COSTAR-COncrete STructures Aging Reference Manual A Structures Condition Assessment Tool

Gregor, Frank E.[1] and Carey, John J. [2]

1) LCM Technology, LC, Tarpon Springs, Florida, USA
2) EPRI, Palo Alto, California, USA

ABSTRACT

In the past there has been a common belief that concrete structures are capable of functioning well beyond the normal life of a power plant. Initial life extension studies carried out by EPRI and others identified a number of concrete and embedment degradation mechanisms which, under certain exposure conditions, could lead to degradation of concrete structures. Effective aging management and early detection and mitigative action, if necessary, assures that the structures continue to be capable of performing their functions. The COSTAR project focussed on identifying, evaluating and recording the applicable research references, studies and plant experiences with concrete structures and developing a software tool for application to plant specific assessments.

COSTAR uses the Microsoft ACCESS database as a platform and consists of two distinct modules: A degradation susceptibility evaluation and a condition assessment process. Both modules rely on the aging degradation database, the functional grouping of the structures and a ranking logic (green, yellow, red) to determine the significance of degradation susceptibility and in-situ observed degraded conditions. COSTAR also contains a library of effective detection/investigation methods and effective mitigative actions down to the procedure level.

An expert review panel was utilized to evaluate the acceptance criteria and logic used in the program. Extensive field testing has been completed to validate the software. Enhancements have been identified to make the program more user friendly and efficient. A Beta version of COSTAR is available for use now and improvements are planned for the future.

INTRODUCTION

The COSTAR (Concrete Structures Aging Reference manual) project was initiated to provide a tool to the utility engineers for the development or enhancement of aging management programs for the nuclear power plant concrete structures. This is accomplished by providing a comprehensive electronic reference manual of current concrete aging and degradation knowledge and applying this information in a quasi expert format to perform initial ranking of the plant structures with respect to degradation susceptibility and functional importance of the structures. A second module contains a condition assessment option to accomplish evaluation of existing (in-situ) or postulated degraded concrete structure conditions, selecting supplemental investigations techniques and aging management options.

PROGRAM DESCRIPTION

Because of its universal use and flexibility, the Microsoft ACCESS data base, Windows 95 version, was chosen as the principal platform for this program. COSTAR consists of two modules, the Structures Screening Module and the Condition Assessment Module. Both modules utilize the same data and structure selection process. The individual steps for each of the modules are as shown on Figure 1.

Screening Module

The main menu of the program lets the user select the applicable plant type (PWR or BWR) and the type of assessment to be performed. The screening module can be used to create an inventory of plant concrete structures, to perform an initial ranking of functional importance and to evaluate the potential susceptibility to concrete aging and degradation, using plant specific information. This module also lends itself to assessment of concrete structures for the purpose of license renewal with respect to susceptibility to degradation using plant specific conditions.

FIG. 1 COSTAR Program Flow Chart

STRUCTURE SCREENING MODULE	CONDITION ASSESSMENT MODULE
SELECT STRUCTURE FROM THE MENU	SELECT THE STRUCTURE AND GROUP
VERIFY STRUCTURE GROUP SELECTION	DETERMINE OBSERVED AGING EFFECTS
CHOOSE FUNCTIONAL ATTRIBUTES	DETERMINE SEVERITY OF OBSERVED CONDITIONS
REVIEW APPLICABLE AGING MECHANISMS	SELECT SUPPLEMENTAL INVESTIGATIONS
SELECT DEGRADATION ATTRIBUTES AND RANKING	SELECT AGING MANAGEMENT OPTIONS
SELECT MITIGATION ATTRIBUTES AND RANKING	DETERMINE INSPECTION FREQUENCY
RESULTS AND REPORT OPTIONS	RESULTS AND REPORT OPTIONS

.Structures Menu

The Structures Menu consists of a comprehensive listing of common concrete structures found in nuclear power plants, representing BWR and PWR plants. Reinforced, unreinforced and precast concrete, reinforced and prestressed containment structures, as well as masonry block structures are included, together with the embedded rebar and steel embedments. Steel structures are not included in the scope of this program. A specific objective was to include all applicable concrete structures, whether safety related or not, underground, underwater, inaccessible or simple slabs or footings. In all 141 structures are listed in the menu, many of them in duplicate due to differing names, functions or configuration.

Structure Groups

Each of the individual concrete structures are categorized into one of twelve Structure Groups with similar function, environmental conditions and exposure. While the structure groups have been predetermined by an expert panel, a different group can be designated based on plant unique conditions. Detailed Structure Group descriptions are provided to assure that the most fitting group is matched with the plant conditions. A specific structure, such as the Reactor Building in a BWR or the Auxiliary Building in a PWR, can be represented by a number of different elements. Each element, exhibiting its own unique condition, function or exposure and belonging to a specific structure group, for instance the Building-Exterior, Buildings-Interior, Below Grade Structures and Equipment Foundations could be evaluated separately for these buildings.

The structure groups are linked to the functional attributes and the aging mechanisms, predetermined by an expert panel.

Functional Attributes

In order to establish the relative importance of the structures, the various functions must be considered. A total of 14 functions have been identified, as shown on Table 1. Detailed descriptions were generated for each function to assure that the user selects the appropriate and applicable functions. To compensate for the fact that not all functions are of equal importance, weighting factors were applied, as indicated on Table 1. Passive functional attributes (i.e., water retention) were assigned a base factor of 1.0, active functional attributes (i.e., vibration, impact) and pressure retaining functions are given a factor of 1.5 and the safety related and risk significant attributes are assigned an importance factor of 2.0.

The functional importance of the structure is based on the cumulative value of these functions and assigning a range to each of three functional importance categories as follows:

A range of 0 to <3.0 is referred to as a "Standard Structure".

A range of 3.0 to 6.0 is referred to as a "Important Structure".

A range of >6.0 is referred to as a "Critical Structure".

TABLE 1
COSTAR Functional Attribute Listing

Functional Attribute	Weighting Factor
Environmental Protection	1
Water Retention	1.5
Flow Channeling	1
Impact Load	1
Vibrational Load	1.5
Pressure Retaining	1.5
Thermal Exposure	1
Encasement	1
Prestressing	1.5
Shielding, Barrier	1
Support Functions (Pullout)	1.5
Leak Tightness	1
Risk Significant	2
Safety Related	2

TABLE 2
COSTAR Aging Mechanisms Listing

Aging Mechanism Name
Abrasion, Erosion And Cavitation
Bio-Fouling
Chemical Attack - Aggressive
Corrosion Of Embedded Steel
Cracking of Masonry
Creep
Current - Cathodic Protection
Elevated Temperature
Environmental Degradation
Fatigue, Vibration
Freeze-Thaw
Irradiation Of Concrete
Leaching of Calcium Hydroxide
Reaction With Aggregates
Settlement
Shrinkage

Aging Mechanisms

A comprehensive review of the available and applicable literature on concrete aging and degradation identified many diverse aging mechanisms, which were eventually grouped into 16 common aging mechanisms. For each of the mechanisms a detailed standard description was generated to assure consistency in the definition of the terms used in this program. Each aging mechanism has been linked to the structure groups to indicate the potential susceptibility and eliminating combinations that are not feasible. The feasible mechanisms for the structure group under consideration are displayed in the program and the user selects those applicable to the structure under consideration and representative of the plant conditions. Other mechanisms can be chosen, however, this would reflect a highly unusual condition.

The aging mechanisms have also been linked to the aging effects (discussed later) and the Degradation and Mitigation Attributes associated with the respective aging mechanism.

Degradation Attributes

Degradation Attributes are those plant specific conditions and features which determine the rate of degradation, the susceptibility of the structure and the long term performance expectations. From the available literature, 14 pertinent degradation attributes were identified as applicable to the nuclear plant concrete structures, as shown on Table 3. Each degradation attribute has a detailed description, discussing the degradation effects, the manifestations, materials affected or susceptible locations. The plausible degradation attributes associated with the aging mechanism have been predetermined, however, the user may choose others or simply select only those which are truly representative of his plant conditions and features. The objective can also be to postulate certain conditions to determine the potential consequences.

For each degradation attribute a Low, Medium and High criteria of severity has been established, utilizing nationally recognized Codes and Standards (ACI, ASTM, ASME) available literature, concrete aging experience and international research. Each criteria is described with respect to its technical basis and cross references have been added to allow further review or interpretation by the user. In some cases, the completion of actual evaluations may require acquisition of additional plant specific data, such as water chemistry or ground water level. The emphasis of the evaluation should focus on the dominant plant specific degradation attributes only, i.e., one or two, which lead to the overall structure ranking.

Mitigation Attributes

Mitigation Attributes are those plant conditions and features which offset or mitigate the effects of the degradation, prolong the life of the concrete structure and protect the structure against unexpected degradation of its functions. An assessment matrix was constructed to link the mitigation attributes with the degradation attributes to verify that each mitigation attribute is capable of offsetting a degradation attribute, as shown on Table 3. The unacceptable combinations were blocked within the program (i.e., surface coatings cannot mitigate radiation effects).

As with the degradation attributes, detailed descriptions are provided for the mitigation attributes and the Low, Medium and High rank criteria were established on the basis of available information, no new data or research was conceived under this program. The criteria bases are described and referenced, to permit additional review or interpretation by the user.

TABLE 3 Matrix of Mitigation and Degradation Attribute Combinations

Mitigation Attribute → Degradation Attribute ↓	Surface Coatings	Cover Concrete	Concrete Quality	Effective Preventive Maintenance
Flow Velocity	X	X	X	X
Suspended Solids	X	X	X	X
Aggressive Water/Soil	X	X	X	X
Type Of Water	X	X	X	X
Surface Cracking	X	X	X	X
Cavitation	X	X	X	X
Surface Porosity	X	X	X	X
Exc.Loads, Impact Vibration	NA	X	X	X
Temperature Exposure	X	X	X	X
High Current Flow	NA	NA	X	X
High Radiation	NA	NA	X	X
Reactive Aggregates	X	X	X	X
Soil And Pile Foundation	NA	NA	X	X
High Fluctuating Ground Water	X	X	X	X

Summation Logic

A numerical logic needed to be developed to take into account the functional importance of the structure, the number of aging mechanisms, the degradation susceptibility and the degradation and mitigation attributes. The logic chosen for use in COSTAR consists of a "Traffic Light" color code linked to the Low, Medium and High criteria scores for the mitigation and degradation attributes as follows:

- A Low Criteria Rank is designated Green with a numerical value of 1.0 or 4.0 for the Degradation and Mitigation Attribute respectively.
- A Medium Criteria Rank is designated Yellow with a numerical value of 2.0
- A High Criteria Rank is designated Red with a numerical value of 4.0 or 1.0 for the Degradation and Mitigation Attribute respectively.
- The sum averages are computed for each aging mechanism
- The individual aging mechanism is determined to be red, yellow or green, using the logic shown on Table 4.
- For structures with several Aging Mechanisms, the results are combined, using the logic shown on Table 5.

The final result of the screening process is to assign the structure into one of three categories:

Green - The structure is not exposed to unusual conditions requiring specific attention or targeted preventive maintenance.

Yellow - The structure is susceptible to degradation and mitigative or preventive actions should be contemplated. The structure deserves closer attention and periodic condition review.

Red - The structure could be subject to degradation which would impair its function over time and within the current life cycle. Preventive or mitigative actions should be considered in the near term and additional investigations should be considered.

Table 4   Scoring Logic For Combining Degradation And Mitigation Attributes

Degradation Attributes		Mitigation Attributes	
SCORE	**DAS**	**SCORE**	**MAS**
LLLLL	1.0	LLLL	4.0
LLLLM	**1.2**	LLLM	3.5
LLLMM	**1.4**	LLMM	3.0
LLMMM	**1.6**	LMMM	2.5
LMMMM	**1.8**	MMMM	2.0
MMMMM	**2.0**	LMMH	2.25
LMMMH	2.2	LMHH	2.0
MMMHH	2.8	**MHHH**	**1.25**
MMHHH	*3.2*	**MMHH**	**1.5**
MHHHH	*3.6*	**LHHH**	**1.75**
LLLHH	2.2	LLHH	2.5
LLMMH	**2.0**		
LLLMH	**1.8**		
LLLLH	**1.6**		
LHHH	*3.25*	LLM	3.33
LMHH	2.75	LMM	2.66
LLMH	**2.0**	MMM	2.0
LLLH	**1.75**	**MMH**	**1.66**
LLMM	**1.5**	**MHH**	**1.33**
LLLM	**1.25**	LLH	3.0
		LHH	2.0
LLM	**1.33**	LMH	2.33
LMM	**1.66**		
MMM	**2.0**	LH	2.5
MMH	2.66	LM	3.0
MHH	*3.33*	**MH**	**1.5**

MAS = Mitigation Attribute Sum Average
i.e., LMMH=4+2+2+1=9/4=2.25

DAS = Degradation Attribute Sum Average

i.e., LMMMH=1+2+2+2+4=11/5=2.2

IF DAS>3.19 THEN SUM=4 (RED), IF DAS<2.19 AND MAS<1.76 THEN SUM=1 (GREEN), ELSE SUM=2 (YELLOW)
BOLD=GREEN COMBINATIONS *ITALIC*=RED COMBINATIONS, ALL OTHER COMBINATIONS ARE YELLOW
GREEN=LOW (L)=1 FOR DEGRADATION AND 4 FOR MITIGATION, YELLOW= MEDIUM (M)=2 FOR BOTH
RED= HIGH (H)=4 FOR DEGRADATION AND 1 FOR MITIGATION

TABLE 5 COSTAR Ranking Logic For Multiple Aging Mechanisms (AM)

AM # 1			AM # 2			AM # 3			AM # 4			STRUCTURE		
L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
X	-	-	X	-	-	X	-	-	X	-	-	X	-	-
-	X	-	X	-	-	X	-	-	X	-	-	-	X	-
-	X	-	-	X	-	X	-	-	X	-	-	-	X	-
-	X	-	-	X	-	-	X	-	X	-	-	-	-	X
-	-	X	X	-	-	X	-	-	X	-	-	-	-	X

In conclusion, the scoring criteria can be summarized as follows:

All the AM's are " L "	Then the Structure is ranked " L " (Green)
One AM is " M "	Then the Structure is ranked " M " (Yellow)
Two AM's are " M "	Then the Structure is ranked " M " (Yellow)
More than two AM's are "M"	Then the Structure is ranked " H " (RED)
Any AM is " H "	Then the Structure is ranked " H " (RED)

Screening Results and Report

After successful entry of all the required data, the results are computed and displayed on a Screening Assessment Form. The form will show the Structure Functional Category (Standard, Important, Critical) and the Structure Rank (Green, Yellow, Red), as explained above. Two report options are provided, a Detailed Structure Report for the individual structure displaying the input data and the results and a Summary Report for all the evaluated structures in a tabular form, sorted by Structure Rank (Red, Yellow, Green).

CONDITION ASSESSMENT MODULE

The Condition Assessment Module can be chosen to start the evaluation of plant specific conditions observed as a result of inspections, walkdowns or ongoing investigations. Of particular importance are conditions identified under the Structural Monitoring Program, such as observed degradation, impaired functions (leaking roof, broken concrete pads) or abnormal conditions. These conditions need to be evaluated quickly for corrective action or disposition and could be appropriate candidates for this COSTAR condition assessment module.

Structure and Structure Group Selection

The selection process for the structure to be evaluated and the applicable structure group selection uses the same data base and methodology described for the Screening Module above. Because the Condition Assessment is plant specific, it is important to select the most applicable structure and associated structure group for the case. Review of the descriptions will help focusing in on the correct choice.

Aging Effects and Aging Mechanisms

Aging Effects are the conditions or manifestations of degraded concrete structures as observed in the field and they are the observable consequences of active aging mechanisms. Based on available industry literature [1 through 19], 10 relevant aging effects have been identified and cross linked to the applicable aging mechanisms capable of causing these effects. Each aging effect is also linked to those supplemental investigations and aging management options which may be applicable to the observed conditions. Using the actual field conditions, the user selects one or more of the Aging Effects and reviews the detailed descriptions for the aging effect and the three evaluation criteria, to determine which most closely matches the in-situ conditions. The criteria values are viewed as ranges of severity and are a guidance to the evaluating utility engineer. Where possible, references have been provided for the technical bases of the criteria.

Aging Effects Ranking Logic

The structure is ranked in accordance with the determined severity of the aging effects. If there were more than one aging effect observed and scored for the structure, the combined ranking is based on the same logic as the one applied to the combination of aging mechanisms, shown on Table 5.

Supplemental Investigations

A significant knowledge base exists, as demonstrated by the available literature, of the methods and procedures to conduct further investigations and root cause analyses of observed concrete degradation. The purpose of these investigations is to quantify the actual damage, look for and quantify secondary effects and to establish a plausible cause. The 23 processes and methods identified in COSTAR include the most common practices, as well as some of the lesser known methods. For each of the processes a description has been provided, procedural details are offered and as appropriate, references are cited for further study.

Aging Management Options

Similar to the supplemental investigations, the Aging Management Options available to monitor, prevent, mitigate, repair or replace the degraded structure have been identified from the key references. Detailed descriptions, taken from the literature or modified for this application, have been included in COSTAR for 25 different options. Each option has been categorized in accordance with standard industry convention as Preventive, Mitigative or Corrective maintenance and the potential applicability to the observed aging effects has been established. The user may select from the menu the most fitting and effective aging management option in case the structure being evaluated ranks in the Red or Yellow regime.

Inspection Periods

Consistent with the Codes and Standards for concrete (ACI 349.3R and ASME XI), recommended Inspection Intervals and frequencies for re-inspection or condition monitoring of degraded concrete structures have been included in COSTAR as follows:

Structure Rank	Corrective Action	Inspection Frequency
H (RED)	Without Corrective Action	12 Months
H (RED)	With Corrective Action	24 Months
M (YELLOW)	Without Corrective Action	36 Months
M (YELLOW)	With Corrective Action	60 Months
L (GREEN)	With Or Without CA	120 Months

The user may select the appropriate frequency, consistent with the plant conditions and the selected corrective actions (Aging Management Options).

Key References

The principal objective of COSTAR was to provide in a single source document a comprehensive manual of technical data and information regarding aging management of concrete structures and to present this data in a logical and organized fashion for ready access and application. The data contained in the COSTAR data base represents the most applicable data from the references cited below.

1. American Concrete Institute, ACI-201.1R-92, "Guide for Making a Condition Survey of Concrete in Service", Detroit, Michigan.
2. American Concrete Institute, ACI-349.3R-96, "Evaluation of Existing Nuclear Safety Related Concrete Structures", Detroit, Michigan.
3. US Nuclear Regulatory Commission, NUREG-1522, March 1995, "Assessment of Inservice Conditions of Safety Related Nuclear Plant Structures".
4. Oak Ridge National Laboratory, ORNL/NRC/LTR-90/17, March 1991, "Structural Aging Assessment Methodology for Concrete Structures in Nuclear Power Plants".
5. Oak Ridge National Laboratory, ORNL/NRC/LTR-90/29, September 1991, "Inservice Inspection and Structural Integrity Assessment Methods for Nuclear Power Plant Concrete Structures".
6. Oak Ridge National Laboratory, NUREG/CR-4652 (ORNL/TM-10059), Sept. 1986, "Concrete Component Aging and its Significance Relative to Life Extension of Nuclear Power Plants".
7. Oak Ridge National Laboratory, NUREG/CR-6424 (ORNL/TM-13148), March 1996, "Report on Aging of Nuclear Power Plant Reinforced Concrete Structures".
8. International Atomic Energy Agency, IAEA-TECDOC-1025, June 1998, "Assessment and Management of Ageing of Major Nuclear Power Plant Components Important to Safety: Concrete Containment Buildings".
9. Electric Power Research Institute, EPRI-TR-103835, July 1994, "PWR Containment Structures, License Renewal Industry Report, Rev. 1".
10. Electric Power Research Institute, EPRI-TR-103840, July 1994, "BWR Containments, License Renewal Industry Report, Rev.1".
11. Electric Power Research Institute, EPRI-TR-103842, July 1994, "Class I Structures, License Renewal Industry Report, Rev. 1".
12. US Nuclear Regulatory Commission, NUREG-CP-00120, July 1992, "Proceedings of The Fifth Workshop on Containment Integrity".
13. Nuclear Energy Institute, NUMARC 93-01, Revision 2, April 1996, "Industry Guideline for Monitoring The Effectiveness Of Maintenance At Nuclear Power Plants".

14. Nuclear Energy Institute, NEI 96-03, Revision D, July 1996, "Industry Guideline For Monitoring The Condition Of Structures At Nuclear Power Plants".
15. US Nuclear Regulatory Commission, Reg. Guide 1.160, Revision 2, March 1997, "Monitoring The Effectiveness Of Maintenance At Nuclear Power Plants".
16. US NRC, NRC Inspection Manual, Inspection Procedure IP-62002, 12/31/96, Inspection Of Structures, Passive Components And Civil Engineering Features At uclear Power Plants".
17. US NRC, NRC Inspection Manual, Inspection Procedure IP-62003, 06/11/97, "Inspection Of Steel And Concrete Containment Structures At Nuclear Power Plants".
18. US NRC, NRC Inspection Manual, Inspection Procedure IP-62706, 08/31/95, "Maintenance Rule".
19. US NRC, NUREG-1611, "Aging Management of Nuclear Power Plant Containments for License Renewal", September 1997.