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ABSTRACT

This paper summarizes and highlights the results of the initial phase of a research project on the assessment of aged and degraded structures and components important to the safe operation of nuclear power plants (NPPs). A review of age-related degradation of structures and passive components at NPPs was performed. Instances of age-related degradation have been collected and reviewed. Data were collected from plant generated documents such as Licensing Event Reports, NRC generic communications, NUREGs and industry reports. Applicable cases of degradation occurrences were reviewed and then entered into a computerized database. The results obtained from the review of degradation occurrences are summarized and discussed. Various trending analyses were performed to identify which structures and components are most affected, whether degradation occurrences are worsening, and what are the most common aging mechanisms. The paper also discusses potential aging issues and degradation-susceptible structures and passive components which would have the greatest impact on plant risk.

1. INTRODUCTION

1.1 Objective

The objective of this research project is to assess the effects of age-related degradation of structures and passive components for U. S. Nuclear Power Plants. The technical basis will be developed for the validation and improvement of analytical methods and acceptance criteria which can be used in making risk informed decisions and to address technical issues related to degradation of structures and passive components.

A three-phased approach was adopted for this project. Phase I consists of data collection, review of existing technical information, and a scoping study. Phase II consists of assessment of the effects of age-related degradation and improvement of available analysis techniques to evaluate degradation. Phase III consists of providing recommendations to the NRC staff for making risk-informed decisions and for resolving specific technical issues related to degradation of structures and passive components.

This paper briefly describes the various activities, results, conclusions, and recommendations under the initial phase of the research project. It also identifies the

structures and components to be included in the subsequent phases of the research project and outlines the future activities for achieving the stated objectives.

1.2 Background

As of 1995, there were 109 operating nuclear power plants (NPPs) in the United States producing approximately 75,000 megawatts of electric power generation. This represents about 22 percent of the Nation's total electric generation. Approximately two-thirds of the NPPs received their construction permit more than 25 years ago and the majority have been operating for 20 years or more. While the performance of safety-related civil structures and passive components at these plants has been good, the number of occurrences of age-related degradation has been increasing as NPPs age.

Numerous examples of age-related degradation of structures and passive components in NPPs are presented in NUREG-1522, "Assessment of Inservice Conditions of Safety-Related Nuclear Plant Structures." Much of the information was obtained from actual walkdowns of structures and components at six NPPs licensed before 1977. Instances of degradation were identified in intake structures/pumphouses, service water piping, tendon galleries, masonry walls, anchorages, containments, and other concrete structures.

Civil structures generally have substantial safety margins when properly designed and constructed. However, the available margins for degraded structures are not well known. In addition, age-related degradation may affect the dynamic properties, structural response, structural resistance/capacity, failure mode, and location of failure initiation. A better understanding of the effect of aging degradation on structures and passive components is useful to ensure that the current licensing basis is maintained under all loading conditions.

Results from risk evaluation programs conducted by the NRC, such as the Individual Plant Examination of External Events (IPEEE) program, indicate that external events such as earthquakes, high winds, and tornadoes can be significant contributors to core damage frequency (CDF). In some cases, structures and passive components have been found to be significant risk contributors when subjected to these external events. As structures and components age, the effect of age-related degradation will become a more significant factor in assessing risk.

1.3 Project Scope

The project scope covers structures and passive components normally found in nuclear power plants in the United States. Structures include buildings and civil engineering features such as masonry walls, canals, embankments, underground structures, and stacks. Passive components consist of equipment which do not move or change their state to perform their intended function. Examples of passive components are tanks, cable tray systems, conduit systems, and HVAC ducts/supports. A more complete definition of the specific structures and passive components included within the scope of this project is presented in Section 2.1.

2. COLLECTION AND REVIEW OF DEGRADATION OCCURRENCES

The first part of the Phase I effort consisted of collecting and reviewing age-related degradation occurrences of structures and passive components at nuclear power plants.

For the purpose of this research project the term "degradation occurrence" is defined as age-related degradation which was reported in NRC generic correspondences, Licensing Event Reports (LERs), NUREGs, and other referenced documents described below.

2.1 Structures and Passive Components Included

Structures and passive components within the scope of the NRC License Renewal Rule 10 CFR Part 54 and the Maintenance Rule 10 CFR 50.65 were considered for review in this research project. This includes structures and passive components: (1) that are safety-related, (2) whose failure could affect safety-related functions, and (3) that meet several other criteria defined within the scope of the license renewal rule and the maintenance rule.

All structures and components identified to be within the scope of review were placed into one of eighteen categories. A complete listing of the eighteen categories of structures and components is presented in Table 1.

Table 1 Eighteen Categories of Structures and Passive Components

Anchorages	HVAC Duct
Cable Tray Systems	Insulation/seal
Concrete	Piping System
Conduit Systems	RPV
Containment	Structural Seismic Gap
Cooling Tower	Structural Steel
Electrical Conductors	Tanks
Exchangers	Vessels
Filters	Water-Control Structures

Since the NRC and industry have been studying and addressing the age-related degradation concerns related to certain structures and components, it was decided to eliminate such items from subsequent phases of this research project. This applies to containments, steam generators, RPVs, piping, and electrical conductors. Additional structures and components were subsequently eliminated because after further research, other industry and/or NRC programs were identified which are addressing degradation concerns. This is discussed further in Section 5.2.

For each of the eighteen components included in the original scope, a number of subcomponents were defined. As an example, the category "anchorages" includes embedded anchors, expansion anchors, undercut anchors, drop-in anchors, embedded studs, and the grout beneath baseplates.

2.2 Sources of Information

Various sources were investigated to identify instances of age-related degradation of structures and passive components. These sources primarily consist of LERs, NRC generic correspondence, NUREGs, and industry reports.

The NRC generic correspondence includes IE Bulletins, Generic Letters, and Information Notices. All of the correspondence contained in the Generic Correspondence Library on the Fedworld Information Network (Internet) was investigated. This was done by reviewing all of the generic correspondence titles. Those that apply to structures and passive components or those that may be related in some manner were identified and retrieved for review. If instances of age-related degradation were noted then that occurrence was recorded for use in this research project.

The LERs were obtained from the Sequence Coding & Search System (SCSS) maintained by the Oak Ridge National Laboratory (ORNL). The SCSS database was developed by the NRC's Office for Analysis and Evaluation of Operating Data through the Nuclear Operations Analysis Center at ORNL. The SCSS is an electronic database developed to allow users to retrieve commercial nuclear plant operating experience data from LERs. The database contains over 35,000 LERs from 1980 to the present time.

Instead of providing the actual LER text, the database reduced the LER descriptive text to coded, searchable sequences. It captures the components, system, effects on the plant unit, as well as personnel errors reported in LERs. For each LER, data on component failures include type and number of components involved, system to which components belong, cause and mode of failure, effect of failures on plant systems and unit, and component vendor and model data (if given in the LER). This information is coded for use in searching specific information. For example, there are over 400 specific component codes and there are over 100 cause and effect code designations. In addition to the coded information, an abstract is available which provides a summary of the event.

In view of the very large number of LERs, it was decided to initially review LERs for the period 1990 to 1997. Then, the search was expanded to include LERs extending back to 1985. Thus the total period reviewed covered 1985 to 1997.

2.3 Degradation Occurrence Database

In order to document and evaluate the enormous amount of data, a computerized database, entitled Degradation Occurrence Database (DOD), was created. The DOD was prepared using the Microsoft database management program "Access". The advantages of this computerized database are: 1) simple entry and update of degradation data, 2), sorting and organizing of data in a meaningful way, 3) quickly locating desired information, 4) creation of tabulated listings or reports, and 5) sharing of data with other authorized users and programs in the system.

A number of tables were created as part of the DOD to fully describe the age-related degradation of structures and passive components. The various tables that were developed include:

1. Structures and Passive Components
2. Degradation Occurrence Table
3. Aging Effects and Mechanisms
4. System Definition Codes
5. Stress Corrosion Codes

The most important table in the DOD is the Degradation Occurrence Table (DOT) which contains all of the degradation occurrences identified as applicable under this research project. A total of 492 degradation occurrences were included in the DOT. It should be noted that there are certainly many more occurrences of degradation than what were identified and reported in this DOT. However, if they were not reported in LERs or other publicly available documents then they would not be included in this database. For example, some degradation occurrences may not be reported in LERs if the event or condition does not seriously affect the plant or result in an unanalyzed condition that significantly compromised plant safety.

For each occurrence the following type of information is provided in the DOT:

1. Component
2. Subcomponent
3. System
4. Aging Effect
5. Aging Mechanism
6. Plant
7. Month, Day, Year
8. How Identified
9. Evaluation Method
10. Repair Method
11. Docket No.
12. Reference Document
13. Reference Document No

As described in Section 2.2, data was obtained by identifying and reviewing LERs, NRC generic correspondence, NUREGs, and industry reports. After evaluating each degradation occurrence, the information was entered into the DOD. The analysis of the data and observations that can be derived from this data are described in the next section.

2.4 Analysis of Degradation Trends

A total of 492 degradation occurrences were identified related to structures and passive components. Using the DOD, a tabulation of the total number of degradation occurrences for each structure/component category was made.

Since all of the data has been entered into a computerized database program, the information can also be searched, sorted, and tabulated in any order or form. For example, the degradation occurrences can be easily sorted by types of components, types of degradation, causes of degradation, plant names, dates, or systems. To evaluate the degradation occurrences the data was filtered and sorted to obtain trending information. Trending data was developed for the following types of distributions:

1. Distribution By Components/Subcomponents
2. Distribution By Years (1985-1997)
3. Distribution By Age of Plants
4. Distribution By Steel Degradation Aging Effects
5. Distribution By Concrete Degradation Aging Effects
6. Distribution by Aging Mechanisms of Degradation
7. Distribution By Types of Cracking Induced by Corrosion
8. Distribution of Subcomponents for Structural Steel
9. Distribution of Subcomponents for Concrete
10. Distribution of Subcomponents for Containment
11. Distribution of Subcomponents for Filters
12. Distribution of Subcomponents for RPV
13. Distribution by Systems
14. Distribution by Methods of Identification

The distribution of degradation by types of components/subcomponents shown in Figure 1 was obtained by compiling the number of occurrences for each of the components listed in Table 1. Where a subcomponent had an extremely large number of occurrences such as piping and steam generators, it was included as a separate item on the bar chart in Figure 1. Where a component had no occurrences identified such as structural seismic gap and vessels (other than steam generators) it was not included on the bar chart.

From this distribution of degradation by types of components/subcomponents, it is evident that piping & tubing, steam generators, RPV, and containments have the largest number of degradation occurrences. This is not surprising since it has been known in the industry that these structures and components have had numerous instances of degradation. Following these, the structures and passive components with the greatest number of occurrences in descending order are filters, concrete, structural steel, heat exchangers, piping supports, tanks, pressurizers, electrical conductors, and anchorages. All of the remaining items have six or less occurrences.

As noted earlier, degradation concerns related to piping, steam generators, RPV, and containments, were eliminate from the subsequent phases of this research project because other NRC and industry programs have been studying and addressing aging issues related these components.

Figure 2 shows the distribution of degradation occurrences by age of plants. The graph represents the average number of occurrences per plant per year for different plant vintages. This was developed by categorizing all U.S. nuclear power plants by their age (1997 minus year of construction permit). Then the total number of occurrences for each group of plants in a given age category was divided by the number of plants in that age category and the age of the plants in that category. Although the actual number of occurrences are not high, this curve demonstrates that as the age of plants increase, the number of occurrences per plant per year also increases. Using the best fit curve, the actual number of occurrences per plant per year over a 14 year period (19 year to 33 year old plants) shows a growth more than three times (from about .065 to .24).

The complete DOD and Trending Data will be included in a future NUREG/CR report on this subject.

3. AGE-RELATED DEGRADATION TECHNOLOGY INFORMATION

In Phase I of this project, existing technical information was collected and reviewed to provide input into the research effort. Information from NRC programs and industry programs regarding inspection, testing, assessment, and repair techniques were identified and reviewed. In addition, information related to aging/degradation mechanisms and effects on material properties/strengths was also reviewed.

To aid the process of collecting and reviewing the various documents related to aging degradation of structures and passive components a Degradation Reference Database (DRD) was created. The DRD includes the codes, industry standards and guidelines, NUREG reports, technical papers, presentations (at conferences), regulatory documents, and other reports that were collected and reviewed in Phase I of this research project. The regulatory documents include 10 CFRs; NRC generic correspondences such as IEs, INs, GLs, etc.; NRC inspection reports; NRC regulatory guides; and NRC SECY papers.

All of the documents and summary information for each was entered into a computerized database. Currently there are over 160 documents in the database which can be sorted in any manner or specific documents can be located by identifying a subject of interest. A copy of this database will be included in a future NUREG/CR report.

The information contained in the database consists of the type of document, the identification or ID (document no.), title of the document, date of publication, author/organization, a summary description, types of components covered, and potential aging issues identified in the document.

Since the DRD, like the DOD described earlier in Section 2.3, was created using the Microsoft program Access, a copy of all the data can be provided on floppy disks which would allow any user to get access and sort or locate specific information.

4. RISK SIGNIFICANCE OF AGING EFFECTS

In the past two decades, seismic PRA studies have been carried out on a large number of NPP's, including the most recent studies as part of the independent plant examination of external events (IPEEE) (NUREG-1407). Surveys on the seismic fragility values used in the past seismic PRA's are also available in numerous publications (e.g., NUREG/CR-4334, Kipp 1988, Cambell 1988, NUREG/CR-3558, and Park 1998). As an example of such surveys, fragility values and dominant failure modes are tabulated in Table 2 for various components. This type of information is useful to identify the components with a relatively low seismic capacity (and therefore, a potential risk contributor).

Table 2 Partial Summary of Fragility Database (Park 1998)

(See reference for complete table of 35 items)

	Category Name	Dominant Failure Mode	Median Fragility Range (g)			
			Past PRA[a]		Other	
			N[c]	Range	N[d]	Range
1	Concrete containment	Shear failure	8	2.50-9.20	-	-
2	Steel containment	Shell wall buckling	1	9.00-9.00	-	-
3	Reactor pressure vessel	Anchor bolt	13	1.04-5.70	3	3.83-3.83
4	Steam generator	Support	9	1.70-6.80	4	2.45-2.45
5	Reactor coolant pump	Support	8	0.90-4.60	3	2.64-2.64
6	Recirculation pump	Bracket	6	0.90-2.20	-	-
7	Core assembly	CRD housing	21	0.60-6.71	5	2.06-2.06
8	Pressurizer	Lateral support	1	5.73-5.73	1	2.00-2.00
9	Piping	Support	14	2.50-13.6	-	-
10	Valves	Yoke support	35	0.80-13.7	22	4.83-20.5
11	Heat exchanger	Anchor bolt	23	0.30-13.0	4	1.00-1.18
12	Flat bottom tank	Shell wall buckling	17	0.20-1.00	8	0.45-2.01
13	Other tanks and vessels	Anchor bolt	28	1.00-46.0	13	1.07-3.91
14	Batteries and racks	Battery cases/plates	16	0.90-5.95	54	0.80-7.30
15	Motor control center	Chattering	17	0.06-4.20	70	0.30-7.63

[a] Ground motion PGA

[b] Local floor ZPA/Ave. Spectral Acceleration values

[c] Number of fragility values

[d] Number of Original data (e.g. test data)

Typically, 5~6 components are singled out as the dominant risk contributors as a result of a seismic PRA study. Based on a survey of a large number of past seismic PRA's (including those of IPEEE), structures and components identified as dominant risk contributors are listed in Table 3 (Park, 1997).

Table 3 Dominant Risk Contributors Identified in Past Seismic PRA's (Park 1997)

Civil Structures

- Shear wall failure
- Roof/slab failure
- Soil liquefaction
- Unreinforced masonry walls
- Ceiling failure in control room
- Turbine building collapse
- Impact between buildings
- Stack failure

Diesel Generator

- Fuel oil (day tank)
- Random failure of diesel gen.
- Oil Cooler

Emergency Feedwater

- E.F. pump
- Random failure of E.F.
- Condensate storage tank

Piping

- Interconnecting pipes

Power Supply

- Offsite power loss
- 125 v DC batteries/racks
- 125 v DC distribution panels
- 125 v DC fuse box
- 250 v DC motor control center (MCC)
- 4 kv switchgear
- 4kv busses
- Transformers
- Cable trays

Reactor Coolant System

- Pressurizer supports
- Control system drive system/housing
- Excessive deflection of core/core shroud
- Reactor coolant pump support
- Random failure of Pressurizer SRV
- Seal failure of RCP

Service Water

- SW pump
- Dam failure (ultimate heat sink)

Based on this listing and the data in Table 2, the following types of structures and passive components may be considered to be the most frequently observed weak links:

- Anchorage and supports of equipment
- Flat-bottom storage tanks
- Critical reinforced concrete members
- Concrete block walls
- Interconnecting pipes (e.g. buried piping)
- Cable trays
- Dams

The information described in Tables 2 and 3 contributed to the determination of the priority ranking of structures/components, which is described in Section 5.

5. TECHNOLOGY NEEDS AND PRIORITY RANKING OF STRUCTURES AND PASSIVE COMPONENTS

5.1 Technology Needs

In order to gain an understanding as to the technology needs and which structures and components require further assessments, a review was conducted of what NRC and industry programs exist and how well they are addressing aging degradation. The programs reviewed covered NRC and industry requirements, as well as NRC and industry research related to aging degradation of structures and components at NPPs.

To facilitate this review and presentation of the results, a table was developed in matrix form for each category such as anchorages, tanks, and reinforced concrete structures. From the original eighteen categories shown in Table 1, eight structures and passive components were selected for this assessment of technology needs. The other ten categories were eliminated because there were either very few degradation occurrences identified in the Degradation Occurrence Database (DOD) or it is well known that there are existing programs that adequately address aging concerns for these items.

The eight types of structures and passive components that were assessed are: masonry walls, tanks, anchorages, concrete structures, buried piping, supports for equipment and systems, concrete containments, and steel containments. For each of the structures and components, the NRC and/or Industry program that relates or addresses aging concerns was tabulated along with a summary of whether the programs adequately address aging. While this tabulation probably did not list every single program, it did capture the major requirements, research programs, and industry programs that address aging.

5.2 Priority Ranking of Structures/Components

To identify which structures and components warrant further review in subsequent phases of the research project, it was decided to rank or prioritize them. The process of ranking the eight structures and passive components discussed in Section 5.1 considered four key parameters: seismic risk significance, degradation occurrences, importance to current licensing basis/license renewal, and adequacy of existing NRC and industry programs. Then a final ranking was developed based on a compilation of all the information from these four key parameters.

Masonry walls (particularly unreinforced walls) and flat bottom steel tanks were rated as very high followed by anchorages, concrete, and buried pipe which were rated as high. Supports for equipment and systems were rated as moderate and concrete and steel containments were rated as low. It should be noted that a rating of low for example does not mean the structure or component is not important or does not experience age-related degradation but rather, relative to the other structures and components, it is not ranked as high. This occurs because several of the key parameters such as seismic risk significance or adequacy of existing nuclear industry programs result in its lower ranking.

6. CONCLUSIONS

Based on the results of the Phase I activities, it has been concluded that Phase II of this project should be continued for the following structures and passive components (SCs): masonry walls, flat bottom tanks, anchorages, reinforced concrete structures (other than containments since they are being addressed in other programs), and buried piping. The Phase II effort is expected to include plant visits to collect additional information on degradation, to confirm the selection of the five structures/components (identified in Section 5), and to verify the research activities proposed below.

The focus of the research will be on improving and developing methods to assess the effects of age-related degradation on the seismic performance of SCs, including the fragility evaluations for PRA/SMA studies. The methodologies that will be developed to determine seismic performance can then be used to quantify the impact of age-related degradation of SCs on overall plant risk. This would lead to greater confidence in the use of risk assessment as a tool in making risk informed decisions for age-degraded structures. The research will also establish the technical bases for resolving specific issues related to degradation of the selected SCs.

The Phase II efforts will include the following activities:

- Evaluation and expansion, if necessary, of existing degradation condition assessment techniques such as inspection, testing (e.g. NDE), assessment, and repair.
- Performance of analytical structural evaluations of degraded SCs (such as utilizing linear or non-linear finite element methods), and collection of available U.S. and foreign test results on naturally degraded or artificially degraded SCs.
- Development of fragility curves for degraded SCs based on results of analytical structural evaluations or tests of degraded SCs.
- Development of degradation acceptance criteria for SCs based on the above activities, existing codes, standards, and other NRC or industry reports.

The results of the Phase II efforts should establish the technical bases for the formulation of recommendations during Phase III for regulatory guidance on the assessment of age-degraded structures

REFERENCES

10 CFR Part 54, Requirements for Renewal of Operating Licenses for Nuclear Power Plants

10 CFR 50.65, Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants

Campbell, R.D., M.K. Ravindra, and R.C. Murray, "Compilation of Fragility Information from Available Probabilistic Risk Assessments," LLNL, UCID-26071, Rev. 1, September 1988.

Kipp, T.R., D.A. Wesley, and D.K. Nakaki, "Seismic Fragilities of Civil Structures and Equipment Components at the Diablo Canyon Power Plant," Attachment Q2d-1, Report Number 1643.02, PG&E, September 1988.

NUREG-1407, "Procedural and Submittal Guidance for the Individual Plant Examination of External Events (IPEEE) for Severe Accident Vulnerabilities," by J.T. Chen, N.C. Chokshi, R.M. Kenneally, G.B. Kelly, W.D. Beckner, C. McCracken, A.J. Murphy, L. Reiter, and D. Jeng, U.S. Nuclear Regulatory Commission, Washington, D.C., June 1991.

NUREG-1522, "Assessment of Inservice Condition of Safety-Related Nuclear Plant Structures," by H. Ashar, and G. Bagchi, U.S. Nuclear Regulatory Commission, Washington, D.C., June 1995.

NUREG/CR-3558, "Handbook of Nuclear Power Plant Seismic Fragilities," by L.E. Cover, M.P. Bohn, D.A. Campbell, and D.A. Wesley, June 1985.

NUREG/CR-4334, "An Approach to the Qualification of Seismic Margins in Nuclear Power Plants," by R.J. Budnitz, P.J. Amico, C.A. Cornell, W.J. Hall, R.P. Kennedy, J.W. Reed, and M. Shinozuka, Lawrence Livermore National Laboratory, July 1985.

Park, Y.J., L. Chu and R.P. Kennedy, "Seismic PRA Workshop, Presented to Beta Project," Moscow, Russian Federation, December 1-5, 1997.

Park, Y.J., C.H. Hofmayer, and N.C. Chokshi, "Survey of Seismic Fragilities Used in PRA Studies of Nuclear Power Plants," *Reliability Engineering & System Safety*, v. 62, No. 3, pp. 185-195, December 1998.

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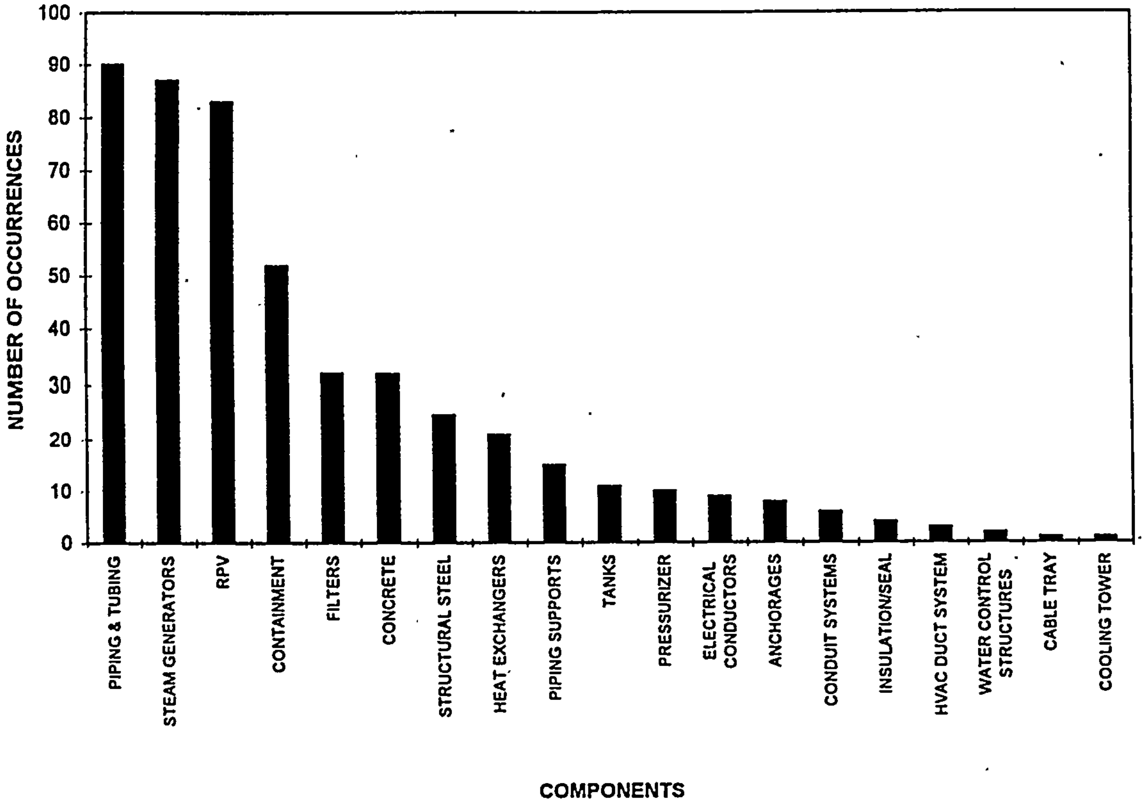

Figure 1 Passive Structures and Components – Degradation Occurrences Distribution by Components/Subcomponents

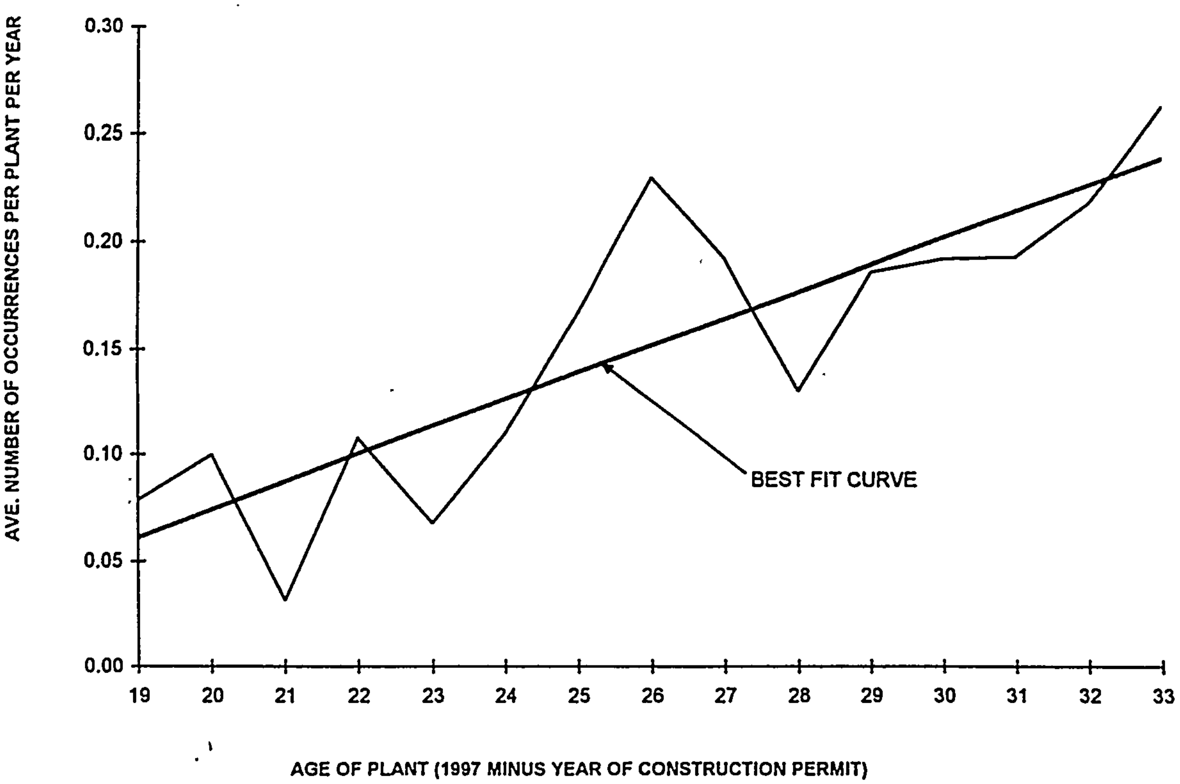

Figure 2 Passive Structures and Components – Degradation Occurrences Distribution by Age of Plants