of these possible sources of fatigue are discussed below.

2.2.5.1.1 Fatigue due to Operating Pressure and Temperature: The possibility of cycles of operating pressure and temperature causing fatigue of the containment structure is discussed herein. This discussion is limited to the containment since it is subjected to the most severe variations in temperature and pressure.

Consider a concrete specimen which is subjected to alternating stresses between σ_{low} and σ_{high}. Fatigue failure will only take place above a limiting value of stress known as the fatigue limit or endurance limit. If σ_{high} is below the fatigue limit, failure in fatigue will not occur [9]. The fatigue limit of concrete is usually described as the limiting stress to which the concrete can be subjected for a given number of cycles. This relationship is usually presented in the form of a Modified Goodman Diagram [9,10]. From such a diagram it can be seen that concrete can withstand 1000 cycles of load which produce stresses that are approximately 91% of its ultimate strength [9,10].

During the design life, the containment at Surry is expected to experience not more than 250 cycles of operating pressure (from 14.7 to 9.0 psia or 0.0 to -5.7 psig) nor more than 400 cycles of temperature variation (from 70°F to 105°F) [1]. Analysis of the containment structure determined that the minimum theoretical yield capacity would occur at 119 psig with temperatures exceeding operating temperature by 325°F [1]. Therefore, it is evident that the pressure and temperature that the containment has been exposed to thus far in its life are a very small fraction of the values which would cause yielding of the containment. Consequently, it is very unlikely that these ranges of operating pressure and temperature will result in stresses of sufficient magnitude ($\simeq$91% of ultimate) to cause fatigue damage.

In addition to the range of stress imposed, the age of the concrete, the rate of loading, and the stress history are also factors which will affect the fatigue resistance of concrete.

Tests performed by Raithby and Galloway [11] evaluated the effect of age on the fatigue resistance of concrete. The test results indicated, in all cases, a substantial increase in the fatigue endurance with age, the actual gain in strength being dependent on the type of concrete and on the level of stress.

Several investigations indicate the variation in the rate of loading between 70 and 900 cycles per minute has little effect on the fatigue strength of concrete [10]. Above this range the fatigue resistance decreases, below it, the fatigue resistance increases. The rates of loading at Surry for cycles of pressure and temperature are approximately 6.25 cycles per year and 10 cycles per year, respectively [1]. These rates are so low that the pressure and temperature loads could be considered quasi-static. In addition, the fatigue strength of concrete is increased by rest periods. This observed increase in strength is attributed to the relaxation of the concrete [9].

The load history of the material which is subjected to cycles of stress also has an effect on the resulting fatigue resistance. Cyclic loading below the fatigue limit is known to increase the fatigue strength of the concrete. It is postulated that this increase in strength is due to densification of the concrete caused by initial low stress level cycling [9].

It should also be mentioned that reinforcing steels exhibit good resistance to fatigue. Fatigue fracture of the reinforcement in a reinforced concrete structure in service has never been reported [12]. If corrosion or other mechanisms do not deteriorate the ductile reinforcing steel, the fatigue resistance of the reinforcement remains essentially unchanged over time.

In conclusion, the containment at Surry is not expected to be affected by fatigue due to cycles of operating pressure and temperature. This conclusion is based on the fact that the cycles of operating pressure and temperature produce stresses which are a very small portion of the ultimate strength of the concrete and these cycles occur at a very low frequency. In addition, the age of the concrete and the stress history at Surry both tend to increase the concrete's resistance to fatigue.

2.2.5.1.2 Fatigue due to Vibration of Equipment or Other Attachments: Various types of rotating and reciprocating machinery are located throughout the plant. The possibility of local mechanical fatigue may exist at the attachment of this equipment to its supporting slabs. In addition, the various other attachments to the concrete structures are regions which may also be susceptible to local mechanical fatigue. The susceptibility of these regions to fatigue damage will be influenced by the type of anchors used.

The "wedge-action" which is generally employed by the three most common types of expansion anchorage bolts is induced by tightening the protruding stud or bolt. This tightening is important in that it preloads the bolt in tension thus "setting" the anchor [13]. Special attention should be paid to anchorage systems which were not preloaded since they may be subject to slippage under sustained vibratory loading [8]. Since it is not known what type of anchorage systems are in use at Surry, plant components which contain rotating or reciprocating machinery will be considered possible locations for local fatigue due to machinery vibration.

2.2.5.1.3 Fatigue in the Vicinity of Penetrations: The possibility of fatigue occurring in the vicinity of the containment penetrations needs to be investigated. Due to the presence of high temperatures, the regions adjacent the main steam line penetrations would be most susceptible to this type of deterioration.

All of the containment structure piping penetrations consist of a basic containment insert. Each insert is a 4-ft 9-in-long pipe sleeve provided with a plate flange near one end and a smaller plate flange near the middle. Reinforcing bars are welded to the sleeve for anchoring the insert to the containment wall [14]. The main steam and feedwater penetrations are provided with adequate space between the piping and the sleeve for the necessary pipe insulation and for a pipe coil outside of the insulation through which

cooling water is circulated [14]. This cooling coil reduces the temperature of the sleeve and prevents any excessive heating of the concrete which is in contact with the sleeve [14]. For these reasons, fatigue of the concrete in the vicinity of the penetrations is not likely to occur.

2.2.5.2 Concrete Degradation due to Liner Stud Overstressing

The possibility of the liner plate studs being overstressed and damaging the concrete is very unlikely. This conclusion is based on tests performed by the stud manufacturer [1] indicating that the studs can develop their full ultimate strength in tension (the primary load condition). The tests also indicated that the probable mode of failure is weld failure at the stud/plate junction rather than concrete failure and stud pull-out. Therefore, damage to the concrete as a result of stud overstressing is highly unlikely.

2.3 Surry Unit One Plant Components

Each nuclear plant component performs a specific function within a nuclear electrical power generation system. Thus, environmental exposure and structural loading conditions which would influence concrete degradation mechanisms are a function of the specific plant component. Relative to the development of the concrete inspection program, Surry Unit One was subdivided into 13 major components and 29 subcomponents which are presented below.

1. Intake and Discharge

    - Intake structure at river
    - Intake canal

- Intake structure at station
- Discharge tunnels
- Seal pits/weirs
- Discharge canal

2. Containment

- Containment structure (exterior dome and cylinder)
- Base mat
- Internal walls
- Internal slabs

3. Cable Vault

- Mat, walls, and roof
- Internal slabs

4. Main Steam Isolation Cubicle

- Steam valve cubicle piles
- Foundation mat
- Walls and roof
- Internal slabs

5. Safeguard Cubicle

- Foundation, walls, and roof
- Internal slab
- Concrete pipe chase

6. Fuel Building

- Foundation mat
- Walls
- Internal slabs

7. Auxiliary Building

- Foundation mat and walls
- Internal slabs

8. Service Building

- Piers, footings, walls and beams
- Internal slab

9. Turbine Building

- Turbine pedestal
- Internal slabs
- Foundation, roof, and walls

10. Boron Recovery Tank Enclosure, Foundation

11. Fuel Oil Pump Vault

12. Fire Pump House

13. Decontamination Building

2.4 Concrete Deterioration Matrices

The identified concrete materials, environment and structural load related concrete deterioration modes and the major plant components and subcomponents of Surry Unit One were organized into four concrete deterioration matrices (material interactions, extreme operating or load exposures, aggressive environments, environment-stress interactions). Each element of the matrices (Tables 1 and 2) was evaluated as to its probability of occurrence at Surry Unit One and assigned a number from zero to four. The number scale from zero to four represents the following conditions:

0 The plant subcomponent is either not exposed to the subject mode of degradation or the probability of occurrence is very small.

1 Although the plant subcomponent is exposed to the subject mode of degradation, there is sufficient evidence that adequate precautions in design and construction have been observed so that the subject mode of deterioration should not occur.

2 The plant subcomponent is exposed to the deterioration mechanism and there is some data but not conclusive evidence that the subject mode of deterioration should not occur.

3 The plant subcomponent is exposed to the destructive environment and no design or preventative actions have

been taken to prevent or delay the occurrence of the subject mode of deterioration.

4 Evidence exists that the plant subcomponent has experienced the subject mode of deterioration.

The above numbering system is to be used in the development of the concept of the concrete inspection system for Surry Unit One.

2.4.1 Material Interactions

The long term stability of portland cement concrete is dependent on its proportions, physical and chemical characteristics of its constituent materials, and construction procedures. The nuclear power plant identified degradation mechanisms evaluated in this section are expansion caused by excess amounts of free lime and/or magnesium oxide in the cement, alkali-aggregate reactions, excessive amounts of clay in the aggregates, heat of hydration, drying shrinkage, mixing water, and excessive amounts of gypsum in the cement. The degradation matrix was used in the evaluation of the mechanism but is not presented because in general the mechanisms apply equally to all of the plant's components. Where exceptions exist, they are discussed under the subject degradation mode.

2.4.1.1 Expansion due to Hydration of Free Lime (CaO) or MgO

CaO and MgO present in the cement in excess amounts can cause swelling in the hardened concrete. Soundness of cement is checked by Autoclave Test (ASTM 151). Bin test reports show that the cement used in the Surry plant construction had insignificant

expansion as defined by the above test [15,16]. A probability of degradation of one (1) is thus assigned to all plant components.

2.4.1.2 Alkali-Silica Reaction

The reaction starts with the attack of the alkalis available in the cement on certain siliceous minerals in the aggregate. As a result, an alkali-silicate gel is formed which absorbs water and alteration of the borders of the aggregate takes place. The swelling of the hard aggregate particles will cause the disintegration of the hardened concrete. For the reaction to take place, moisture, an excessive amount of alkalis in the cement, and reactive aggregates are necessary. The reaction is accelerated under conditions of alternating wetting and drying [17].

Although the cement was referred in the bin and mill tests as low alkali cement, the alkali content of the cement is <u>not</u> presented on the report forms [15,16]. Also, the aggregates were tested for reactivity according to ASTM C289 and were considered non-reactive [18]. However, presently many concrete experts consider ASTM C289 to be a non-conclusive test because the reactivity is accelerated whereas field reactive aggregates are significantly slower to react [19,20,21,22]. The general consensus is that ASTM C289 is a one-sided test. That is, if the aggregate is to be considered deleterious then the alkali-silica reaction will occur. However, if the test results indicate that the aggregate is considered innocuous then the results of the test should not be interpreted to mean that the alkali-silica reaction will not occur.

Other reports identified the sources of the aggregates used in the construction of Surry Unit One. However, contact with Virginia Department of Transportation personnel did not produce a service record for these aggregates [21].

Because water is necessary for the destructive alkali-silica reaction to take place, all plant subcomponents not exposed to sufficient water to become saturated and remain saturated for significantly long periods of time were assigned a degradation number of one (1). All concrete plant subcomponents that become saturated and remain saturated for significant time periods were assigned a concrete degradation number of two (2). Thus, the six plant subcomponents of the intake and discharge system and the spent fuel pool in the fuel building were assigned a two (2) and all other components were assigned a one (1).

2.4.1.3 Alkali-Carbonate Reaction

Alkali-Carbonate reactions occur between some dolomitic limestone aggregates and the alkalis in the cement. Expansion of concrete takes place under humid conditions and cracking develops in the paste surrounding the reactive aggregate. A concrete degradation number of one (1) was assigned to all plant subcomponents except the intake and discharge structures and the spent fuel pool which were assigned a two (2) for the same reasons cited above for alkali-silica reaction.

More conclusive data is needed to further refine the probability of occurrence of the alkali-carbonate reaction. Thus, it is recommended that cores be taken for petrographic analyses.

2.4.1.4 Clay Contaminated Aggregates

Clay particles present in aggregates absorb water during the mixing of the fresh concrete thus increasing the water to cement ratio which causes a loss in strength and durability. Test results show that the coarse aggregate contained only a trace of clay and silt and

the fine aggregate contained less than 1.2 percent clay and silt [18]. These quantities of silt and clay in the aggregates are considered innocuous relative to their effect on concrete durability. Thus, a probability value of one (1) has been assigned to all plant components.

2.4.1.5 Cracks due to High Heat of Hydration

In massive structures heat of hydration may cause a temperature rise as much as 50°F to 60°F [19]. Much of this heat is generated during the early age of the concrete and causes expansion in the volume of fresh concrete. When the heat is dissipated or removed, there is a decrease in the temperature and consequent contraction of the concrete. As this shrinkage occurs, tensile stresses are induced which can exceed the tensile strength of the concrete and cause cracking. Surry's construction records show that along with type II cement [15,16] (low heat of hydration), ice had been used in massive concrete placings, such as the containment building, to lower the net increase in temperature due to heat of hydration. Thus, a probability value of one (1) has been assigned to all plant components for this mode of degradation.

2.4.1.6 Cracks due to Drying Shrinkage

The relative humidity of the medium surrounding the fresh concrete greatly effects the magnitude of shrinkage. Fresh concrete exposed to humidity below 94 percent [23] will shrink and crack if it is left unprotected. Extra reinforcement is normally designed to carry the load induced by the shrinkage. The cracks caused by the drying shrinkage normally occur in the freshly poured concrete within several hours after placement. Visual inspection performed during the construction period [1,2,3] did not reveal any cracks due to drying shrinkage. However, the concrete at Surry will continue to dry and

shrink long after the construction period. Drying shrinkage cracking by itself normally does not pose a degradation problem. Therefore, a probability degradation number of zero (0) was assigned to all plant components for this mode of deterioration. However, it should be pointed out that drying shrinkage cracking can interact with environmental factors which will result in the deterioration of concrete. Interactions will be addressed in Section 2.4.4 in this report.

2.4.1.7 Degradation due to the Presence of Deleterious Substances in the Mixing Water

Chemical analysis of the water used for mixing the concrete in 1967 [24] showed that there was no excessive amount of any deleterious substance in the water. A probability value of one (1) has been assigned for this mode of degradation for all plant components.

2.4.1.8 Expansion due to Reaction Between Tri-Calcium Aluminate and Gypsum

Excessive amounts of gypsum present in the cement can cause disruption by reacting with C_3A present in the cement. Cement tests [15,16] show that both of these substances are present in the cement within the allowable limits given by ASTM 150. Thus, a probability degradation value of one (1) was assigned to all plant components.

2.4.2 Short-Term Extreme Operating or Load Exposures

During the operating life of a nuclear power plant, reinforced concrete subcomponents may be subjected to extreme environmental events or loading conditions which may damage or deteriorate the concrete. These events and conditions include:

- Fire (chemical, equipment, or furnishings)
- Temperature shock (spilling of hot fluids)
- Chemical spills or leaks (demineralized water, sodium hydroxide, sulfuric acid, lithium hydroxide, potassium chromate, or boric acid) [2]
- Earthquake loads (operating, design, or safe shutdown)
- Tornado, hurricane, or tsunami loads
- Missile loads (plant generated or external environment)
- Design basis accident loads (pressure, temperature, jet reaction, jet impingment, or pipe whip)
- Mechanical overloading (SAT and ILRT's)

Since each of the extreme conditions are short-term in nature and their occurrence will be evident, it is recommended that control inspections be conduced to establish a baseline for comparison should any of the above environmental events or loading conditions occur. Because each plant component may be subjected to one or more of the extreme conditions during the operating life of the plant, a probability degradation value of two (2) was assigned to each element of the short-term extreme operating or load exposure concrete degradation matrix. Since every plant component is assigned the same degradation value, the short-term extreme operating or load exposure degradation matrix is not presented.

2.4.3 Aggressive Environments

Long-term exposure to the environment may also result in the degradation of the concrete components of nuclear power plants. Environmental exposure conditions aggressive to concrete at Surry include freezing and thawing (cement and aggregates), stray currents, sulfate attack (ground and river water), wetting and drying, steel corrosion, abrasion, erosion, cavitation, acid rain (degradation of the cement and reduction in concrete pH induce steel corrosion), temperature changes, irradiation, seepage, carbonation, creep, and fatigue [1,2,3,4,6,7]. The aggressive (long-term) environmental modes of degradation matrix is presented as Table 1. A discussion of each element in the matrix is presented in the following subsections. Because of the unique environmental exposure conditions of the intake, discharge, and containment structures relative to the other plant components, these structures will be discussed separately. The remaining plant components will be discussed in Section 2.4.3.3, Cable Vault and Tunnel and Other Components.

2.4.3.1 Intake and Discharge

2.4.3.1.1 Freezing and Thawing: Concrete contains a network of channels and pores that is accessible to the water. Water contained in large pores and channels freezes when exposed to ambient temperatures below 28°F. If the concrete is critically saturated (when greater than 91% of the water accessible voids are filled with water) [25], the expansion of the freezing water will cause hydraulic pressures which will disintegrate concrete which has an air void structure with a spacing factor greater than 0.008 inches and a specific surface greater than 400 square inches per cubic inch. Two possible modes of degradation exist, disintegration of the cement matrix and/or coarse aggregate.

For severe exposure and structure types, as at Surry, the American Concrete Institute recommends a water to cement ratio of 0.50 and an air content of 5.5 percent for one and one-half inch maximum aggregate size and 7 percent for one-half inch maximum aggregate size [26]. Consolidated concrete with a water to cement ratio less than 0.50 has a relatively low permeability which will resist rapid water saturation. Air contents of 5.5 percent for one and one-half inch maximum aggregate size and 7 percent for one-half inch aggregate size will normally contain a sufficient amount of air voids to produce a spacing factor less than 0.008 inches and a specific surface greater than 400 inches per cubic inch.

In the construction of Surry, all structures except the canal linings were constructed with one and one-half inch maximum aggregate size with a water to cement ratio in excess of 0.55 and an air content of about 4.5 percent [27]. For the canals, the water to cement ratio was greater than 0.50 and the air content was about 5.5 percent [27]. Therefore, a value of two (2) was assigned to the cement matrix disintegration mode of failure for the intake and discharge structures exposed to water and freezing temperatures (intake structures at the river and the station and the intake and discharge canals). The discharge tunnels are located below ground frost penetration level and the constant flow of warm water through the seal pits/weirs should prevent the freezing of the concrete. Thus, a zero (0) is assigned to the seal pits/weirs and the discharge tunnels. Air content analyses of minimum four-inch-diameter diamond drilled cores are recommended to further evaluate this suspected degradation mode. The air content analyses are to be performed in accordance with ASTM C457, "Standard Practice for Microscopical Determination of Air-Void Content and Parameters of the Air-Void System in Hardened Concrete."

With respect to the coarse aggregate, the results of several soundness tests (ASTM C88) are available [18]. Present literature indicates that this method, by itself, should not be considered a totally reliable method for determining the freezing and thawing resistance of coarse aggregate in portland cement concrete [28,29]. The apparent lack of reliability of the results of ASTM C88 may be due to the lack of any theoretical or experimental support indicating that the test simulates exposure to freezing and thawing of aggregates in concrete or that the test gives a reliable indication of field performance [30]. The current version of ASTM C88-83, states the following under the heading "Scope":

> This test method furnishes information helpful in judging the soundness of aggregates when adequate information is not available from service records of the materials exposed to actual weathering conditions.

The overall most reliable measure of aggregate freeze-thaw soundness is probably derived from freezing and thawing tests of concrete [31]. Therefore, a probability value of two (2) is assigned to those components exposed to water and freezing temperatures (intake structures at the river and the station and the intake and discharge canals) and a zero (0) where freezing will not occur (seal pits/weirs and discharge tunnels). Petrographic analyses of minimum four-inch-diameter cores are recommended to resolve the potential for this suspected degradation mode. The petrographic analyses should be performed in accordance with ASTM C856-83, "Standard Practice for Petrographic Examination of Hardened Concrete."

2.4.3.1.2 Stray Currents: The passage of direct electrical current through concrete may cause rapid corrosion of the reinforcing steel. Such current has frequently been caused by electrical leakage or by failure to provide positive and permanent means of grounding electrical systems [32]. There are pumps and other electrical equipment located at the intake structures at the river and the station. Corrosion could occur if any direct current

equipment or neutral transformer leads are grounded to the reinforcing steel in the concrete. Further investigation should determine if the reinforcing steel in the concrete has been used as ground connections at these structures thereby possibly activating the stray current mode of degradation. Because of the unknown conditions, a probability value of three (3) is assigned to the intake structures at the river and the station. The intake canal, discharge tunnels, seal pits/weirs, and the discharge canal do not house electrical equipment and are thus assigned a value of zero (0).

2.4.3.1.3 Sulfate Attack from Ground and River Water: Some clays contain alkali, magnesium, and calcium sulfates. Groundwater exposed to these clays is a sulfate solution which will attack concrete. The reaction products are expansive in nature and cause internal pressures which may cause disruption in the concrete. The sulfate content of the groundwater at Surry is very low (7 ppm) and would have negligible effect on concrete [33]. Also, because the intake and discharge structures are significantly higher than the water table at Surry (elevation 5), these components are not exposed to the groundwater. A probability value of zero (0) is assigned to all of the intake and discharge subcomponents. In addition, it should be noted that type II cement, a moderately sulfate resistant cement, was used in construction of the Surry units.

The James River at Surry contains about 35 ppm of sodium sulfate and is to be considered as having a negligible effect on portland cement concrete [33]. In addition, type II cement was used. Thus, a probability value of zero (0) is assigned for the sulfate attack from river water mode of degradation to all of the intake and discharge plant subcomponents.

2.4.3.1.4 Wetting and Drying: The degradation of concrete can occur from exposure to wetting and drying by recrystalization of certain salts and by differential stresses caused

by differences in volume change characteristics of the ingredients. Concrete at Surry has a relatively high water to cement ratio of about 0.55 and will saturate and dry relatively quickly when exposed to wet and dry conditions. Wetting and drying cycles would occur at the intake structures at the river and station, intake canal, seal pits/weirs, and the discharge canal. A probability value of three (3) is assigned to these subcomponents. The discharge tunnels are not expected to undergo wetting and drying cycles and are assigned a zero (0).

The concrete aggregates used at Surry are of good quality [18] relative to differential stress deterioration caused by wetting and drying cycles. A zero (0) is assigned to all of the intake and discharge subcomponents of Surry for this mode of deterioration.

2.4.3.1.5 Corrosion of Reinforcing Steel: Corrosion of reinforcing steel is caused by chloride ions diffusing through concrete and destroying the passive iron oxide layer which forms in the high pH ($\simeq$12.5) environment of concrete or by carbonation or possibility acid rain reducing the pH at the steel below 10. Concrete cracking to the depth of the reinforcing steel would decrease the time to initiate corrosion and accelerate the degradation rate of the concrete caused by corroding steel. The role of cracks will be discussed in Section 2.4.4, Interactions. The effects of carbonation will be discussed under Section 2.4.3.1.13, Carbonation.

The James River at Surry is brackish water. The probability of chloride diffusion induced corrosion is a possibility at this writing and thus a probability of two (2) is assigned to all reinforced concrete subcomponents of Surry exposed to river water or wind blown river water. Thus a probability value of two (2) is assigned to the intake structures at the river and the station, intake canal, discharge tunnels and seal pits/weirs. A

probability value of zero (0) is assigned to the discharge canal because the concrete does not contain reinforcing steel.

Sampling for the chloride content of the concrete at Surry is recommended to better define the role chloride diffusion induced corrosion will play in the degradation of the reinforced concrete at Surry. The chloride content of the concrete, as a function of the depth from the exposed surface, is to be determined from powder samples crushed from sliced two-inch-diameter cores in accordance with FHWA procedures [34].

2.4.3.1.6 Abrasion: Abrasion is the dry attrition of concrete caused by wear, such as in the case of wear on pavements and industrial floors by vehicular traffic [33]. A zero (0) is assigned to all subcomponents of the intake and discharge components of Surry because of the very small probability of these structures being exposed to abrasive forces.

2.4.3.1.7 Erosion: Erosion is caused by abrasive action of fluids containing solid particles in suspension [33]. When the solid particles are small, silt size (0.02 to 0.004 mm and smaller), and the bottom velocity is less than 6 ft/sec, erosion is negligible [33]. The erosion rate of concrete is dependent upon the porosity of the cement paste and the aggregate's resistance to wear. Because of the strong correlation between porosity and compressive strength, ACI Committee 201 recommends that in no case should the compressive strength be less than 4000 psi [32]. The concrete design strength for Surry is 3000 psi at 28 days. A typical cumulative average 28 day concrete strength for Surry is 3790 psi with a coefficient of variation of 9.2%. Because of the relatively high water to cement ratio and subsequently low strength in addition to estimated velocities in the intake and discharge canals of 5.5 and 7.0 ft/sec, respectively [35], a probability value of two (2) is assigned to the intake canal, discharge tunnels, seal pits/weirs, and the dis-

charge canal. The intake structures at the river and the station are not exposed to erosive action and therefore a value of zero (0) is assigned to these subcomponents.

It should be pointed out that the discharge canal was constructed by injecting concrete into porous nylon woven forms and the elevated temperature of the cooling water in the discharge canal will accelerate the erosion of concrete. However, the nylon will provide some level of protection against erosion and thus a probability value of occurrence of one (1) is assigned.

2.4.3.1.8 Cavitation: On open channel concrete surfaces subjected to flow velocities in excess of 40 ft/sec an obstruction or abrupt change in surface alignment may cause a zone of severe subatmospheric pressure to be formed against the surface immediately downstream from the obstruction or abrupt change [33]. Vapor bubbles form and flow downstream and on entering an area of high pressure, collapse with great impact. The impact of the collapse has been estimated to produce pressures as high as 100,000 pounds per square inch. The velocities of flow are too low for cavitation to take place in all of the intake and discharge subcomponents except for possibility in the seal pit/weir area where the water exits the discharge tunnel and enters the discharge canal [3]. Thus, a probability value of zero (0) is assigned to all of the intake and discharge subcomponents except the seal pits/weirs which are assigned a value of four (4) because the discharge canal collapsed in December of 1984. The collapse of the discharge liner appeared to be the result of the erosion of the subgrade soil caused by the corrosion of a corrugated metal pipe culvert where it projected through the sloping surface of the liner in the seal pit/weir area. The corrosion of the corrugated metal pipe may have been caused by the high velocity of flow of brackish water or cavitation-erosion or the interaction of both [36].

2.4.3.1.9 Acid Rain: Acid rain may result in the degradation of reinforced concrete in two ways. First, the low pH of about 4.1 [37] of the rain in the Surry area reacting with the highly basic hydrated cement may corrode the cement matrix. Second, as indicated in the corrosion mode of failure discussion, the acid rain may enter cracks, lowering the pH of the concrete at the reinforcing steel locations and initiate corrosion cells. The role of cracks and acid rain will be addressed further in the Interaction Section, 2.4.4, of this report. In this subsection, acid rain degradation of the cement matrix will be addressed.

Since no actions were taken in the design process or as maintenance activities to prevent or reduce the rate of cement matrix degradation caused by acid rain, a value of three (3) is assigned to all of the intake and discharge reinforced concrete subcomponents exposed to acid rain (intake structures at the river and the station and the intake canal). A value of zero (0) is assigned to the discharge tunnels and the seal pits/weirs because these structures are not exposed to the acid rain. A value of two (2) is assigned to the discharge canal because the nylon forms may provide some protection against acid rain corrosion of the cement paste.

2.4.3.1.10 Temperature Changes: Plant operating and exposure temperatures which may have an effect on the deterioration of the cement paste and/or aggregate/cement bond will be addressed in the section. Thermal load cycling has already been addressed in Section 2.2.5.1. The possibility of fatigue occurring at the intake and discharge components due to cyclic thermal loads will be discussed in Section 2.4.3.1.15, Fatigue. Elevated temperatures caused by irradiation will be addressed in Section 2.4.3.1.11, Irradiation.

Concrete degradation caused by elevated temperature may be related to either the degradation of the cement paste and/or cement/aggregate bond strength caused by a

marked difference between the thermal expansion-contraction properties of the aggregate and cement matrix. For cement paste, absorbed water is vaporized at temperatures slightly above 212°F with little or no change in the mechanical properties of the concrete. Dehydration of calcium hydroxide, one of the cementitious products of cement, occurs at temperatures above 750°F. At 750°F there is little or no change in the compressive strength of concrete if it is heated under load and tested hot [7,23]. If heated to 750°F without application of load and tested hot there is about a 15 percent reduction in compressive strength. If heated to 750° without application of load, stored at 70°F for seven days and tested cold, there is about a 50 percent reduction in strength. Between 212°F and 750°F, absorbed water is vaporized. The reduction in strength is almost linear with temperature for the above loss of strength conditions.

For the modulus of elasticity, there is little or no difference in the range of 70°F to 212°F [7,23]. From 212°F to 750°F, there is almost a linear reduction with increasing temperature in the modulus of elasticity to about 40% of its original value.

When the temperature does not vary outside of the range of 40°F to 140°F, a large difference in the coefficient of thermal expansion between the aggregates and the paste is not necessarily detrimental. However, when the two coefficients differ by more than $3x10^{-6}$ per °F, the durability of the concrete subjected to cyclic temperatures from 40°F to 0°F and below may be affected by thermal contraction and expansion [23].

None of the intake and discharge subcomponents of Surry Power Station are exposed to operating temperatures above 212°F. Therefore, a probability value of zero (0) is assigned to all of the intake and discharge subcomponents for the temperature change paste mode of concrete degradation. However, the intake structures at the river and the station and the intake and discharge canals are exposed to cyclic temperatures from 40°F to zero and below. Thus, a probability value of three (3) is assigned to these structures

for the temperature change aggregate mode of concrete deterioration because no evidence was found indicating that the aggregate or concrete characteristics promoting this mode of deterioration were tested for during the construction of the plant. A probability value of zero (0) is assigned to the discharge tunnels and the seal pits/weirs because they will not be subject to cyclic temperatures from 40°F to zero and below.

2.4.3.1.11 Irradiation: Irradiation in the form of either fast and thermal neutrons or gamma rays can affect concrete [7]. Atomic displacements caused by fast neutrons have resulted in considerable growth in aggregates. Gamma rays produce radiolysis of water in the cement paste. Radiation energy absorbed by concrete is converted to heat and temperature rises in concrete of 180°F have been recorded. Damage to concrete by irradiation is less than the associated temperature effects [7]. However, limited data are available on the long-term effects of irradiation on concrete [7]. Thus, a long-term monitoring program to determine the effects of irradiation on the mechanical properties of exposed concrete at Surry is recommended. Concrete exposed to irradiation is thus assigned a probability value of two (2). Concrete not exposed to irradiation, such as all the intake and discharge components, is assigned a probability degradation value of zero (0).

2.4.3.1.12 Seepage: Waterstops were used at many of the concrete construction joints at Surry. The purpose of a waterstop is to either keep water from flowing out of the construction joint and seeping through the soil as in the case of the canals, or to prevent water from flowing into structures. Seepage through structures is generally not a problem unless the velocity of flow increases to where piping of solids or the removal of soluble materials occurs. The potential for damage is great and failures may be catastrophic. Thus, it is recommended that seepage monitoring be performed.

In some instances the monitoring would be part of "good housekeeping". In others, it would be included in the inspection system. For the seepage mode, a one (1) is assigned to those subcomponents where seepage would be a housekeeping concern and a probability factor of two (2) or greater is assigned to the structural subcomponents where seepage should be included in the inspection program.

A probability value of four (4) is assigned to the seepage mode of failure for the intake canal and seal pits/weir because these subcomponents have experienced failures which may have been caused by seepage or a similar mechanism. The discharge tunnels and discharge canal are assigned a value of two (2) because of the risk of seepage at joints and the magnitude of the impact of a seepage failure on the operation of Surry. The intake structures at the river and station are assigned values of zero (0) because of the small probability of failure due to seepage.

2.4.3.1.13 Carbonation: Carbonation shrinkage of concrete is the result of a reaction between carbon dioxide and calcium hydroxide (one of the cementitious products of the hydration process). The amount of carbon dioxide in the air, the relative humidity, and the permeability of the concrete influences the rate of carbonation. The maximum rate of carbonation occurs at a relative humidity of 50% with the rate being reduced when the relative humidity is greater than or less than 50%. The water to cement ratio of the concrete at Surry was generally about 0.55 indicating that the concrete would have a moderate permeability. The carbon dioxide in the air should not be greater than normal because most of the industrial installations near Surry are located to the north and northeast and the predominant wind directions at the plant are from the south and southwest. Also, the relative humidity at Surry is generally greater than 50%. Thus, the carbonation shrinkage mode of degradation would have a very small probability of oc-

currence at Surry. Therefore, a value of zero (0) is assigned to all of the intake and discharge subcomponents.

It should be pointed out that carbonation may take place at a faster rate in cracks and may initiate the corrosion of reinforcing steel. This deterioration mechanism will be addressed in the Interaction Section, 2.4.4, of this report.

2.4.3.1.14 Creep: Creep is an increase in strain with time under a sustained stress and can effect the performance of concrete components with respect to increased deformation (alignment). The creep in concrete is a function of time, temperature, aggregate type, and stress level [7]. Below 212°F at moderate stress levels, creep originates in the cement paste and approaches an asymptotic value between about 10 and 15 years depending upon the aggregate type. Since Surry Power Station began commercial operation in December 1972, it has been under a sustained operating stress level for approximately 15 years. Therefore, creep should not significantly affect the long-term performance of Surry's concrete components since evidence of creep damage at Surry has not surfaced. Therefore, a value of zero (0) is assigned to all of the intake and discharge subcomponents of Surry Power Station.

2.4.3.1.15 Fatigue: Mechanical equipment at the intake structure includes an emergency diesel engine, an auxiliary motor drive, trash rack raking mechanism, and dewatering sump pumps [3]. The only probable cause of mechanically induced fatigue would be the vibration of the emergency diesel engine. This vibration could, over time, loosen the bolts which attach the engine to its concrete supporting slab while producing some cracking. However, a value of zero (0) is assigned because of the limited use of the emergency diesel engine.

Mechanical equipment at the high-level intake structure at the station include a trash rack, a traveling screen, a screen wash pump, and dewatering sump pumps [3]. None of this equipment produces sufficient vibration to be of concern. Thus, a value of zero (0) is assigned to the intake structure at the station for this mode of concrete degradation.

The intake and discharge canals, discharge tunnels, and seal pits/weirs are not subjected to mechanical vibrations. For this reason, no mechanical fatigue is expected and a value of zero (0) is assigned.

2.4.3.2 Containment

2.4.3.2.1 Freezing and Thawing: A portion of the exterior cylinder walls located underground but above the frost penetration depth and above ground may become critically saturated from soil moisture and capillary rise. Also, a section of the dome and cylinder which is exposed to condensing steam may also become critically saturated. These locations are assigned a probability of degradation value of two (2). The other subcomponents of the containment are not subjected to freezing and thawing cycles and are assigned a value of zero (0).

2.4.3.2.2 Stray Currents: Because of the unknown conditions that reinforcing steel may have been used as ground connections for electrical equipment or lighting rods, a value of three (3) has been assigned to all of the subcomponents of the containment.

2.4.3.2.3 Sulfate Attack from Ground and River Water: The containment is not exposed to the ground or river water at Surry. In addition, type II cement, a moderate sulfate resistant cement, was used in the construction of Surry. Also, the ground and river wa-

ter contains low amounts of sulfate, 7 ppm and 35 ppm, respectively [33] and thus would have a negligible effect on portland cement concrete. Therefore, a value of zero (0) is assigned to the containment for the sulfate attack mode of degradation.

2.4.3.2.4 Wetting and Drying: The containment concrete is not exposed to severe cycles of wetting and drying and the aggregates used in construction are of good quality [18] relative to differential stress deterioration caused by wetting and drying. A value of zero (0) is assigned to the containment for these modes of deterioration.

2.4.3.2.5 Corrosion of Reinforcing Steel: Windblown brackish water from the James River may induce chloride diffusion initiated corrosion of the reinforcing steel in the exterior portion of the containment structure. A value of two (2) is assigned to the exterior portion of the containment structure and zero (0) to the interior subcomponents (base mat, internal walls and slabs).

2.4.3.2.6 Abrasion: The containment's concrete floor slabs at Surry Power Station are subjected to abrasive forces which may degrade the concrete. Many of the floor slabs are topped with a one-half inch thick or greater monolithic-granolithic or granolithic abrasive resistance finish [2]. However, regardless of the finish type, all concrete abrades. The amount of abrasion loss is dependent upon the exact cause of the wear which includes scraping, impact, and frictional attrition. Therefore, a value of two (2) is assigned to the containment internal slabs and a zero (0) is assigned to all the remaining containment subcomponents because they are not exposed to abrasive forces.

2.4.3.2.7 Erosion: The containment is not subjected to erosion and thus is assigned a value of zero (0).

2.4.3.2.8 Cavitation: The containment is not subjected to cavitation and therefore is assigned a value of zero (0).

2.4.3.2.9 Acid Rain: The exterior surfaces of the containment structure are exposed to acid rain and a value of three (3) is assigned to this subcomponent because no provisions have been taken to reduce or prevent this mode of failure. The other subcomponents of the containment are not exposed to acid rain and are assigned a value of zero (0).

2.4.3.2.10 Temperature Changes: (Aggregates). A value of three (3) is assigned to the exterior surfaces of the containment structure because it is exposed to freezing temperatures. All other subcomponents of the containment are assigned a value of zero (0) because they are not exposed to freezing temperatures.

(Cement Paste). Hot pipes, such as the main steam line piping, penetrating the reinforced concrete containment wall may thermally degrade the hydrated portland cement paste in the area surrounding the penetrations in time. However, all thermally hot pipes penetrating the reinforced concrete containment wall pass through individual sleeves and each sleeve is equipped with two water-cooled heat exchangers to limit the temperature of the concrete in contact with the sleeve [38]. Therefore, a value of one (1) is assigned to the containment building for temperature changes paste mode of concrete degradation. All the other subcomponents of the containment are assigned a value of zero (0) because they are not exposed to temperature changes large enough to degrade hydrated portland cement.

2.4.3.2.11 Irradiation: A value of two (2) is assigned to the concrete base mat, internal walls, and internal slabs of the containment because they are exposed to relatively high levels of radiation. A value of zero (0) is assigned to the containment structure because

the interior cylinder walls and dome are lined with steel and the concrete should not be significantly exposed to any radiation during normal operation.

2.4.3.2.12 Seepage: A zero (0) is assigned to the internal slabs and walls because these subcomponents are not exposed to the seepage mode of degradation. A one (1) is assigned to the containment structure and base mat subcomponents because the drainage system for the containment maintains the ground water level two to three and one-half feet below the containment floor liner [1].

2.4.3.2.13 Carbonation: Carbonation shrinkage mode of the deterioration of the containment has a very small probability of occurrence at Surry and thus, a value of zero (0) is assigned to the containment subcomponents.

2.4.3.2.14 Creep: Creep should not significantly affect the long term performance of Surry's containment because concrete undergoes in five years over 95% of the creep deformations it would experience in forty years. A value of zero (0) is assigned to the containment subcomponents.

2.4.3.2.15 Fatigue: As discussed previously in Section 2.2.5.1, cycles of operating pressure and temperature in the containment and cycles of temperature in the piping which penetrate the containment are not likely to cause fatigue. However, with the various attachments to the containment shell, mat, internal walls, slabs, and/or steel liner the possibility exists for the occurrence of local mechanical fatigue due to vibration. Therefore, a value of two (2) is assigned to this mode of degradation for all of the subcomponents of the containment.

2.4.3.3 Cable Vault and Tunnel and Other Components

2.4.3.3.1 Freezing and Thawing: Approximately 22 feet of the cable vault and tunnel is above ground and exposed to freezing and thawing cycles but not all sections of the exposed concrete subcomponents will become critically saturated. The exposed sections most likely to be critically saturated and exposed to freezing and thawing cycles are those sections several feet above and below ground level. A value of two (2) is assigned to these subcomponents and a value of zero (0) to those subcomponents not exposed to freezing and thawing temperatures and/or saturating conditions.

The main steam isolation cubicle, safeguard cubicle, fuel building, auxiliary building, service building, turbine building, boron recovery tank, fuel oil pump vault, fire pump house, and decontamination building have similar exposure conditions as the cable vault and tunnel and are assigned like probability degradation numbers.

2.4.3.3.2 Stray Currents: A value of three (3) is assigned to all of the subcomponents of the cable vault and tunnel because it is not known if the reinforcing steel is subjected to stray currents.

Subcomponents of the main steam isolation cubicle, safeguard cubicle, fuel building, auxiliary building, service building, turbine building, boron recovery tank, fuel oil pump vault, fire pump house, and decontamination building have similar exposure conditions or house electrical equipment and are assigned a value of three (3). Those subcomponents not exposed to stray currents are assigned a value of zero (0).

2.4.3.3.3 Sulfate Attack from Ground and River Water: The ground and river waters at Surry contain low amounts of sulfate, 7 ppm and 35 ppm, respectively [33]. In addition,

Type II cement, a moderate sulfate resistant cement, was used in the plant construction. For these reasons, exposure to the ground and river waters would have a negligible effect on the durability of the portland cement concrete. Therefore, a value of zero (0) is assigned to the cable vault and tunnel and other plant components for the sulfate attack mode of concrete degradation.

2.4.3.3.4 Wetting and Drying: The cable vault and tunnel and the other plant components are not exposed to severe cycles of wetting and drying and the aggregates used in construction are of good quality relative to differential stress deterioration caused by wetting and drying [18]. Therefore, a value of zero (0) is assigned to the cable vault and tunnel and the other plant components for this mode of concrete degradation.

2.4.3.3.5 Corrosion of Reinforcing Steel: A value of two (2) is assigned to all exterior portions of the subcomponents which are exposed to windblown chlorides and a zero (0) to the internal subcomponents. The remaining components have similar chloride exposure conditions and are assigned the same probability of occurrence values.

2.4.3.3.6 Abrasion: Concrete slab elements of the cable vault and tunnel, main steam isolation cubicle, safeguards cubicle, fuel building, auxiliary building, service building, turbine building, and decontamination building are subjected to abrasive forces. Since all concrete abrades regardless of the finish type, a value of two (2) is assigned to the above listed subcomponents and a zero (0) is assigned to all of the remaining subcomponents.

2.4.3.3.7 Erosion: The cable vault and tunnel, main steam isolation cubicle, safeguards cubicle, fuel building, auxiliary building, service building, turbine building, boron recov-

ery tank enclosure foundation, fuel oil pump vault, fire pump house, and decontamination building are not subjected to erosive forces and are assigned a value of zero (0).

2.4.3.3.8 Cavitation: The entire cable vault and tunnel and other components at Surry Power Generation facility are not subjected to cavitation and are assigned a value of zero (0).

2.4.3.3.9 Acid Rain: The exterior portions of the cable vault and tunnel are assigned a value of three (3) and all interior portions are assigned a zero (0). The other components have similar acid rain exposure conditions and are assigned the same probability of occurrence values.

2.4.3.3.10 Temperature Changes: (Aggregate). A value of three (3) is assigned to sections of the subcomponents of the cable vault and other components which are exposed to freezing temperatures and all other subcomponents not exposed are assigned a zero (0).

(Cement Paste). The cable vault and tunnel and other components are not subjected to the paste temperature change mode of deterioration and are assigned a value of zero (0).

2.4.3.3.11 Irradiation: A value of zero (0) is assigned to all subcomponents of the cable vault and tunnel because the component is not exposed to significant levels of radiation [2]. Concrete components of Surry Power Station which are exposed to radiation in addition to the containment internal structure include the auxiliary building, safeguards cubicle, main steam cubicle, service building, fuel building (in particular the fuel pool in the fuel building), and the decontamination building [2]. Because of the unknown effects

of long-term irradiation on concrete, a value of two (2) is assigned to the subcomponents of these radiation exposed components.

The remaining plant components (turbine building, boron recovery tank enclosure, fuel oil pump vault, and fire pump house) are not exposed to radiation and are assigned a value of zero (0).

2.4.3.3.12 Seepage: The cable vault and tunnel building is located above the water table and any moisture which may seep into the building would come after extensive periods of precipitation [2]. A value of one (1) is assigned. The other components are also located above the water table and subcomponents susceptible to seepage after extensive periods of precipitation are assigned a value of one (1). All the other subcomponents of the other components which are not susceptible to the seepage mode are assigned a zero (0).

2.4.3.3.13 Carbonation: The carbonation shrinkage mode of degradation has a very small probability of occurrence at Surry. This conclusion is based on the fact that the carbon dioxide in the air is not excessive and the relative humidity is generally greater than 50%. Both of these factors tend to reduce the probability of carbonation shrinkage occurrence. It should be mentioned that the exhaust from the diesel and gasoline engines located throughout the plant is not expected to increase the probability of carbonation shrinkage. These engines are generally used as back-up power supplies and thus are not operated frequently. In addition, the exhausts from these engines is vented to the exterior of the buildings further reducing the possibility of carbon dioxide build-up. For these reasons, a value of zero (0) is assigned to the cable vault and tunnel and other components for this mode of degradation.

2.4.3.3.14 Creep: Creep deformations have already taken place at Surry without any evidence that damage has occurred. Thus, a value of zero (0) is assigned to the cable vault and tunnel and other plant components for this mode of concrete degradation.

2.4.3.3.15 Fatigue: As discussed previously in Section 2.2.5.1, cycles of operating pressure and temperature in the containment and cycles of temperature in the piping which penetrate the containment are not likely to cause fatigue. Since cycles of pressure and temperature in the cable vault and tunnel and other remaining components are less severe than those in the containment, it is concluded that fatigue due to pressure and temperature is not likely to occur in these components. However, with the various attachments to the plant structures for piping systems and rotating and/or reciprocating machinery, the occurrence of local mechanical fatigue due to vibration is possible.

The following plant components are assigned a value of zero (0) for the fatigue mode of concrete degradation since the possibility of local mechanical fatigue is not likely.

- Fuel building
- Auxiliary building
- Service building
- Boron recovery tank enclosure
- Decontamination building

It should be mentioned that fatigue in the emergency diesel generator cubicle of the Service building is not likely to occur since the generator is used very infrequently. Also, fatigue of the turbine pedestal in the Turbine building is not expected. This conclusion

is based on the results of a dynamic analysis by Stone & Webster [2] which concluded that the turbine would shutdown before allowing vibrations of a magnitude sufficient to cause cracking of the concrete.

The remaining plant components may be susceptible to local mechanical fatigue due to vibration of piping or machinery attachments and are therefore assigned the value (2).

2.4.4 Environment-Stress Interactions

The permeability of concrete is relatively low and is dependent upon the water to cement ratio. For water to cement ratios greater than 0.55, the permeability of concrete increases rapidly. The concrete used in the construction of Surry Power Station had a water to cement ratio of about 0.57. Even though the permeability of the concrete at Surry would be relatively high, it should be low enough to prevent moisture and gases from rapidly penetrating the concrete and thus prevent the activation of some of the concrete degradation mechanisms. However, cracks in the concrete would allow moisture, carbon dioxide, and acid rain to penetrate the concrete and possibly activate the alkali-aggregate reactions, leaching of calcium hydroxide, freezing and thawing, wetting and drying, and corrosion of the reinforcing steel concrete degradation mechanisms at Surry.

Because of the low tensile strength of concrete, cracks occur in all concrete structures. Cracks may be active or dormant and as indicated above are an important avenue for the ingress of hostile environment. The causes of concrete cracking may be related to material components, environmental induced stresses, or structural loads. Cracking of concrete at Surry Power Station most likely would be related to drying shrinkage, thermal stresses, or structural loads. Thus for every interaction matrix subcomponent-mode

element which may have external cracked concrete sections, a probability of occurrence value of three (3) is assigned to the alkali-aggregate, leaching of calcium hydroxide, freezing and thawing, wetting and drying and corrosion of reinforcing steel modes of degradation. All other elements of the matrix are assigned a value of zero (0). See Table 2.

Table 1. Matrix of Aggressive (Long-Term) Environmental Modes of Degradation

Plant Component	Possible Degradation Mode																	
	Freezing & Thawing		Stray	Sulfate Attack		Wetting	Steel					Temperature Changes						
	Cement	Aggregate	Currents	Ground Water	River Water	& Drying	Corrosion	Abrasion	Erosion	Cavitation	Acid Rain	Paste	Aggregate	Irradiation	Seepage	Carbonation	Creep	Fatigue
INTAKE & DISCHARGE																		
-Intake Struct. at River	2	2	3	0	0	3	2	0	0	0	3	0	3	0	0	0	0	0
-Intake Canal	2	2	0	0	0	3	2	0	2	0	3	0	3	0	4	0	0	0
-Intake Struct. at Station	2	2	3	0	0	3	2	0	0	0	3	0	3	0	0	0	0	0
-Discharge Tunnels	0	0	0	0	0	0	2	0	2	0	0	0	0	0	2	0	0	0
-Seal Pits/Weirs	0	0	0	0	0	3	2	0	2	4	0	0	0	0	4	0	0	0
-Discharge Canal	2	2	0	0	0	3	0	0	1	0	2	0	3	0	2	0	0	0
CONTAINMENT																		
-Containment Structure	2	2	3	0	0	0	2	0	0	0	3	1	3	0	1	0	0	2
-Containment Base, Mat	0	0	3	0	0	0	0	0	0	0	0	0	0	2	1	0	0	2
-Internal Walls	0	0	3	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2
-Internal Slabs	0	0	3	0	0	0	0	2	0	0	0	0	0	2	0	0	0	2
CABLE VAULT & TUNNEL																		
-Mat, Walls, and Roof	2	2	3	0	0	0	2	0	0	0	3	0	3	0	1	0	0	0
-Internal Slabs	0	0	3	0	0	0	0	2	0	0	0	0	0	0	1	0	0	0
MAIN STEAM ISOLATION CUBICLE																		
-Cubicle Piles	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-Foundation Mat	0	0	3	0	0	0	0	0	0	0	0	0	0	2	1	0	0	2
-Walls & Roof	2	2	3	0	0	0	2	0	0	0	3	0	3	2	1	0	0	2
-Internal Slabs	0	0	3	0	0	0	0	2	0	0	0	0	0	2	1	0	0	2
SAFEGUARDS CUBICLE																		
-Foundation, Walls, Roof	2	2	0	0	0	0	2	0	0	0	3	0	3	2	1	0	0	2
-Internal Slab	0	0	3	0	0	0	0	2	0	0	0	0	0	2	1	0	0	2
-Concrete Pipe Chase	2	2	0	0	0	0	0	0	0	0	3	0	3	2	1	0	0	2
FUEL BUILDING																		
-Foundation Mat	0	0	3	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0
-Walls	2	2	0	0	0	0	2	0	0	0	3	0	3	2	1	0	0	0
-Internal Slabs	0	0	0	0	0	0	0	2	0	0	0	0	0	2	1	0	0	0
AUXILIARY BUILDING																		
-Foundation Mat, Walls	2	2	0	0	0	0	2	0	0	0	3	0	3	2	1	0	0	0
-Internal Slabs	0	0	0	0	0	0	0	2	0	0	0	0	0	2	1	0	0	0
SERVICE BUILDING																		
-Piers, Footings, Walls	2	2	0	0	0	0	2	0	0	0	3	0	3	2	1	0	0	0
-Internal Slab	0	0	0	0	0	0	0	2	0	0	0	0	0	2	0	0	0	0
TURBINE BUILDING																		
-Turbine Pedestal	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-Internal Slabs	0	0	3	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2
-Foundation, Roof, Walls	2	2	0	0	0	0	2	0	0	0	3	0	3	0	1	0	0	2
BORON RECOVERY TANK FOUNDATION	2	2	0	0	0	0	2	0	0	0	3	0	3	0	1	0	0	0
FUEL OIL PUMP VAULT	2	2	3	0	0	0	2	0	0	0	3	0	3	0	1	0	0	2
FIRE PUMP HOUSE	2	2	3	0	0	0	2	0	0	0	3	0	3	0	1	0	0	2
DECONTAMINATION BUILDING	2	2	0	0	0	0	2	2	0	0	3	0	3	2	0	0	0	0

Table 2. Matrix of Environment-Stress Interaction Modes of Degradation

Plant Components	Possible Degradation Mode				
	Alkali-Aggregate Reactions	Leaching of Calcium Hydroxide	Freezing and Thawing	Wetting and Drying	Corrosion of Steel
INTAKE & DISCHARGE					
-Intake Struct. at River	3	3	3	3	3
-Intake Canal	3	3	3	3	3
-Intake Struct. at Station	3	3	3	3	3
-Discharge Tunnels	3	3	0	0	3
-Seal Pits/Weirs	3	3	0	0	3
-Discharge Canal	3	3	3	3	0
CONTAINMENT					
-Containment Structure	3	3	3	3	3
-Containment Base, Mat	3	3	0	0	0
-Internal Walls	0	0	0	0	0
-Internal Slabs	0	0	0	0	0
CABLE VAULT & TUNNEL					
-Mat, Walls, and Roof	3	3	3	3	3
-Internal Slabs	0	0	0	0	0
MAIN STEAM ISOLATION CUBICLE					
-Cubicle Piles	3	3	0	0	0
-Foundation Mat	3	3	0	0	0
-Walls & Roof	3	3	3	3	3
-Internal Slabs	0	0	0	0	0
SAFEGUARDS CUBICLE					
-Foundation, Walls, Roof	3	3	3	3	3
-Internal Slab	0	0	0	0	0
-Concrete Pipe Chase	3	3	3	0	0
FUEL BUILDING					
-Foundation Mat	3	3	0	0	0
-Walls	3	3	3	3	3
-Internal Slabs	0	0	0	0	0
AUXILIARY BUILDING					
-Foundation Mat, Walls	3	3	3	0	3
-Internal Slabs	0	0	0	0	0
SERVICE BUILDING					
-Piers, Footings, Walls	3	3	3	3	3
-Internal Slab	0	0	0	0	0
TURBINE BUILDING					
-Turbine Pedestal	0	0	0	0	0
-Internal Slabs	0	0	0	0	0
-Foundation, Roof, Walls	3	3	3	3	3
BORON RECOVERY TANK FOUNDATION	3	3	3	3	3
FUEL OIL PUMP VAULT	3	3	3	3	3
FIRE PUMP HOUSE	3	3	3	3	3
DECONTAMINATION BUILDING	0	0	3	0	3

3 CONCEPT OF THE INSPECTION SYSTEM

3.1 Concept of Surry Concrete Inspection System

The purpose of the Surry concrete inspection system is to establish a concrete condition database that will assist Virginia Power personnel in maintaining the economic production of electric power at Surry while ensuring public safety. The concrete condition database established from inspections should be able to define the condition of concrete components at the time an inspection is conducted and estimate its future condition. Thus, the concrete inspection system should be able to at some acceptable reliable state detect modes of concrete degradation in their incipient stage. Therefore, a Reliability Centered Detection System (RCDS) has been selected as the basis for the development of an incipient concrete degradation detection system.

To apply the RCDS technique for detecting incipient concrete degradation, the inspection team needs to know the locations and modes where potential problems are likely to originate. The four concrete degradation matrices presented in Section 2.4 of this report identify the locations and modes of concrete degradation. A probability of two (2) or above indicates a degradation mode is likely to occur at a location and is to be included in the inspection system. Test data taken at these locations over time would

define the safety and operating condition of Surry's concrete components. Procedures are to be chosen such that incipient degradation conditions may be detected and recorded by an expert concrete materials inspection team. Once an anomaly has been detected, further testing will define the present condition, project future conditions, and recommend corrective actions.

Thus, the developed inspection system will consider inspection procedures, frequency of inspections, reports, records, and qualifications of the inspection team. The inspection procedures should be cost-effective. That is, inspections need to be fast and reliable with more costly procedures used to better define detected anomalies. Procedures will most likely consist of nondestructive testing comprised of both qualitative and quantitative data. Since qualitative evaluations are more subjective and open to interpretative variances, measures will have to be developed to reduce the variance of interpolations and thus interject quality assurance in the inspection system. Frequency of inspections are to be based on plant operation characteristics and the rates of the identified likely modes of degradation. The reports need to identify the location, mode of degradation, inspection procedure used, and qualitative and quantitative observations, recommend further actions, and priority of the recommendation. Records of inspections should be able to identify the history of the performance of Surry's concrete components. The quality of the inspection system has to be maintained. Thus, qualifications of the inspection team will be addressed in the developed concrete inspection system.

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Vita

Daniel L. Staron was born in Springfield, Illinois on March 23, 1963. He attended Lake Braddock Secondary School in Burke, Virginia where he graduated on June 14, 1981. He attended George Mason University in Fairfax, Virginia for one year prior to transferring to Virginia Polytechnic Institute and State University. He participated in the Cooperative Education Program at Virginia Tech and received his Bachelor of Science degree in June of 1986. Upon completion of the requirements for the Master of Science degree he intends to pursue a career as a consulting engineer and eventually obtain his professional engineering registration.