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Engineering Technology Division

DEGRADATION ASSESSMENT METHODOLOGY FOR APPLICATION TO STEEL CONTAINMENT'S AND LINERS OF REINFORCED CONCRETE STRUCTURES IN NUCLEAR POWER PLANTS

C. B. Oland
D. J. Naus

December 1995

(Milestone C.2.1 .E)

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 3783 1
managed by
LOCKHEED MARTIN ENERGY SYSTEMS, INC.
for the
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DEGRADATION ASSESSMENT METHODOLOGY FOR APPLICATION TO STEEL CONTAINMENTS AND LINERS OF REINFORCED CONCRETE STRUCTURES IN NUCLEAR POWER PLANTS

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D. J. Naus

ABSTRACT

This report was prepared as part of a program that is being conducted at the Oak Ridge National Laboratory (ORNL) to assist the Nuclear Regulatory Commission (NRC) in their assessment of the effects of corrosion on the structural capacity and leaktight integrity of metal containment vessels and steel liners of reinforced concrete structures in nuclear power plants. Discussions focus on a degradation assessment methodology intended for use in characterizing the in-service condition of metal and concrete containment pressure boundary components and quantifying the amount of damage that may be present. Condition assessments play an important part in the aging management of nuclear containment systems by providing vital information for continued service evaluations and service life estimations. In-service condition assessments involve detecting damage in areas of the containment pressure boundary that are potentially vulnerable to in-service deterioration or attack, classifying the types of damage that may be present, determining the root cause of the problem, and quantifying the extent of degradation that may have occurred. Knowledge gained from condition assessments can serve as a baseline for evaluating the safety significance of any damage that may be present and defining in-service inspection programs and maintenance strategies. Condition assessment results can also be used in estimating future performance and remaining service life.

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1. INTRODUCTION

1.1 BACKGROUND

A program is being conducted at the Oak Ridge National Laboratory (ORNL) to assist the Nuclear Regulatory Commission (NRC) in their assessment of the effects of potential degradation on the structural capacity and leaktight integrity of metal containment vessels and steel liners of reinforced concrete structures in nuclear power plants. Metal and concrete containment systems are designed to resist pressure and temperature loadings associated with loss-of-coolant accidents and to prevent the release of radioactive fission products into the environment (Refs. 1.1 and 1.2). Acting alone or in concert with other structures such as the Mark III shield building, containments are required to provide biological shielding under both normal and postulated accident conditions and to protect equipment and personnel from all types of environmental hazards including earth-

quakes, tornadoes, and floods. Containments are safety-related structures that are designated seismic Category I*.

One of the program objectives is to develop a degradation assessment methodology that can be used to characterize the in-service condition of degraded containment pressure boundary components and quantify the amount of damage that is present. Condition assessments play an important part in the aging management of nuclear containment systems by providing vital information for continued service evaluations and service life estimations. In-service condition assessments involve detecting damage in areas of the containment pressure boundary that are potentially vulnerable to in-service deterioration or attack, classifying the types of damage that may be present, determining the root cause of the problem, and quantifying the extent of degradation that may have occurred. Degradation in this context is considered to be any phenomenon that damages a component by decreasing its load-carrying capacity, limiting its ability to contain a fluid medium, or reducing its service life. Component damage can occur when the microstructure of a material is modified by exposure to a hostile environment or when the geometry of a component is altered. Corrosion, fatigue, hydrogen embrittlement, mechanically assisted degradation, environmentally induce cracking, irradiation, and extreme-temperature exposure can cause component damage that, if unmitigated, could result in loss of functional or safety capabilities.

1.2 CONTAINMENT SYSTEMS DESCRIPTION

Approximately 110 boiling-water reactor (BWR) and pressurized-water reactor (PWR) nuclear power plants are licensed by the NRC for commercial operation in the United States. In some cases, two or more plants are located at a particular site. Each nuclear reactor is located inside a much larger metal or concrete containment vessel that houses and supports the primary coolant system components. The shapes of BWR and PWR containment vessels are significantly different, but in all cases, leaktightness is ensured by a continuous pressure boundary consisting of nonmetallic seals and gaskets and metallic components that are either welded or bolted together. Nonmetallic components are used to prevent leakage from pumps, pipes, valves, personnel airlocks, equipment hatches, manways, and mechanical and electrical penetration assemblies. The remaining pressure boundary consists primarily of steel components such as metal containment shells, concrete containment liners, penetration liners, heads, nozzles, structural and non-structural attachments, embedment anchors, pipes, tubes, fittings, fasteners, and bolting items that are used to join other pressure-retaining components. Each containment type includes numerous access and process penetrations that complete the pressure boundary. The four major types of containment penetrations are listed in Table 1.1. Descriptions and typical design configurations for these penetrations are provided in Ref. 1.3. Although concrete floors, walls, supports, and basemats are an integral part of any containment structure, these components are not considered part of the containment pressure boundary.

Rules for design and construction of metal and concrete containment vessels are prepared by the American Society of Mechanical Engineers (ASME) and published in the ASME Boiler and Pressure Vessel Code. New editions of the Code are issued every three years, but addenda, which contain updated information and revisions, are provided annually. Since nuclear power plants were first constructed in the late 1950s and early 1960s, numerous rule changes for containments have occurred. However, the most significant changes occurred when rules for Class MC (metal) and Class CC (concrete) containments were issued. Development of rules for the care and maintenance of nuclear power plant components began in the late 1960s. The focus of this effort was to address conditions not considered in the original design and to establish rules for in-service

* Category I structures are those essential to the function of the safety class systems and components, or that house, support, or protect safety class systems or components, and whose failure could lead to loss of function of the safety class systems and components housed, supported, or protected (Ref. 1.2).

repairs. Current requirements for in-service inspection, repair, and replacement of metal containments and liners of concrete,, containments are provided in Section XI, Division 1, Subsection IWE of the Code (Ref. 1.4). However, the requirements in Subsection IWE have not yet been approved by the NRC and therefore are not currently being imposed upon licensees. Additional requirements pertaining to containment performance, design, construction, fabrication, erection, inspection, and testing are provided in Title 10, Part 50 of the U.S. Code of Federal Regulations (Ref. 1.5). These regulations impose requirements for periodic leakage rate testing and general visual examination" of the containment.

All PWR and BWR containments vessels, with the possible exception of spherical metal containments, include portions of interior and exterior pressure boundary surfaces that are inaccessible for direct or indirect visual examination.. These surfaces, which may or may not be coated, are either backed by concrete, embedded in concrete, hidden behind caulking or flashing, covered by sand, or located within a relatively short distance of a physical obstruction. Although damage that occurs in inaccessible areas may not be detected by visual examination, the leaktightness of the entire pressure boundary is verified each time a leakage rate test is performed. Unfortunately, integrated leak rate tests of the entire containment, vessel are not very effective in detecting small defects such as through-thickness cracks or pits and damage in inaccessible areas may not be detected before significant degradation has occurred.

1.2.1 Metal Containments

Except for spherical containments, which are exposed to the natural environment, metal containment vessels are free-standing, welded steel structures that are enclosed in a reinforced concrete reactor or shield building. Although these buildings are not part of the containment system, they provide protection for the vessel from missiles and natural phenomenon; permit access to airlocks, manways, and external vessel surfaces; and house other safety components and systems. Over 40 metal containment vessels have been built at nuclear power plants throughout the United States, but there are only six basic design types (Refs. 1.1 and 1.3). These designs are commonly referred to as (1) BWR Mark I, which'is the most numerous, (2) BWR Mark II, (3) BWR Mark III, (4) BWR and PWR spherical, (5) PWR cylindrical with hemispherical dome and ellipsoidal base, and (6) PWR cylindrical with hemispherical dome and flat base (e.g., ice condenser) metal containments. The containment system includes (1) the containment vessel; (2) all penetration assemblies or appurtenances attached to the containment vessel; and (3) all piping, pumps, and valves attached to the containment vessel, or to penetration assemblies out to and including any valves required to isolate the system and provide a pressure boundary for the containment function (Ref. 1.6). Components used to construct metal containment vessels, are generally much thicker than the liners. of reinforced concrete containment vessels because they are required to resist applied loads and operating pressures as well as create a leaktight pressure boundary.

Prior to 1963, metal containment vessels for nuclear power plants were designed according to rules for unfired pressure vessels contained in Section. VIII of the Code. Subsequent metal containment vessels were designed either as Class B vessels or as Class MC components according to rules provided in Section III of the Code. Current rules for construction of metal containment vessels are provided in Section III, Division 1, Subsection NE of the Code (Ref. 1.6). These rules only cover containment vessels and their appurtenances. Piping, pumps, and valves that are part of the containment system or that penetrate or are attached to the containment vessel are classified as Class 1 or Class 2 components. These components are covered by rules that appear in other subsections of Section III, Division 1 of the Code.

1.2.2 Concrete Containments

Concrete containment vessels are metal-lined, pressure-resisting, reinforced concrete structures that, in some cases, may also be post-tensioned. There are six basic design types including (1) PWR dry, (2) PWR subatmospheric, (3) PWR ice condenser, (4) BWR Mark I, (5) BWR Mark II, and (6) BWR Mark III concrete containments (Refs. 1.2 and 1.3). The most common configuration is the PWR dry post-tensioned concrete containment. The concrete containment system includes the pressure-resisting shell concrete and related structural components, shell metallic liners, and penetration liners that extend the containment liner through the surrounding shell concrete (Ref. 1.7). The reinforced concrete shell, which generally consists of a cylindrical wall with a hemispherical or ellipsoidal dome and flat base slab, provides structural support and resistance to gravity loads and pressure-induced forces. Leaktightness is provided by a welded steel liner that is fabricated from plates that may be as thin as 6.4 mm (0.25 in.). Anchorage of the liner to the concrete is provided by studs or continuous rolled shapes that are welded to the liner at prescribed intervals. As non-structural components, concrete containment liners are not required to resist gravity loads or pressure-induced forces.

In 1972, a proposed standard-code for concrete reactor vessels and containments was issued combining information available in American Concrete Institute (ACI) and ASME committee-~ reports. This effort was needed because rules for design construction, inspection, and testing of concrete reactor vessels and containments for nuclear power reactors did not exist. After three drafts, two public hearings, and a trial-use and comment period of about one year, a consensus document was formed creating the basis for the rules that now appear in Section III, Division 2. Prior to 1975, concrete containments were designed using technology and building code requirements developed for conventional reinforced and prestresed concrete structures. Current rules for construction of Class CC (concrete) containments are provided in Section III, Division 2, Subsection CC of the Code (Ref. 1.7). Parts or appurtenances that are not backed by structural concrete for load-carrying purposes are covered by appropriate rules that appear in Section III, Division 1 of the Code.

1.3 CONTAINMENT PRESSURE BOUNDARY MATERIALS

All containments include pipes, electrical penetration assemblies, equipment hatches, manways, airlocks, etc., as part of the pressure boundary. These components are generally either welded or bolted to the steel liners and metal shells and typically have compositions and properties that are significantly different from those of the liner and shell materials. Material specifications and property values for ferrous materials permitted for construction of metal and concrete containments are provided in Section II, Parts A and D of the Code (Refs. 1.8 and 1.9). Part A contains material specifications for ferrous metals. These specifications, which were developed by the American Society for Testing and Materials (ASTM) and adopted by ASME, represent a consensus among producers, specifiers, fabricators, and users of steel products. Material specifications adopted by ASME are identified by the prefix "S" followed by the appropriate ASTM designation. For example, specifications ASME SA-5 16/SA-5 16M (Ref. 1.8) and ASTM A 5 16/A 5 16M-86 (Ref. 1.10) are identical. Part D contains maximum allowable stress values, design stress intensity values, and thermal properties for all ferrous and nonferrous materials cited in the Code. Tabulated information in Part D is organized according to the nominal composition of the materials. The ASME specification designations are used to distinguish one material from another, and materials with similar compositions and characteristics are grouped together.

The Code only permits the use of certain materials for construction of concrete and metal containment pressure boundary components. These materials must conform to ASME or ASTM material specifications. Tables 1.2 to 1.6 list the material specifications permitted by the 1992 edition of the Code (Refs. 1.6 and 1.7) for this purpose. The Code also specifies which grade,

class, or type of steel is permitted for a particular application. For example, even though specifications ASME SA-738/SA-738M (Ref. 1.8) and ASTM A 738/A 738M (Ref. 1.11) are identical, steel plates that conform to Grade A, B, and C requirements are permitted for use in construction of concrete containment vessel liners, but only plates that conform to Grade A and C requirements are permitted for use in construction of metal containment vessels. The lists of materials permitted for use in containment construction often change from one edition or addenda of the Code to another as a result of actions taken by ASME and ASTM committees to delete, merge, edit, or modify existing materials specifications and to adopt new ones.

Depending on the alloy content, ferrous metals permitted for construction of concrete and metal containment pressure boundary components are usually classified as either carbon, low-alloy, or high-alloy steels. Ferrous metals are composed of iron and carbon plus other elements that are either introduced during the manufacturing process as part of the raw materials or intentionally added as alloying elements. In general, carbon steels contain at least 0.12 percent carbon, low-alloy steels contain up to ten percent alloying elements, and high-alloy steels contain at least ten percent alloying elements. The alloy content of steel is typically determined using a sample of molten metal removed from the ladle or furnace. Results of the chemical analysis are considered to be an accurate representation of the entire heat of steel. Alloy contents of products made from large heats of steel can also be determined, but the variability of these results tends to be somewhat greater that the corresponding heat analysis results.

1.3.1 Carbon Steels

Carbon steels, which may contain up to two percent total alloying elements, are often subdivided into categories based on carbon content. In general, low-carbon steels contain up to 0.30 percent carbon and are used primarily to make flat-rolled products including sheets, strips, plates, and shapes for structural applications. Most of the carbon steels used to construct metal containment shells and concrete containment liners are low-carbon steels. Medium-carbon steels contain from 0.30 to 0.60 percent carbon and from 0.60 to 1.65 percent manganese. Rails, railway wheels, rail axles, shafts, couplings, gears, and forgings are products commonly manufactured from medium-carbon steels. Some medium-carbon steels with improved strengths are used in the quenched and tempered condition. High-carbon steels contain at least 0.60 percent carbon and have manganese contents that range from 0.30 to 0.90 percent. High-strength wires and springs are usually manufactured using high-carbon steel.

1.3.2 Low-Alloy Steels

Low-alloy steels tend to exhibit mechanical properties that are superior to plain carbon steels. Differences in performance are due primarily to the addition of alloying elements such as nickel, chromium, and molybdenum. In general, alloy contents for these steels range from about two to ten percent. Terms commonly used to identify low-alloy steels include low-carbon quenched and tempered steels, medium-carbon ultrahigh-strength steels, bearing steels, chromium-molybdenum heat-resistant steels, and high-strength low-alloy steels.

1.3.3 High-Alloy Steels

High-alloy steels include a broad family of materials known as stainless steels. Stainless steels are iron-based alloys that contain at least 10.5 percent chromium (Ref. 1.12). Corrosion resistance and extreme-temperature mechanical properties are the most important characteristics of stainless steels. Terms commonly used to identify different types of stainless steels include martensitic, ferritic, austenitic, duplex (ferritic-austenitic), and precipitation hardening. Austenitic stainless steels are used most often for containment construction, but certain martensitic and precipitation hardening stainless steels are permitted and occasionally used.

Martensitic stainless steels have a body-centered cubic (bcc) crystalline structure (martensitic) and chromium contents ranging from about 10.5 to 18 percent. Generally resistant to relatively mild environments, these steels can be hardened by heat treating to increase wear resistance or to maintain cutting edges. Martensitic steels are rarely used as construction materials for pressure vessel components.

Ferritic stainless steels also have a bcc crystalline structure, but the chromium content for these steels ranges from 10.5 to about 30 percent. Compared to austenitic stainless steels, the high-temperature strengths of ferritic stainless steels are relatively poor and toughness is somewhat limited at low temperatures. Ferritic steels cannot be hardened by heat treatment.

Austenitic stainless steels have a face-centered cubic (fcc) crystalline structure (austenite) resulting from the addition of austenitizing elements such as nickel, manganese, and nitrogen. Essentially nonmagnetic, austenitic stainless steels are highly resistant to corrosion at temperatures up to 8 15°C (1,500°F), can only be hardened by cold working, and possess high impact strength at low temperatures. The chromium content ranges from 16 to 26 percent and the nickel content may approach 35 percent. Properties of austenitic stainless steels are generally excellent at cryogenic temperatures and strengths are good at high temperatures. Many austenitic stainless steels can be identified by either a 200 or 300 series (Type 201, 304, 347, etc.) numerical designation. These designations are used to distinguish one type of austenitic stainless steel from another. However, as Table 1.2 shows, materials with the same numerical designation may conform to different material specifications. Most of the high-alloy materials permitted for construction of containment pressure boundary components are 300 series austenitic stainless steels.

Duplex stainless steels have a mixture of bcc and fcc crystalline structures. Compared to austenitic stainless steels, the corrosion resistance of duplex stainless steels are about the same, but the tensile and yield strengths are higher and the resistance to stress-corrosion cracking is improved.

Precipitation-hardening stainless steels are chromium-nickel alloys that contain precipitation hardening elements such as copper, aluminum, and titanium. In most cases, these materials are used for components that require corrosion resistance and high strength at room temperature. These steels attain high strength by precipitation hardening of the martensitic structure.

1.4 IN-SERVICE EXPERIENCE

Since nuclear power plants have been in operation, in-service performance of metal and concrete containments has generally been satisfactory. However, instances of wall thinning, coating degradation, moisture barrier deterioration, and component damage have been reported. Operating experience suggests that problems with containment pressure boundary components can be related to general or pitting corrosion of steel components, cracking or loss of function of electrical and mechanical penetration assemblies, and corrosion and cracking of expansion bellows. Past experience also suggests that degradation can occur on the inside as well as the outside of the containment vessel.

Whenever minor containment damage is detected, corrective actions are usually taken to identify and eliminate the source of the problem and thereby halt the degradation process. However, when significant wall thinning, cracking, surface defects, or leakage are detected and containment integrity is jeopardized, defective areas are either evaluated, repaired, or replaced before the plant is returned to service. Under certain conditions, in-service inspection programs have even been initiated to periodically examine suspect areas or to monitor the long-term performance of degraded components.

1.4.1 Steel Component Degradation

Coating degradation of metal containment shells and concrete containment steel liners is the most common containment degradation mechanism, but instances of corrosion have also been reported. Factors associated with pressure-retaining steel component degradation are summarized in Table 1.7 (Ref. 1.13).

Corrosion has been detected in the sand cushion regions of BWR Mark I containments (Refs. 1.14 to 1.17), at the interface between concrete and steel surfaces in BWR and PWR containments (Refs. 1.18 and 1.19), on BWR Mark I torus surfaces (Refs. 1.20 and 1.21), and along shell surfaces of BWR Mark I and II containments that are adjacent to filler material (used to create a gap between the metal containment shell and the concrete) (Ref. 1.19). Because corrosion of containment pressure boundary components has occurred in numerous plants and because it is not related to a specific BWR or PWR containment design, corrosion is a generic containment aging issue (Ref. 1.1). Coating degradation has occurred in the torus region of BWR Mark I containments due to exposure to aqueous solutions (Refs. 1.22 and 1.23) and on surfaces of a BWR Mark I that were exposed to elevated temperatures (Ref. 1.24).

1.4.2 Penetration Assembly Degradation

Mechanical and electrical penetration assemblies that are part of the containment pressure boundary have experienced loss of mechanical and electrical function and contributed to excessive containment leakage. Causes for the degradation have been attributed to corrosion, fatigue, seal and gasket aging, wear, cable deterioration, disbonding and cracking of ceramic inserts, chemical breakdown, and physical damage (Ref. 1.25). Although mechanical and electrical penetration assemblies are part of the containment pressure boundary, their evaluation and assessment are beyond the scope of this investigation and the degradation assessment methodology described in this report does not specifically address these components.

1.4.3 Bellows Degradation

Excessive leakage from stainless steel bellows has been reported. The leakage was caused by transgranular stress-corrosion cracking resulting from exposure to chlorides, fluorides, and sulfides that might have accumulated during fabrication, construction, or operation (Refs. 1.1, 1.25, and 1.26). After the defective bellows were identified, they were either repaired or replaced. These bellows problems have not been associated with a particular design, fabrication procedure, or plant type. Consequently, bellows of similar construction may be susceptible to leakage caused by cracking. The degradation assessment methodology described in this report does not specifically address bellows because the characteristic behavior and mechanical performance of containment bellows is currently being investigated as part of another research program sponsored by the NRC (Ref. 1.27).

1.5 DESCRIPTION OF THE DEGRADATION ASSESSMENT METHODOLOGY

The balance of this report describes a degradation assessment methodology intended for use in characterizing the in-service condition of metal and concrete containment pressure boundary components and quantifying the amount of damage that is present. Condition assessments are essential to reliable continued service evaluations and informed aging-management decisions. From an aging management view point, metal and concrete containment pressure boundary components that exhibit satisfactory long-term performance and do not experience in-service degradation can be considered acceptable for continued service. However, components found by routine examination or in-service inspection to be deteriorated or damaged must be evaluated to determine whether continued service is appropriate or whether repairs, replacements, or retrofits are needed.

Damage is considered significant when it adversely affects structural capacity, leaktight integrity, or remaining service life. Requirements for corrective actions that are to be taken when evidence of structural deterioration is discovered are provided in 10 CFR 50, Appendix J (Ref. 1.5). More detailed acceptance standards and evaluation criteria for use in determining the acceptability of degraded components for continue service are provided in Section XI, Division 1, Subsection IWE of the Code (Refs. 1.4 and 1.13). A diagram that illustrates the continued service evaluation process presented in Subsection IWE is shown in Fig. 1.1.

Continued service evaluations are performed by qualified engineers and authorized personnel who determine the adequacy of degraded components for their intended use (Ref. 1.28). The decision-making process begins with an understanding of the in-service condition of each containment component (Ref. 1.29 and 1.30). Condition assessments that provide essential information for continued service evaluations involve detecting damage in areas of the containment pressure boundary that are potentially vulnerable to in-service deterioration or attack, classifying the types of damage that may be present, determining the root cause of the problem, and quantifying the extent of degradation that may have occurred. Knowledge gained from condition assessments can serve as a baseline for evaluating the safety significance of any damage that may be present and defining in-service inspection programs and maintenance strategies. Condition assessment results can also be used to estimate future performance and remaining service life.

Table 1.8 identifies and defines four elements associated with in-service condition assessments for metal and concrete containment pressure boundary components. These elements focus on damage detection, damage classification, root-cause determination, and damage measurement. Major topics pertaining to each element are listed in Fig. 1.2 and described in detail in the remainder of this report. Because information required to characterize and quantify the condition of degraded components must be established on a case-by-case basis taking into considerations unique containment design features and plant operating constraints, some of the topics addressed in this report may not always be relevant while other issues that are considered important may not be addressed. For this reason, the degradation assessment methodology described in this report does not include a step-by-step procedure for performing in-service condition assessments or conducting continued service evaluations but provides general, non-prescriptive guidance.

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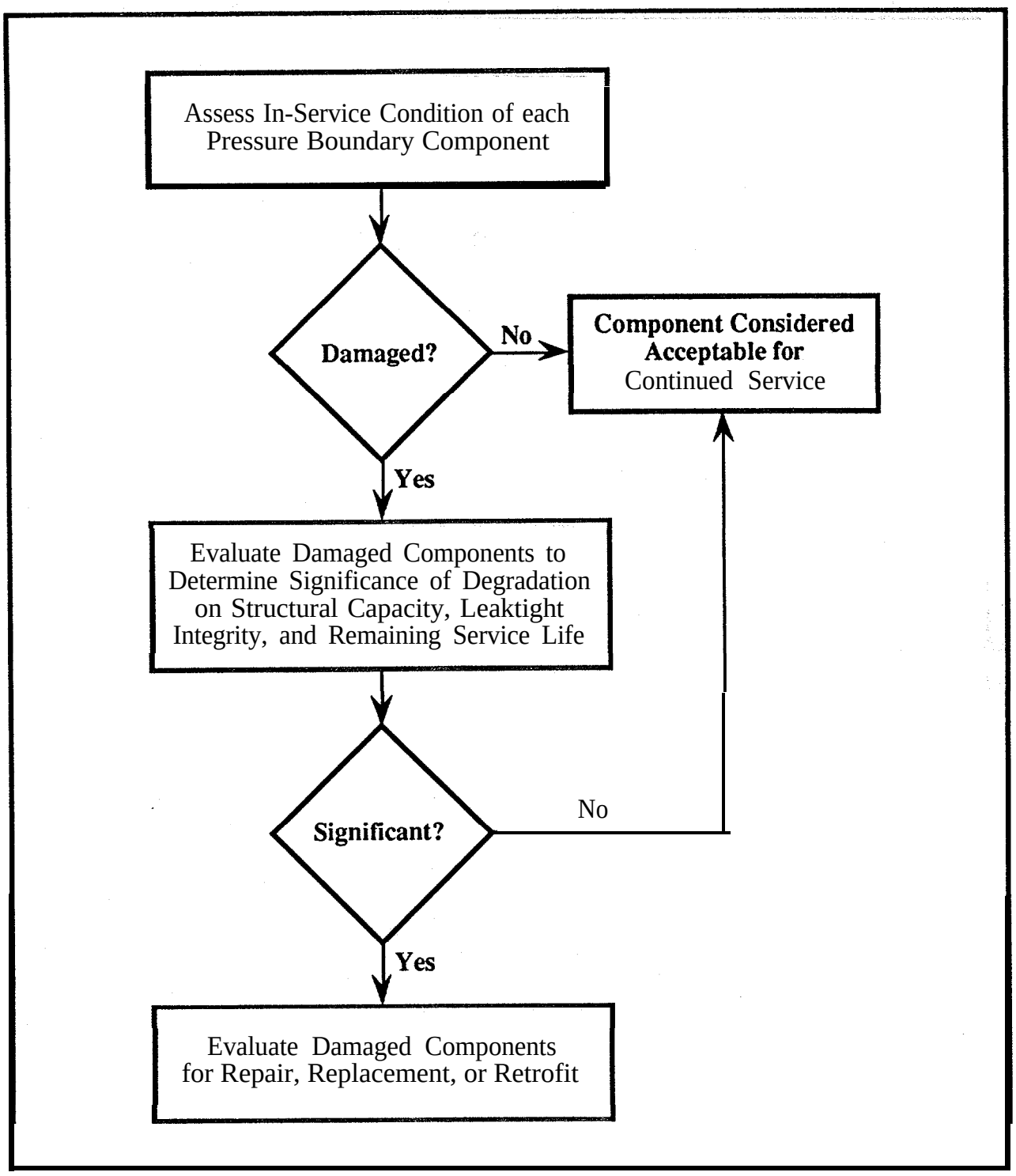

Fig. 1.1 Continued service evaluation process for containment pressure boundary components.

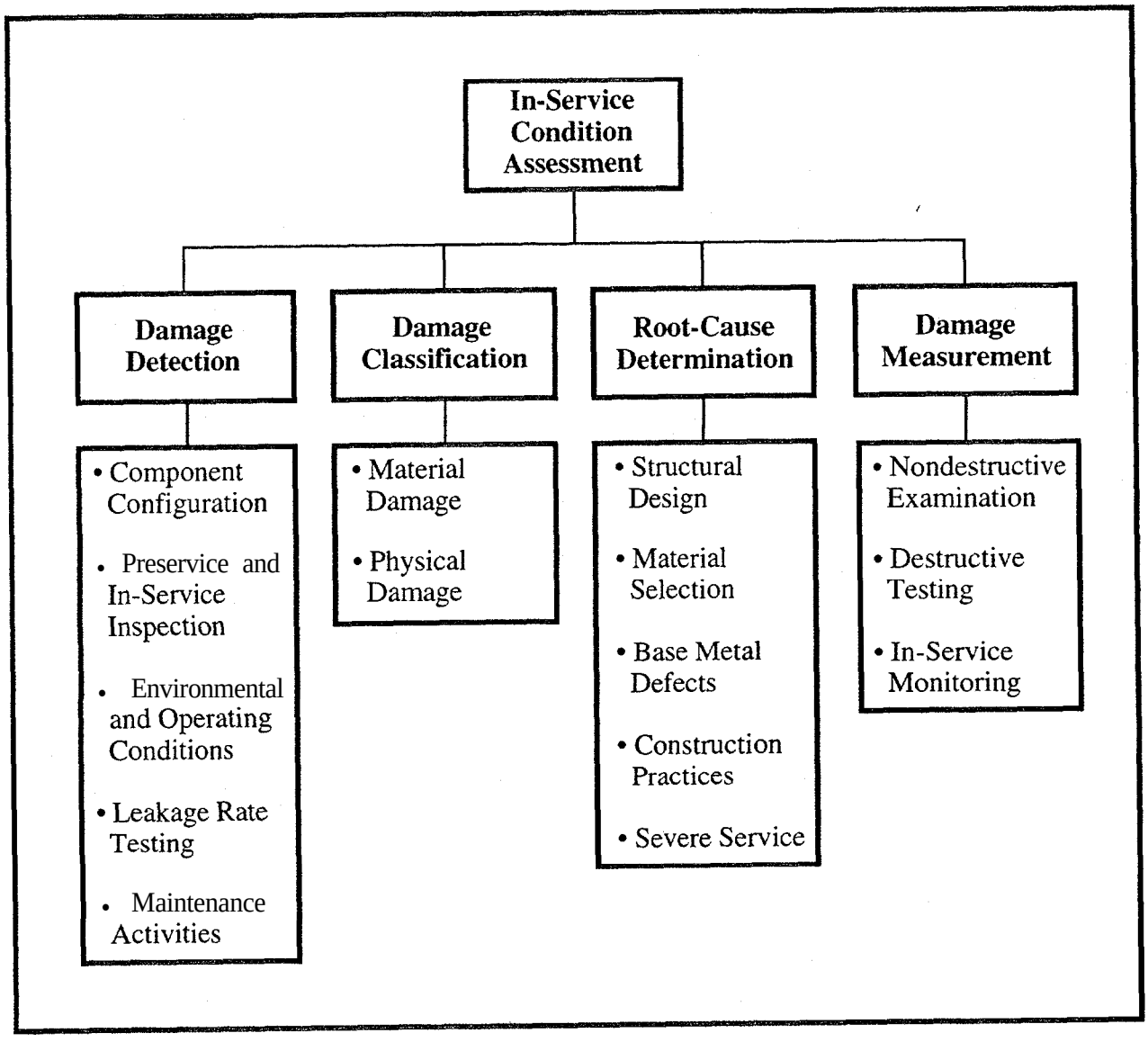

Fig. 1.2 Major topics pertaining to in-service condition assessments.

Table 1.1 Major access and process penetrations that complete the containment pressure boundary.

Large Opening Penetrations
Equipment hatch
Personnel airlock
BWR drywell head
Fuel transfer tube
Control rod drive removal hatch
Purge and Vent System Isolation Valves
Piping Penetrations
Electrical Penetration Assemblies

Source: Ref. 1.3

Table 1.2 Material specifications permitted for construction of Class MC components.

ASME Specification Designation	ASTM Specification Designation
Carbon Steels	
SA-36”	A36
SA-105”	A 105
SA-106	A 106
SA-178”	A 178
SA-181”	A 181
SA-210	A210
SA-216	A216
SA-234”	A 234
SA-266”	A 266
SA-299”	A 299
SA-333”	A 333
SA-334*	A 334
SA-350*	A 350
SA-352	A 352
SA-420	A 420
SA-442”	A442
SA-487”	A 487
SA-508	A 508
SA-516*	A516
SA-537”	A 537
SA-54 1 *	A541
SA-67 1	A671
SA-69 1	A691
SA-695	A 695
SA-696*	A 696
SA-737”	A 737
SA-738”	A738
Precipitation Hardening Steels	
SA-564	A564
SA-693”	A 693
SA-705	A 705
High-Alloy Type 304 Stainless Steels	
SA-182	A 182
SA-213	A213
SA-240	A 240
SA-249	A 249
SA-312”	A312

Table 1.2 (cont.) Material specifications permitted for construction of Class MC components.

ASME Specification Designation	ASTM Specification Designation
High-Alloy Type 304 Stainless Steels (cont.)	
SA-336	A 336
SA-35 1	A351
SA-358	A 358
SA-376	A 376
SA-403	A 403
SA-430”	A 430
SA-452*	A 452
SA-479	A 479
SA-813”	A813
SA-8 14*	A814
High-Alloy Type 316 Stainless Steels	
SA-182	A 182
SA-2 13	A213
SA-240	A 240
SA-249	A 249
SA-3 12”	A312
SA-336	A 336
SA-35 1	A351
SA-358	A 358’
SA-376	A 376
SA-403	A”403
SA-430*	A 430
SA-452”	A 452
SA-479	A 479
S A - 8 1 3 ”	A 813
SA-8 14”	A 814
High-Alloy Type 309 and 310 Stainless Steels	
SA-182	A182
SA-213	A213
SA-240	A 240
SA-249	A 249
SA-3 12”	A312
SA-336	A 336
SA-35 1	A351
SA-376	A 376
SA-403	A 403
SA-430*	A 430

Table 1.2 (cont.) Material specifications permitted for construction of Class MC components.

ASME Specification Designation	ASTM Specification Designation
High-Alloy Type 309 and 310 Stainless Steels (cont.)	
SA-479	A 479
SA-813*	A813
SA-8 14”	A814
High-Alloy Type 347 and 348 Stainless Steels	
SA-182	A 182
SA-213	A213
SA-240	A 240
SA-249	A 249
SA-3 12”	A312
SA-336	A 336
SA-35 1	A351
SA-376	A 376
SA-403	A 403
SA-430*	A 430
SA-452”	A 452
SA-479	A 479
SA-813”	A813
SA-8 14”	A 814
High-Alloy Type XM-19 Stainless Steels	
SA-182	A 182
SA-240	A 240
SA-249	A 249
SA-312*	A312
SA-358	A 358
SA-403	A 403
SA-412	A 412
SA-479	A 479
SA-813”	A 813
SA-8 14”	A 814

* Identical with corresponding ASTM specification.

Table 1.3 Material specifications permitted for bolting materials.

ASME Specification Designation	ASTM Specification Designation
Low-Alloy Steels	
SA-193	A 193
SA-320*	A 320
High-Alloy Steels	
SA-193	A 193
SA-437*	A 437
SA-453*	A 453

* Identical with corresponding ASTM specification.

Table 1.4 Material specifications permitted for construction of concrete containment liners.

ASME Specification Designation	ASTM Specification Designation
Carbon Steels	
SA-36*	A36
SA-105*	A 105
SA-106	A 106
SA-178”	A 178
SA-181*	A 181
SA-210	A210
SA-216	A216
SA-234*	A 234
SA-266*	A 266
SA-285*	A 285
SA-299”	A 299
SA-333*	A 333
SA-334”	A 334
SA-350*	A 350
SA-420	A 420
SA-442”	A442
SA-508	A 508
SA-516*	A516
SA-537*	A 537
SA-541*	A541
SA-738*	A 738
High-Alloy Steels	
SA-213	A213
SA-240	A 240
SA-312”	A312
SA-35 1	A351
SA-358	A 358
SA-376	A 376
SA-403	A 403
SA-430*	A 430

* Identical with corresponding ASTM specification.

Table 1.5 Material specifications permitted for reinforcing bar splice sleeves attached to concrete containment liners.

ASME Specification Designation	ASTM Specification Designation
Carbon Steels	
**	A 108
**	A513
**	A 519

** No corresponding ASME specification has been established.

Table 1.6 Material specifications permitted for load bearing steels that are embedded in concrete containments.

ASME Specification Designation	ASTM Specification Designation
Carbon Steels	
SA-36”	A36
SA-307”	A 307
SA-325”	A 325
SA-354”	A 354
SA-449”	A449
**	A 490
SA-540”	A 540
SA-563”	A 563
**	A 687
**	F 436

* Identical with corresponding ASTM specification.
** No corresponding ASME specification has been established.

Table 1.7 Factors associated 'with pressure-retaining steel component degradation.

Factor	Description
Pressure-Retaining Steel Components	Degradation can adversely affect the structural capacity or leak-tight integrity of metal containment shells, concrete containment liners, penetration liners, heads, nozzles, structural and non-structural attachments, embedment anchors, pipes, tubes, fittings, fasteners, and bolting items that are used to join other pressure-retaining components.
Damage Characteristics	Damage could involve loss of net section or wall thinning, cracks, pits, crevices, erosion, cavitation, surface flaws, arc strikes, plastic deformation, buckling, fracture, or bulging.
Damage Indicators	Rust, discoloration, staining, blistering and peeling of coatings, spalling of concrete, buckling or separation of liners, leakage from drains, and clogged drains often serve as damage indicators.
Potential Problem Areas	Locations where degradation could be suspected include areas of water accumulation; surfaces exposed to chemical or borated water spills; flashed, caulked, or sealed joints; dissimilar metal connections; penetrations; condensation and leakage paths; sand pockets or cushions; heat trace areas; and locations with stray electrical currents.
Damage Detection	Damage detection techniques include leakage rate testing, visual inspection, destructive testing, and nondestructive examination.
Mitigation Procedures	Effects of degradation can potentially be mitigated by eliminating leaks; repairing or replacing defective components; removing and replacing cracked or torn seals, gaskets, and caulked joints; opening clogged drains; providing additional drains; repairing or replacing damaged coatings; proving improved spill response; and installing cathodic protection systems.
Potential Failure Modes	Degradation can cause cracking, fracture, instability, distortion, or excessive displacement that could result in loss of leaktight integrity, decreased load-carrying capacity, or reduced service life.

Source: Ref. 1.13

Table 1.8 Elements of in-service condition assessments for metal and concrete containment pressure boundary components.

Element Designation	Element Definition
Damage Detection	Containment pressure boundary components that have experienced in-service degradation are generally detected by routine visual examination, in-service inspection, leakage rate testing, or other nondestructive examination techniques. Knowledge about component design and in-service performance can be useful in identifying components that are susceptible to degradation. Information from past service failures can also provide valuable guidance on the types of damage to expect.
Damage Classification	Degradation can be classified as either material or physical damage. Material damage occurs when the microstructure of a metal is modified causing its properties to change. Physical damage occurs when the geometry of a component is altered due to formation of cracks, fissures, or voids, or its dimensions change due to fracture, buckling, corrosion, oxidation, erosion, or other surface damage.
Root-Cause Determination	Degradation of containment pressure boundary components can generally be related to a design deficiency, improper material selection, defective base metal, an incorrect construction practice, or excessively severe service conditions. Determining the root cause of the degradation can be helpful in classifying the type of damage that has occurred and defining actions to be taken to reduce or eliminate further deterioration. Normal operations, maintenance procedures, and repair activities can cause physical damage including general and localized corrosion, mechanically assisted degradation, and environmentally induced cracking that can adversely affect the ability of containment pressure boundary components to perform satisfactorily during an accident. Time-dependent change can occur as a result of metallurgically induced corrosion, fatigue, neutron irradiation, hydrogen embrittlement, and extreme-temperature exposure.
Damage Measurement	The degree of degradation can be measured by destructive testing of material samples or by nondestructive examinations. In-service monitoring can also be used to measure the rate of degradation and to detect changes in operating conditions that can adversely affect structural capacity or leaktight integrity.

2. DAMAGE DETECTION

2.1 CONSIDERATIONS AND PARAMETERS

Detection of deteriorated or damaged containment pressure boundary components is the first and most important step in the condition assessment process. Certain types of damage such as grooves and gouges that can potentially jeopardize containment structural capacity or leaktight integrity are often easy to identify by visual inspection, particularly when they occur in areas that are readily accessible. However, damage occurring in less accessible areas such as beneath nuts and washers, between flanges, or adjacent to seals and gaskets can be difficult to detect unless the components are disassembled. Damage that occurs in enclosed spaces such as corrosion of steel liner plate embedded in concrete or steel, covered- by flashing or caulking can only be reliably detected by removing the obstruction and exposing the suspect area. Routine observation, general visual inspections, leakage rate testing, and nondestructive examinations are techniques frequently used to identify areas of the containment that have experienced degradation.

Knowing where to inspect and what type of damage to anticipate often requires information about the design features of the containment and the materials used to construct its pressure-retaining components. Design basis documentation is an important source of plant-specific information. As a living document, the design basis includes information such as the original design codes, material standards, fabrication drawings, design calculations, stress analyses, loading combinations, safety margins, corrosion allowances, and inspection reports as well as subsequent design changes and plant modifications. Construction details and dimensions of suspect areas can usually be obtained from design or as-built drawings, construction specifications, inspection reports, and plant logs. Areas of the containment pressure boundary considered suspect may include carbon and stainless steel component surfaces located along the path of borated water leaks, carbon steel surfaces exposed to water or condensation, and regions where the relative humidity is high (above 60 percent). NRC documents such as Office of, Inspection and Enforcement Bulletins, Information Notices, inspection and test reports, Generic Letters, Licensee Event Reports (LERs), NUREG reports, Federal Register notices, correspondence, and docket files (Refs. 2.1 to 2.35) describing degradation that has occurred at one or more plants can also be helpful in identifying suspect areas and preparing effective in-service inspection plans and programs.

Thirty-seven occurrences of containment pressure boundary component degradation at commercial nuclear power plants in the United States are described in Table 2.1. Twenty-six are related to metal containments and involve either-steel corrosion, coating degradation, bellows leakage, anchor bolt deformation, cracking of the torus shell, or brittle fracture of the vent header inside the torus or the nitrogen purge line. The remaining eleven occurrences are related to concrete containments and involve either coating degradation, steel liner corrosion, liner plate separation, or liner leakage. A summary of these occurrences is provided in Table 2.2. Factors that contributed to the discovery of these instances of contain-ment degradation are among the damage detection parameters identified in Fig. 2.1 and described in the following sections. Techniques for classifying and quantifying degradation are described later in this report.

2.2 COMPONENT CONFIGURATION

The leaktightness of concrete and metal containment systems is ensured by a continuous pressure boundary consisting primarily of steel components that are either welded or bolted together. Each containment system includes the containment vessel and all penetrations assemblies and appurtenances attached to the containment vessel as well as pipes, valve, and pumps required to complete the pressure boundary. Appurtenances are items intended to be attached to a compo-

nent. An attachment is an element that is in contact with or connected to the inside or outside of the pressure-retaining portion of a containment vessel. It may be either a pressure-retaining or nonpressure-retaining element that provides either a structural or nonstructural function (Ref. 2.36). Attachments with a pressure-retaining function include items such as stiffeners and vessel opening reinforcement. Those with nonpressure-retaining function include items such as thermal sleeves, turning vanes, and containment vessel supports. The boundary between the containment vessel and an attachment is defined in the design specification. Design specifications are documents that provide the basis for design and construction of a containment vessel in accordance with requirements provided in the ASME Boiler and Pressure Vessel Code. Specific rules for defining the containment vessel boundary are provided in Section III, Division 1, Subsection NE and Division 2, Subsection CC of the Code (Refs. 2.36 and 2.37).

2.2.1 Design Features

Dimensions and locations of pressure boundary components are shown in the design drawings. These drawings illustrate the structural and mechanical details described in the design specifications. Terms commonly used to designate components that may be represented in design drawings and specifications include liners, electrical and mechanical penetration assemblies, piping penetrations, equipment hatches, airlocks, manways, leak chase channels, nozzles, knuckles, closures, shells, heads, welds, bellows, torus, covers, supports, liner anchors, and embedments.

2.2.2 Construction Materials

Containment pressure boundary components are fabricated primarily from carbon steel plates, shapes, bars, strips, pipes, tubes, castings, and forgings. However, low- and high-alloy steels are used in certain bolting applications, and high-alloy or stainless steels are used to fabricate special components such as bellows expansion joints. One way to identify the type, class, or grade of steel used to fabricate a particular component is to examine the design drawings and construction specifications. These documents generally use ASTM or ASME material specification designations to distinguish one steel from another. Accurate material identification is a very important damage detection parameter because it establishes baseline properties for the material, characterizes expected material performance, and focuses the search for possible degradation mechanisms.

ASTM has adopted a unique serial designation system for its material specifications. Each designation includes a capital letter (A for ferrous metals) followed by a serial number (one to four digits). When a material specification contains chemical or strength requirements for more than one material, its designation is supplemented with at least one additional term such as Grade 35, Type A, or Class 1. The designation system adopted by ASME for its material specifications is very similar to the one adopted by ASTM. ASME material specification designations use the prefix "S" followed immediately by the complete ASTM material specification designation. Tables 1.1 to 1.4 contain lists of ASME and ASTM material specifications permitted in the 1992 edition of the Code (Refs. 2.36 and 2.37) for use in construction of containment pressure boundary components. Although these tables are complete, they do not include certain material specifications that were permitted in earlier editions of the Code. Steel conforming to ASTM A 212 (Ref. 2.38) requirements is one such material that was used in the 1960s for containment construction. This material specification, which included requirements for Grades A and B steel plates, was discontinued in 1966 and replaced by ASTM A 5 1.5 and A 5 16 (Refs. 2.39 and 2.40). General information and elevated-temperature mechanical properties for ASTM A 2 12, Grade B steel are provided in Ref. 2.41.

Relatively thin low-carbon steel plates ranging in thickness from about 6 to 5 1 mm (0.25 to 2 in.) are used to construct metal containment shells and concrete containments liners. The carbon content of these steels is typically less than about 0.30 percent making them suitable for

welding. Plates conforming 'to ASTM A 5 16/A 5 16M (Ref. 2.42) material specification requirements are frequently used in containment vessel applications, but material specifications listed in Tables 1.1 and 1.3 are also permitted and occasionally used for this purpose. The chemical composition and specified tensile strength properties of steel plates conforming to ASTM A 516/A 516M, Grades 55, 60, 65, and 70 requirements are summarized in Tables 2.3 and 2.4. These values are only provided for reference, but they represent requirements that are typical for many-other low-carbon steels used for containment construction. Strength values in Table 2.4 are reported in customary units and in the International Systems of Units (SI), but the values are not exact equivalents (Ref. 2.43). Each system is regarded as standard, and each set of values must be used independently of the other.

2.3 ENVIRONMENTAL AND OPERATING CONDITIONS

Knowledge about the environmental and operating conditions inside and outside the containment and information from operating experience, maintenance activities, and past service failures can provide valuable guidance on where to anticipate degradation, how to identify damage, and what degradation mechanisms caused the damage. The paragraphs in this section describe conditions normally found inside and outside the containment.

2.3 . 1 Conditions Inside the Containment

Environmental conditions inside BWR and PWR containments are controlled, during normal plant operations. In certain plants, the containment is maintained under a slight vacuum and in others a small over pressure is applied. Heat generated by the nuclear reactor is removed by a heating, ventilation, and cooling system. The average temperature inside BWR Mark I containments ranges from about 57 to 66°C (135 to 150°F) while the average temperature inside PWR containments is about 49°C (120°F). Air chemistry inside the containment is also monitored and continuously adjusted to maintain a nearly constant environment. BWR Mark I and Mark II containments are inerted with nitrogen to prevent hydrogen-oxygen recombination. The oxygen content inside these containments is generally maintained at a level of less than four percent by volume (Ref. 2.44). BWR Mark III and PWR containments are filled with air.

Acceptable service temperature limits for concrete and metallic materials used in containment construction are provided in the Code (Ref. 2.36 and 2.37). These limits have a significant influence on the allowable operating temperature range of the containment. According to-requirements in Section III, Division 2, Subsection CC of the Code (Ref. 2.37), the temperature of the concrete is not allowed to exceed 66°C (150°F) except for local areas, such as around penetrations, where the concrete temperature cannot exceed 93°C (200°F). The lowest temperature that the steel in a metal containment can experience while the plant is in operation is defined in Section III, Division 1, Subsection NE of the Code (Ref. 2.36) as the lowest service metal temperature (LST). This value is based on the minimum temperature that the inside of the containment vessel can experience during plant operations and is related to the nil-ductility transition temperature (Ref. 2.45) of the steels used to construct the containment pressure boundary components.

During normal plant operations, water is usually not present inside PWR containments and relative humidity levels generally range from about 15 to 40 percent except for PWRs with ice-condensers where levels can range up to 60 percent. However, under certain conditions, condensate can form on colder surfaces located near the ice-condensers, or steam can be released inside the containment as a result of leaky flanges, valves, and pumps. Water produced in these instances is considered undesirable because it can create potentially corrosive situations as it flows over safety-related items or accumulates on pressure-retaining component surfaces. Unlike PWR containments, water is normally present inside BWR containments in the pressure suppression pools and chambers. The quality and chemistry of the water can influence the rate of corrosion of

pressure boundary components that are in contact with the water. The relative humidity inside BWR containments can range up to 60 percent, but the humidity level varies from one location to another because the average temperature inside the containments does not always remain constant and because the operating temperature in one area may be different from that in another.

Although high radiation levels are generated inside the nuclear reactor, biological shielding effectively limits exposure of the containment pressure boundary materials to levels that are considered safe for occupational workers. Consequently, end-of-life fluence of containment components is anticipated to be quite small (Ref. 2.44). Only in the unlikely event of a severe accident can the radiation levels inside the containment become significant.

2.3.2 Conditions Outside the Containment

Environmental conditions outside the containment can be significantly different from the conditions on the inside. The three spherical containments at Big Rock Point, San Onofre 1, and Yankee Rowe are exposed to the natural environment because these plants were constructed without reactor shield buildings. Exposed surfaces of these three containments are protected by an' extensive coating system that can be periodically inspected and maintained. Part of the Big Rock Point steel shell is embedded in the concrete basemat, but the other two containments are supported on steel columns. All other BWR and PWR metal containments are enclosed in a reactor shield building that protects the vessel from sun, wind, rain, sleet, snow, etc., but the atmospheric conditions inside these buildings may or may not be controlled. Outer surfaces of metal containments are either exposed directly to the reactor shield building environment, in contact with compressible filler material that separates the steel shell from the concrete reactor shield building, or embedded in the basemat concrete. For reinforced and post-tensioned concrete containments, outer surfaces of the pressure boundary are in direct contact with hardened concrete that protects the carbon steel liner and other metallic components from exposure to the natural environment and provides the necessary structural support.

Carbon steel shells, anchors, and concrete containment liners that are embedded in portland cement concrete are normally exposed to a high pH environment that ranges from about 12.5 to 13. This environment promotes the formation of a passive iron oxide film that tends to inhibit corrosion. However, even in this high pH environment, chloride ions that penetrate the concrete can destroy the passive film on the steel and produce corrosion. Potential sources of chloride ion contamination include seawater for plants affected by ocean environments and ground water contaminated with chloride ions that permeates through the concrete to the level of the embedded carbon steel components. Water intrusion between the carbon steel shell of metal containments and the adjacent concrete can also produce corrosion (Ref. 2.46). For this reason, caulking, flashing, and sealants are provided at concrete-to-steel interfaces to restrict access of moisture to steel surfaces in contact with concrete. In some metal containments, a sand pocket is located at the concrete-to-steel interface to reduce stress concentrations. These sand pockets are connected to drains that keep excess moisture from accumulating near the carbon steel shell. When the drains function properly, corrosion of the shell is usually not significant. However, when the drains fail or the water in not promptly removed, significant thinning of the shell can occur as a result of general or localized corrosion. In some BWR Mark I containments, galvanized steel plates cover the sand pockets and prevent moisture from entering these potentially vulnerable areas.

The distance between the metal containment shell and the reactor shield building varies from one plant to another. In BWR Mark III and PWR plants with cylindrical containments, there is a large annular space between the steel shell and the reactor shield building. This space, which can be as large as 1.8 meters (six feet), allows access to the outer surface of the containment for direct inspection and maintenance. The annular space between the steel shell and the reactor shield building in BWR Mark I and Mark II plants is much smaller and in some cases impossible to inspect or maintain. During construction of the reactor shield building in these plants, a

compressible filler material was placed against the steel shell to form a permanent 51- to 76-mm (2- to 3-in.) gap between the steel shell and the concrete shield wall. The gap was sized to accommodate differences in thermal expansion and contraction between the concrete and the steel shell and to permit unrestricted deformation" during design-basis accidents. In some plants, the filler material was removed after construction, but in others it was left in place. Although water is not usually present in these gaps, the upper regions of most BWR drywells are flooded during refueling causing cycles of wetting and drying in these areas. In addition, leaks from failed penetration seals, piping gaskets, and bellows expansion joints have introduced water into the gap areas creating potentially corrosive environments. In plants where the compressible filler material has not been removed, water can become trapped against the steel shell and cause corrosion. Contaminants leached from the filler materials, can accelerate the corrosion process (Ref. 2.44). Water that eventually flows through the gap can end up accumulating m the sand pocket creating another potentially corrosive situation.

2.4 MAINTENANCE ACTIVITIES

Maintenance and repair activities are usually performed to offset the effects of aging and deterioration. These activities. are occasionally required to correct deficiencies that were not anticipated in the original design, but mostly they are performed to mitigate the effects of degradation or to prevent future failures. Based on past operating experience, maintenance activities typically involve repair or replacement of seals, gaskets, coatings, and bellows expansion joints, but grinding and welding are occasionally required to repair surface defects or corrosion damage.

Caulking, sealants, elastomeric seals, and gaskets are used in containment applications to make fluid-tight joints between components. Over time, these materials become brittle or resinous and lose their elastic properties. This effect is time-dependent and irreversible. Environmental conditions and material. formulation influence the deterioration rate, but periodic replacement is usually required to assure continuous leaktight integrity. Occasionally, seals or gaskets fail in service. These failures can disrupt operations and often require corrective actions to restore leak-tight integrity. Fluids that leak from faulty joints can create additional maintenance problems particularly when the fluids are corrosive to pressure boundary components.

Paints and other protective coatings are applied to carbon steel surfaces to enhance their corrosion resistance by providing a physical barrier between the steel and the surrounding environment. The integrity of the coating influences its ability to resist corrosion. In order to assure satisfactory long-term performance, periodic in-service inspection and maintenance of coated surfaces is required to detect coating degradation and to repair physical damage. Coating degradation can occur as a result of exposure to high-temperature and high-humidity environments, radiation, condensation, and immersion in water or other chemical "solutions. Chipping, flaking, gouging, abrasion, cracking, pin holes, and wear can also influence coating performance in localized areas and lead to corrosion of the base metal. In-service inspection is an important part of coating maintenance because aging effects have not yet been quantified (Ref. 2.44). Unfortunately, not all surfaces of the. containment are accessible for coating inspection and maintenance, but under water inspection and repair of deteriorated coatings and base metal is feasible (Ref. 2.47).

Bellows expansion joints are intended to be maintenance-free components, but occasionally maintenance is required when in-service inspection reveals physical damage or when leaks are detected by a pressure test. Surface defects such as cracks, dents, and gouges that can affect bellows performance are repaired whenever possible, but defective bellows are usually replaced. Because stainless steel bellows.-expansion joints are susceptible to stress-corrosion cracking, care should be exercised when solutions that contain chlorides, fluorides, or sulfides are used in the vicinity of the bellows.

Maintenance activities that involve repair or replacement of containment pressure boundary components must comply with requirements in Section XI, Division 1, Subsection IWA of the Code (Ref. 2.48). These rules address examination, inspection, and pressure testing of weld repairs, defect removal, and installation of replacements.

2.5 LEAKAGE RATE TESTING

Regulations for preservice and subsequent periodic containment leakage rate testing are provided in 10 CFR 50, Appendix J (Ref. 2.49 and 2.50). This regulation contains requirements pertaining to Type A, B, and C leakage rate tests that must be performed by each licensee as a condition of their operating license. Type A tests are designed to measure the overall leakage rate of the entire containment system. The terms "Type A test," "integrated leak rate test," and "ILRT" are often used interchangeably to refer to a Type A leakage rate test. Type B tests are conducted to detect local leaks and to measure leakage rates across penetrations with flexible metal seals, bellows expansion joints, airlock door seals, doors and penetrations with resilient seals or gaskets, and other components. All Type B testing is performed by local pneumatic pressurization of the penetration. Type C tests measure isolation valve leakage rates. All Type C testing is performed by local pressurization. The purpose of these tests is to periodically verify that leakage through the containment system and pressure-retaining components does not exceed allowable leakage rate values specified in the plant technical specifications and to ensure that the integrity of the containment structure is maintained during its service life.

In September 1995, the NRC amended Appendix J (60 FR 49495) to provide a performance-based option for leakage rate testing as an alternative to the existing prescriptive requirements (Ref. 2.50). The amendment is aimed at improving the focus of the body of regulations by eliminating prescriptive requirements that are marginal to safety and by providing licensees greater flexibility for cost-effective implementation methods for regulatory safety objectives. Now that Appendix J has been amended, either Option A-Prescriptive Requirements or Option B—Performance-Based Requirements can be chosen by a licensee to meet the requirements of Appendix J.

2.5.1 Option A-Prescriptive Requirements

According to Option A requirements, Type A, B, and C leakage rate tests must be performed at prescribed time intervals without regard for past operations or performance history. Discussions contained in Appendix J about test frequency, leakage rate acceptance criteria, test methodology, and reporting requirements for each type of test are briefly summarized below.

Type A tests are designed to measure the overall leakage rate of the entire containment system at an internal pressure that is related to the design basis accident. Three Type A tests must be conducted at approximately equal time intervals during each IO-year service period. The maximum allowable leakage rate (La) for the containment system is specified in the plant technical specifications, but the acceptable leakage rate for a Type A test may not exceed 0.75 La. A general inspection of accessible interior and exterior surfaces of the containment structure and components must be performed prior to each Type A test. The purpose of the inspections, which are usually based on visual observations, is to detect any evidence of structural deterioration that could adversely affect containment structural capacity or leaktight integrity. If structural deterioration is detected, corrective actions must be taken before the Type A test can be conducted.

Type B tests are conducted to detect local leaks and to measure leakage rates across penetrations with flexible metal seals, bellows expansion joints, airlock door seals, doors and penetrations with resilient seals or gaskets, and other components. Except for airlocks, these tests are

conducted during the time the reactor is shutdown for refueling or at other convenient intervals, but in no case at intervals greater than two years. Airlocks must be tested at least once every six months or at more frequent intervals depending on usage. The test pressure must not be less than the pressure associated with the design basis accident

Type C tests measure isolation valve leakage rates. These tests are conducted each time the reactor is shutdown for refueling, but in no case at intervals greater than two years. The test pressure must not be. less than the pressure associated with the design basis accident. Combined allowable leakage for all penetrations and valves subject to Type B and C tests is 0.60 La.

A summary technical report containing leakage rate test results must be prepared and submitted to the NRC for each periodic test. The report must include Type A, B, and C test results, an analysis and interpretation of the Type A test results, and a summary analysis of periodic Type B and C tests that were performed since the last Type A test. A separate summary report must also be provided if any Type A, B, or C test fails to meet the acceptance criteria.

2.5.2 Option B—Performance-Based Requirements

Now that Appendix J has been amended (Ref. 2.50), licensees may voluntarily comply with Option B requirements rather than continue using established leakage rate test schedules. Option B allows licensees with good integrated leak rate test performance history to reduce the Type A testing frequency from three tests in 10 years to one test in 10 years. For Type B and C tests, Option B allows licensees to reduce testing frequency on a plant-specific basis based on the operating experience for each component and establish controls to. ensure continued performance during the extended testing interval. The NRC position on performance-based containment leak testing is discussed in Regulatory Guide 1.163 (Ref. 2.5 1). Methods considered acceptable to the NRC staff for complying with the provisions of Option B are provided in guidance documentation (Ref. 2.52) prepared by the Nuclear Energy Institute (NEI).

The NEI document presents an industry guideline for implementing the performance-based option and contains an approach that includes continued assurance of the leakage integrity of the containment without adversely affecting public health and safety, licensee flexibility to implement cost-effective testing methods, a framework to acknowledge good performance, and utilization of risk and performance-based methods. The guideline delineates the basis for a performance-based approach for determining Type A, B, and C containment leakage rate surveillance testing frequencies using industry performance data, plant-specific performance data, and risk insights. It does not address how to perform the tests because these. details can be found. in existing documents (Ref. 2.53). Licensees may elect to use other suitable methods or. approaches to comply with Option B, but they must obtain NRC approval prior to implementation. However, a general inspection of accessible interior and exterior surfaces of the containment structure and components must be performed prior to each Type A test and during two other refueling outages before the next Type A test if the interval for the Type A test has been extended to 10 years (Ref. 2.51).

2.6 INSPECTION REQUIREMENTS IN SUBSECTION IWE

Preset-vice and in-service inspection requirements for metal and concrete containment pressure boundaries and rules for containment pressure testing are provided in Section XI, Division 1, Subsection IWE of the Code (Refs. 2.54 and 2.55). This consensus standard addresses examination of accessible metal, surfaces; seals, gaskets, and moisture barriers; dissimilar metal welds; and pressure-retaining bolting. Requirements for system pressure testing and criteria for establishing inspection programs and pressure test schedules-are also included. The inspections are intended to detect problems that could adversely affect the structural capacity of the containment and to periodically verify its leaktight integrity. Although preservice and in-service inspection

requirements have been incorporated into Section XI of the Code, they are not currently being imposed upon licensees because Subsection IWE has not yet been approved by the NRC.

2.6.1 Containment Surfaces

Containment surface inspection requirements apply to metal containment pressure-retaining components and their integral attachments and to metallic shell and penetration liners of concrete containments. Areas requiring inspection include base metal and pressure-retaining weld surfaces that are accessible for either direct or remote visual examination. Surfaces that do not generally require in-service inspection include inaccessible portions of the containment vessel and parts that are embedded in concrete. Inspection requirements for piping, pumps, and valves that complete the pressure boundary are provided elsewhere in Section XI.

Rules for containment surface inspection are intended to address the general inspection requirements specified in 10 CFR 50, Appendix J (Ref. 2.49 and 2.50) and to provide requirements for periodic visual examinations of weld and base metal surfaces. According to the rules, containment surfaces must be inspected three times in a IO-year period. Although an exact inspection schedule is not prescribed, the inspections can be performed during times when the plant is shutdown for refueling or maintenance. Rules pertaining specifically to general visual examinations; examinations of coated, non-coated, and weld surfaces; and containment surfaces requiring augmented examinations are provided in Subsection IWE and summarixed below.

General Visual Examinations

A general visual examination of all accessible containment weld and base metal surfaces (not including surface areas that are submerged or insulated) is required prior to each Type A leakage rate test or during two other refueling outages before the next Type A test if the interval for the Type A test has been extended to 10 years (Ref. 2.51). The examination is performed either directly or remotely by an examiner with visual acuity sufficient to detect evidence of degradation that could adversely affect either the containment structural capacity or leaktight integrity. Conditions considered suspect are required to be further evaluated, repaired, or replaced before the Type A leakage rate test can be performed. Requirements for leakage rate testing are provided in 10 CFR 50, Appendix J (Ref. 2.49 and 2.50) and briefly summarized in Sect. 2.5.

Coated. Non-Coated. and Weld Surface Examinations

Detailed inspections of specific containment surface areas and pressure-retaining welds are required in conjunction with the general visual examination. These inspections are conducted by direct visual examination from a distance of 1.22 m (48 in.) or less. Areas requiring periodic examination from at least one side of the vessel are listed in Table 2.5. In areas that are painted or coated, evidence of flaking, blistering, peeling, discoloration, and other signs of distress may be considered suspect and could require further evaluation, repair, or replacement. In areas that are not coated or painted, evidence of cracking, discoloration, wear, pitting, excessive corrosion, arc strikes, gouges, surface discontinuities, dents, and other signs of surface irregularities may also require further evaluation, repair, or replacement.

When surface flaws or suspect areas requiring further evaluation are detected, supplemental surface or volumetric nondestructive examinations may be required to determine the character of the flaw or to measure the extent of degradation. Magnetic particle and liquid penetrant are two surface examination techniques that could be used to establish the size, shape, and orientation of flaws. Radiographic, ultrasonic, and eddy current are three volumetric examination techniques that are commonly used to measure the extent of subsurface degradation. Additional information about these and other nondestructive examination and inspection techniques is provided in Sect. 4.2.

Decisions to accept, repair, or replace defective- areas are often based on comparisons between current nondestructive examination results and "recorded results from preservice and prior in-service examinations. Areas that have experienced change but are considered acceptable can be placed back into service without repair or replacement. However, the nondestructive examination results must be recorded for use in future evaluations, and the defective areas must be periodically reexamined until the area remains essentially unchanged for three consecutive inspection periods.

Containment Surfaces Reauirine Augmented Examinations

Surface areas likely to experience accelerated degradation and aging require augmented examinations. These areas are specifically identified in the inspection program document prepared by the licensee and may include interior and exterior containment surfaces such as those identified in Table 2.6 (Refs. 2.54, 2.56, 2.57, 2.58, and 2.59). Coated and uncoated areas requiring augmented examination are visually examined for evidence of coating degradation or surface flaws. Areas requiring further evaluation are then inspected using supplemental surface or volumetric examination techniques.

Examinations that reveal material loss exceeding 10 percent of the nominal containment wall thickness must be documented, evaluated, and then either accepted, repaired, or replaced. Flaws or degraded areas that are evaluated and considered nonstructural in nature or have. no effect on the structural integrity of the containment can be considered acceptable for continued service without repair or replacement. However, areas that contain these flaws or degradation must be periodically reexamined until the area remains essentially unchanged for three consecutive inspection periods.

2.6.2 Seals, Gaskets, and Moisture Barriers

Containment seals, gaskets, and accessible surfaces of moisture barriers are required to be visually examined during each in-service inspection to detect wear, damage, erosion, tear, surface cracks, or other defects that could affect leaktight integrity. Seals and gaskets that are used to prevent leakage through airlocks, hatches, and other devices tie required to be examined over their entire length. However, disassembly of sealed or gasketed connections is not required just to provide access for inspection. Surfaces of containment moisture barriers include flashing, caulking, and other sealants must be inspected if they are accessible. Moisture barriers, which may be located on the inside or outside of the containment, are used at concrete-to-metal interfaces to prevent intrusion of moisture between the steel shell or liner and the concrete. Items considered defective must either be repaired or replaced.

'2 . 6.3 Dissimilar Metal Welds

Surfaces of pressure-retaining dissimilar metal welds subject to cyclic loads and thermal stresses during normal plant operations are required to be visually examined during each in-service inspection. Dissimilar metal welds includethose between carbon or low-alloy steels and high-alloy steels, carbon or low-alloy steels and high nickel alloys, and high-alloy steels and high nickel alloys. The examination area includes the weld metal and the base metal for 12.7 mm (0.5 in.) beyond the edge of the weld. Surface examinations are performed to detect planar flaws, but during any particular in-service inspection, only 50 percent of the dissimilar metal welds require inspection. Allowable flaw sizes are provided in Section XI, Division 1, Subsection IWB of the Code (Ref. 2.60).

2.6.4 Pressure-Retaining Bolting

Pressure-retaining bolted connections are required to be examined and tested during each in-service inspection. Surfaces of bolts, studs, nuts, bushings, washers, and threads in base metal

and flange ligaments must be visually inspected for defects that could cause the connection to violate either leaktight or structural integrity. However, disassembly of the connection is not required just to provide access for inspection. Items considered defective must be replaced.

Bolt torque or tension testing is also required during the inspection but only for bolted connections that were not disassembled and reassembled during the inspection interval. Either bolt torque or bolt tension are required to be within limits specified in the original design documents. When no limits have been specified, acceptable bolt torque or bolt tension limits must be established and used.

2.6.5 System Pressure Tests

Containment system pressure testing requirements are provided in Subsection IWE. These requirements are essentially the same as those provided in 10 CFR 50, Appendix J (Ref. 2.49 and 2.50) for Type A and Type B leakage rate testing. Requirements for Type C pressure testing of isolation values are not included because these components are not considered an integral part of the containment pressure vessel system. A description of Type A and Type B leakage rate testing is provided in Sect. 2.5.

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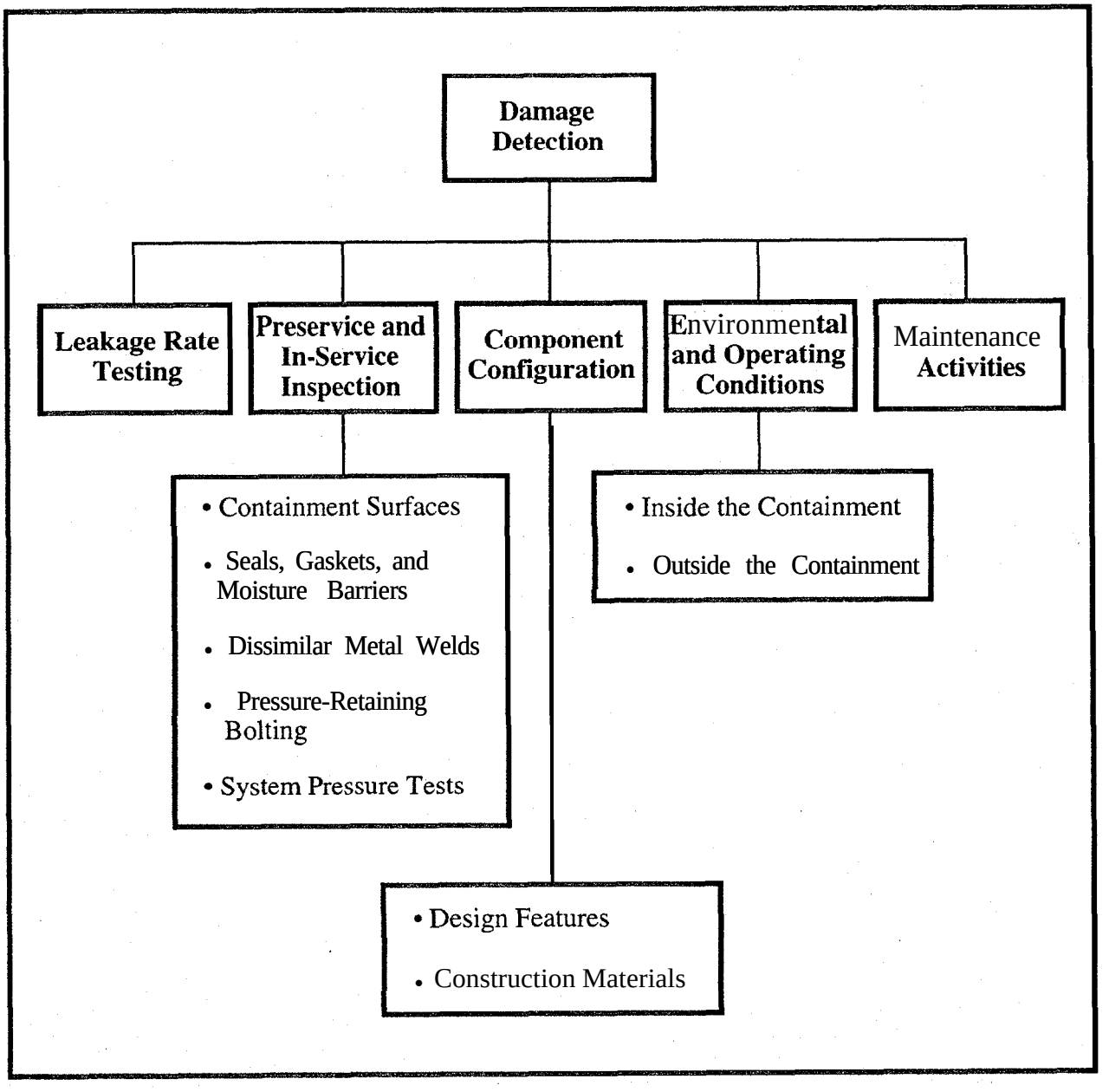

Fig. 2.1 Damage detection parameters.

Table 2.1 Instances of containment pressure boundary component degradation at commercial nuclear power plants in the United States.

Plant Designation (Occurrence Date) Plant Type (Source)	Containment Description (No. of Similar Plants)	Degradation Description	Detection Method
Vermont Yankee (1978) BWR (Ref. 2.1)	Mark I Steel drywell and wetwell (22)	Surface cracks in the overlay weld to torus base metal heat-affected zone	Visual examination (As part of modifications to restore the originally intended design safety margins)
Hatch 2 (1984) BWR (Refs. 2.2, 2.3, and 2.6)	Mark I Steel drywell and wetwell (22)	Through-wall cracks around containment vent headers within the containment torus (Brittle fracture caused by injection of cold nitrogen into torus during inerting)	Visual examination of torus interior
Hatch 1 (1985) BWR (Ref. 2.6)	Mark I Steel drywell and wetwell (22)	Through-wall crack in nitrogen inerting and purge line (Brittle fracture caused by injection of cold nitrogen during inerting)	In-service inspection testing using magnetic particle inspection method
Monticello (1986) BWR (Ref. 2.56)	Mark I Steel drywell and wetwell (22)	Polysulfide seal at the concrete-to-shell interface became brittle allowing moisture to reach the steel shell	Visual examination (A small portion of the drywell shell was excavated as a part of a life extension study)
Dresden 3 (1986) BWR (Ref. 2.7)	Mark I Steel drywell and wetwell (22)	Coating degradation due to exposure to fire with peak metal temperatures of 260°C (500°F) and general corrosion of metal shell by water used to extinguish fire	Visual examination (Polyurethane between the drywell shell and concrete shield wall was ignited by arc-air cutting activities producing smoke and heat)
Oyster Creek (1986) BWR (Refs. 2.8, 2.22, and 2.35)	Mark I Steel drywell and wetwell (22)	Defective gasket at the refueling pool allowed water to eventually reach the sand cushion region causing drywell shell corrosion	Visual examination of uncoated areas and ultrasonic inspection
Fitzpatrick (1987) BWR (Refs. 2.56 and 2.29)	Mark I Steel drywell and wetwell (22)	Degradation of torus coating with associated pitting	Visual examination of uncoated areas and ultrasonic inspection (Technical specification surveillance performed during outage)
Millstone 1 (1987) BWR (Ref. 2.29)	Mark I Steel drywell and wetwell (22)	Degradation of torus coating	Visual examination of uncoated areas and ultrasonic inspection (The torus had been drained for modifications)

Table 2.1 (cont.) Instances of containment pressure boundary component degradation at commercial nuclear power plants in the United States.

Plant Designation (Occurrence Date) Plant Type (Source)	Containment Description (No. of Similar Plants)	Degradation Description	Detection Method
Oyster Creek (1987) BWR (Ref. 2.29)	Mark I Steel drywell and wetwell (22)	Degradation of torus coating with associated pitting	Visual examination of uncoated areas and ultrasonic inspection
Brunswick 1 (1987) BWR (Ref. 2.18)	Mark I Reinforced concrete with steel liner (9)	Corrosion of steel liner	General visual examination of coated areas
Nine Mile Point 1 (1988) BWR (Ref. 2.9)	Mark I Steel drywell and wetwell (22)	Corrosion of uncoated torus surfaces	Visual examination of uncoated areas and ultrasonic inspection
Pilgrim (1988) BWR (Ref. 2.29)	Mark I Steel drywell and wetwell (22)	Degradation of torus coating	Visual examination of uncoated areas and ultrasonic inspection (Licensee inspection as a result of occurrences at similar plants)
Brunswick 2 (1988) BWR (Ref. 2.18)	Mark I Reinforced concrete with steel liner (9)	Corrosion of steel liner	General visual examination of coated areas
Dresden 2 (1988) BWR (Ref. 2.23)	Mark I Steel drywell and wetwell (22)	Coating, electrical cable, and valve operator component degradation due to excessive operating temperatures	Visual examination of uncoated areas and ultrasonic inspection (Ventilation hatches in the drywell refueling bulkhead inadvertently left closed)
Hatch 1 and 2 (1989) BWR (Ref. 2.11)	Mark I Steel drywell and wetwell (22)	Bent anchor bolts in torus supports (due to weld induced radial shrinkage)	Visual examination
McGuire 2 (1989) PWR (Ref. 2.15)	Ice Condenser Steel cylinder (16)	Corrosion on outside of steel cylinder in the annular region at the intersection with the concrete floor	General visual examination prior to Type A leakage rate test
McGuire 1 (1989) PWR (Ref. 2.15)	Ice Condenser Steel cylinder (16)	Corrosion on outside of steel cylinder in the annular region at the intersection with the concrete floor	General visual examination (Inspection initiated as a result of corrosion detected at McGuire 2)

Table 2.1 (cont.) Instances of containment pressure boundary component degradation at commercial nuclear power plants in the United States.

Plant Designation (Occurrence Date) Plant Type (Source)	Containment Description (No. of Similar Plants)	Degradation Description	Detection Method
Catawba 1 (1989) PWR (Refs. 2.15 and 2.25)	Ice Condenser Steel cylinder (16)	Corrosion on outside of steel cylinder in the annular region	General visual examination (Inspection initiated as a result of corrosion detected at McGuire 2)
Catawba 2 (1989) PWR (Ref. 2.15)	Ice Condenser Steel cylinder (16)	Corrosion on outside of steel cylinder in the annular region	General visual examination (Inspection initiated as a result of corrosion detected at McGuire 2)
McGuire 1 (1990) PWR (Ref. 2.24)	Ice Condenser Steel cylinder (16)	Corrosion on outside of steel cylinder in the annular region	General visual examination (Follow-up inspection by licensee)
McGuire 1 (1990) PWR (Ref. 2.16, 2.24 and 2.26)	Ice Condenser Steel cylinder (16)	Corrosion on inside surface of coated containment shell under the ice condenser and between the floors near the cork filler material	Visual examination and ultrasonic inspection (Degradation possibly caused by moisture from the ice condenser or condensation)
Quad Cities 1 (1991) BWR (Refs. 2.30, 2.31, and 2.17)	Mark I Steel drywell and wetwell (22)	Two-ply containment penetration bellows leaked due to transgranular stress-corrosion cracking	General visual examination (Excessive leakage detected)
Quad Cities 2 (1991) BWR (Refs. 2.30 and 2.3 1)	Mark I Steel drywell and wetwell (22)	Two-ply containment penetration bellows leaked due to transgranular stress-corrosion cracking	General visual examination (Excessive leakage detected)
Dresden 3 (1991) BWR (Ref. 2.31)	Mark I Steel drywell and wetwell (22)	Two-ply containment penetration bellows leaked due to transgranular stress-corrosion cracking	General visual examination (Excessive leakage detected)
Point Beach 2 (1992) PWR (Ref. 2.27)	Post-tensioned concrete cylinder with steel liner (41)	Liner plate separated from concrete	General visual examination
H. B. Robinson (1992) PWR (Ref. 2.27)	Post-tensioned concrete cylinder with steel liner (41)	Degradation of liner coating	General visual examination
Cooper (1992) BWR (Ref. 2.27)	Mark I Steel drywell and wetwell (22)	Corrosion of interior torus surfaces and corrosion stains on exterior torus surface in one area	General visual examination

Table 2.1 (cont.) Instances of containment pressure boundary component degradation at commercial nuclear power plants in the United States.

Plant Designation (Occurrence Date) Plant Type (Source)	Containment Description (No. of Similar Plants)	Degradation Description	Detection Method
Beaver Valley 1 (1992) PWR (Refs. 2.27 and 2.33)	Subatmospheric Reinforced concrete cylinder with steel liner (7)	Corrosion of steel liner, degradation of liner coating, and instances of liner bulging	General visual examination prior to Type A leakage rate test
Salem 2 (1993) PWR (Ref. 2.32)	Reinforced concrete cylinder with steel liner (11)	Corrosion of steel liner	General visual examination prior to Type A leakage rate test
Sequoyah 1 (1993) PWR (Ref. 2.20)	Ice Condenser Steel cylinder with concrete shield building (8)	Degradation of moisture barriers resulting in corrosion of the steel shell	General visual examination and visual examination of coated areas
Sequoyah 2 (1993) PWR (Ref. 2.20)	Ice Condenser Steel cylinder with concrete shield building (8)	Degradation of moisture barriers resulting in corrosion of the steel shell	General visual examination and visual examination of coated areas
Brunswick 2 (1993) BWR (Refs. 2.18 and 2.19)	Mark I Reinforced concrete with steel liner (9)	Corrosion of steel liner	General visual examination and visual examination of coated areas (Follow-up inspection based on conditions noted in 1988)
Brunswick 1 (1993) BWR (Ref. 2.19)	Mark I Reinforced concrete with steel liner (9)	Corrosion of steel liner	General visual examination and visual examination of coated areas (Inspection initiated as a result of corrosion detected at Brunswick 2)
McGuire 1 (1993) PWR (Ref. 2.34)	Ice Condenser Steel cylinder (16)	Main steam isolation line bellows leakage	Leakage testing conducted on bellows following successful Type A leakage rate test
Braidwood 1 (1994) PWR (Ref. 2.21)	Post-tensioned concrete cylinder with steel liner (41)	Liner leakage detected but not located	Type A leakage rate test

Table 2.2 Summary of metal and concrete containment pressure boundary component degradation occurrences.

Containment Type	Degradation Description	Affected Component	Number of Similar Occurrences
Metal	Corrosion	Steel shell or other pressure-retaining component	12
Metal	Cracking	Bellows	4
Metal	Coating Degradation in High-Temperature Environment	Steel shell	2
Metal	Coating Degradation in Aqueous Environment	Steel shell (torus)	4
Metal	Cracking	Steel shell (torus)	1
Metal	Brittle Fracture	Vent header (inside torus) or nitrogen purge line	2
Metal	Torus Anchor Bolt Deformation	Anchor bolts (torus)	1
Concrete	Corrosion	Steel liner	6
Concrete	Coating Degradation	Steel liner	2
Concrete	Liner Plate Separation	Steel liner	2
Concrete	Liner Leakage	Steel liner	1

Table 2.3 Summary of chemical requirements for steel plates conforming to ASTM A 5 16/A 5 16M-86 material specification requirements.

Chemical Composition, percent	Grade 55 [Grade 380]	Grade 60 [Grade 415]	Grade 65 [Grade 450]	Grade 70 [Grade 485]
Carbon, max.:				
12.5 mm and under (0.5) and under	0.18	0.21	0.24	0.27
12.5 to 50 mm (0.5 to 2 in.)	0.20	0.23	0.26	0.28
50 to 100 mm (2 to 4 in.)	0.22	0.25	0.28	0.30
100 to 200 mm (4 to 8 in.)	0.24	0.27	0.29	0.31
over 200 mm (over 4 in.)	0.26	0.27	0.29	0.31
Manganese:				
12.5 mm and under (0.5) and under:				
Heat analysis	0.60-0.90	0.60-0.90	0.85-1 .20	0.85-1.20
Product analysis	0.55-0.98	0.55-0.98	0.79- 1.30	0.79-1.30
Over (12.5 mm (0.5 in.):				
Heat analysis	0.60-1.20	0.85-1.20	0.85-1 .20	0.85-1 .20
Product analysis	0.55-1 .30	0.79-1.30	0.79- 1.30	0.79-1.30
Phosphorus, max.:	0.035	0.035	0.035	0.035
Sulfur, max.:	0.04	0.04	0.04	0.04
Silicon:				
Heat analysis	0.15-0.40	0.15-0.40	0.15-0.40	0.15-0.40
Product analysis	0.13-0.45	0.13-0.45	0.13-0.45	0.13-0.45

Source: Ref. 2.42

Table 2.4 Summary of tensile requirements for steel plates conforming to ASTM A 516/A 516M-86 material specification requirements.

Tensile Requirement	Grade 55 [Grade 380]	Grade 60 [Grade 415]	Grade 65 [Grade 450]	Grade 70 [Grade 485]
Tensile strength, MPa (ksi)	380-515 (55-75)	415-550 (60-80)	450-585 (65-85)	485-620 (70-90)
Yield strength, min., MPa (ksi)	205 (30)	220 (32)	240 (35)	260 (38)
Min. elongation in 200 mm (8 in.), percent	23	21	19	17
Min. elongation in 50 mm (2 in.), percent	27	25	23	21

Source: Ref. 2.42

Table 2.5 Accessible containment surface areas and pressure-retaining welds that require visual examination.

- Structures that are parts of reinforcing structure, such as stiffening rings, manhole frames, and reinforcement around openings
- Wetted surfaces of submerged areas (required to satisfy minimum surface area requirements)
- Portions of insulated surface areas (required to satisfy minimum surface area requirements)
- Flow channeling devices within containment vessels
- Attachment welds between structural attachments and the pressure-retaining boundary or reinforcing structure
- Containment penetration welds subject to cyclic loads and thermal stress during normal plant operation
  - Longitudinal welds
  - Circumferential welds
  - Flued head and bellows seal circumferential welds joined to the penetration
- Flange welds
- Nozzle-to-shell welds

Source: Ref. 2.54

Table 2.6 Interior and exterior containment surface areas that could experience accelerated degradation and aging.

Environmental or Operating Conditions	Typical Areas	Likely Locations
Areas subject to accelerated corrosion with no or minimal corrosion allowance or Areas where the absence or repeated loss of protective coatings has resulted in substantial corrosion or pitting	Areas exposed to standing water Areas exposed to repeated wetting and drying Areas where persistent leakage has occurred Areas subject to microbiological attack Areas with geometries that permit water accumulation	Penetration sleeves and bellows Surfaces wetted during refueling Concrete-to-steel shell or liner interface Shell regions embedded in concrete including areas shielded by diaphragm floors Leak chase channels Drain areas including sand pocket regions Sump liners Interior surfaces of BWR Mark I and II suppression pools Exterior surfaces of BWR Mark I and II drywells Emergency core cooling system suction intake at the bottom of BWR suppression pool Dissimilar metal welds
Areas subject to excessive wear from abrasion or erosion	Areas where mechanical wear, abrasion, or erosion cause a loss of protective coatings, deformations, or material loss Areas that experience frequent vibration	Surfaces subject to substantial traffic Sliding pads or supports (baseplates of BWR Mark I suppression chamber support columns) Pins or clevises Shear lugs Seismic restraints Surfaces exposed to water jets from testing operations Safety relief valve discharge areas BWR drywell head, vent system supports, and downcomers and bracing Personnel airlocks, equipment hatches, and control rod drive (CRD) hatches

Source: Refs. 2.54, 2.56, 2.57, 2.58, and 2.59

3. DAMAGE CLASSIFICATION AND ROOT-CAUSE DETERMINATION

3.1 SERVICE-RELATED DEGRADATION

Rules for design, fabrication, examination, testing, and inspection of Class MC (metal) and Class CC (concrete) containments are provided in Section III of the ASME Boiler .and Pressure Vessel Code (Refs. 3.1 and 3.2). The Code even recognizes that service-related component degradation is possible and includes methods for calculating the required minimum thickness of pressure-retaining components. However, rules for assessing effects of in-service degradation are outside its scope. According to the Code, it is the Owner's responsible to select materials that are suitable for the service conditions and to increase the minimum required thickness of the base metal to offset material thinning due to corrosion, erosion, mechanical abrasion, or other environmental effects.

Service-related degradation can affect the ability of a containment to perform satisfactorily in the unlikely event of a severe accident by reducing its structural capacity or jeopardizing its leak-tight integrity. Degradation is considered to be any phenomenon that decreases the load-carrying capacity of a pressure-retaining component, limits its ability to contain a fluid medium, or reduces its service life. The root cause for component degradation can generally be linked to a design or construction problem, inappropriate material application, a base-metal flaw*, or an excessively severe service condition. Determining what caused the degradation can help identify the type of damage that has occurred and define actions to be taken to reduce or eliminate further deterioration.

The significance of component degradation can be assessed by comparing its in-service condition to its condition immediately after construction or following a repair. Condition assessments require knowledge about potential degradation mechanisms and an understanding of environmental conditions that can promote deterioration. The following discussions focus on two important aspects of the "condition assessment process — damage classification and root-cause determination.

3.2 TYPES OF DAMAGE

Component degradation can be classified as either material or physical damage. Damage occurs when the microstructure of a material is modified by exposure to a severe environment or when the geometry of a component is altered. Determining whether material or physical damage has occurred often requires information about the service conditions to which the component was exposed and an understanding of the degradation mechanisms that could cause such damage. Figure 3.1 lists the potential degradation mechanisms associated with each damage category. Additional information about material and physical damage is presented in the next two sections.

3.3 MATERIAL DAMAGE

Material damage occurs when the microstructure of a metal is modified causing changes in its mechanical properties. When produced under controlled conditions, changes in the microstructure of a metal can have a beneficial effect. For example, metals such as high-carbon steels and certain alloy steels are often heat treated to produce a specified hardness. However, when the exposure conditions are not controlled, such as in a fire, the mechanical properties (e.g., tensile

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* Flaws are imperfections or unintentional discontinuities that are detectable by nondestructive examination (Ref. 3.3). A defect is a flaw, discontinuity, or group of discontinuities whose indications do not meet specified acceptance criteria (Ref. 3.4).

and yield strength) of the affected metal can degrade to such an extent that the component is no longer suitable for its intended use. Degradation mechanisms that can potentially cause material damage to containment steels are listed in Table 3.1.

Indications that material damage has occurred can occasionally be detected by visual examination or other nondestructive inspection techniques. For example, color variations in a metal surface may indicate that a component has been exposed to elevated temperatures (Ref. 3.5), and microscopic examination of a metal section may show differences in microstructure caused by chemical attack. However, the effects of changes in microstructure on mechanical properties can only be determined by testing samples of the affected material. The magnitude of change in a mechanical property value is generally determined by comparing results obtained from specimens subjected to the environmental conditions of interest to results obtained from companion specimens tested under controlled laboratory conditions. Information of this type for containment steels is being collected and assembled at the Structural Materials Information Center (Ref. 3.6).

3.3.1 Low-Temperature Exposure

Steel structures exposed to low temperatures are susceptible to brittle failure that can initiate at flaws and cracks caused by fatigue, arc welding strikes, gouges, or other types of mechanically assisted damage. Because structures cannot be fabricated perfectly, material flaws and minor construction imperfections will always be present. However, chances for brittle failure can be minimized or eliminated by proper material selection and periodic in-service inspection. To ensure safe and reliable operation, critical structural components are generally constructed using steels that exhibit adequate low-temperature fracture toughness. Effects of flaw size and low temperature on mechanical properties and ductility are generally investigated using tensile and fracture toughness testing techniques.

Steels used to construct containment pressure boundary components must comply with the fracture toughness requirements provided in Section III of the Code (Refs. 3.1 and 3.2). These rules, which factor in the nil-ductility transition temperature of the steel (Ref. 3.7) and the lowest temperature that the steel would be expected to experience while the plant is in operation, are used to establish the permissible lowest service metal temperature (LSMT). The fracture toughness requirements in the Code suggest that as long as suitable steels are selected and the temperature of pressure-retaining steel components remains above the LSMT, the fracture toughness will be adequate to ensure safe and reliable operation. The effects of low-temperature on the properties of containment steels is not considered to be a significant containment issue because low-temperature exposure and fracture toughness are addressed during containment design and operation below the LSMT is not expected.

3.3.2 High-Temperature Exposure

Carbon, low-alloy, and stainless steels are used routinely for elevated-temperature structural applications even though strength and elastic properties of these materials change as exposure temperature increases. Suggested maximum operating temperature limits range from about 400 to 540°C (750 to 1,000°F) for carbon steels to about 815°C (1,500°F) for certain stainless steels (Ref. 3.8). Effects of elevated-temperature exposure on the mechanical properties of steels are determined by testing material samples in the laboratory.

Temperature-dependent stress limits and high-temperature design rules for steels permitted for use in construction of containment pressure boundary components are provided in Sections II and III of the Code (Refs. 3.1, 3.2, and 3.9). According to Code rules, the design temperature for metal containments is the maximum containment temperature that can occur while the maximum containment pressure is being applied. Normal upper operating temperatures inside metal containments ranges from 57 to 66°C (135 to 150°F) for BWR Mark I containments and up to 49°C

(120°F) for PWR containments '(Ref. 3.10). Concrete containment liner temperature limits are established by the concrete temperature limits specified in the Code. The Code requires that concrete temperatures remain below 66°C (150°F) during normal plant operations [93°C (200°F) at local areas such as around, penetrations] and never exceed 343°C (650°F) during a pipe failure event. Because elevated temperatures can affect metal properties and influence containment performance, temperature-dependent property values for steels permitted for containment construction are provided in Section II, Part D of the Code (Ref. 3.9).

3.3.3 Metallurgically Influenced Corrosion

Material damage to stainless steels and nickel-based alloys can also be caused by metallurgically influenced corrosion. This type of corrosion alters the chemical composition of the metal and changes its microstructure. Intergranular and dealloying corrosion are two forms of metallurgically influenced corrosion that are affected by alloy chemistry and heat treatment (Ref. 3.8).

Intergranular Corrosion

Intergranular corrosion takes place when the corrosion rate of the grain-boundary areas of an alloy exceeds that of the grain interiors. It initiates on the. surface, and progresses by corroding a narrow path along the grain boundaries of the metal. Differences in composition between the grain boundaries and the interior cause differences in the corrosion rates. As the grain boundaries dissolve, the unaffected grains are undermined and in extreme cases can even fall out leaving loose individual grains. Metals that experience intergranular corrosion exhibit time-dependent weight loss that can accelerate with time. Affected metals may also experience a drop in elongation that can become appreciable before any significant loss of ultimate tensile strength or yield strength can be detected. In severe cases, loss of tensile properties can occur even though only a small volume of metal has corroded. Stainless steels and aluminum alloys are two' types of metals that are most susceptible to intergranular corrosion (Ref. 3.11).

Austenitic and ferritic stainless steels and nickel-based alloys are generally supplied in a heat-treated condition such that they are free of carbide precipitates that are detrimental to corrosion resistance. However, these alloys are susceptible to sensitization from welding, improper heat treatment, and service in the sensitizing temperature range (Ref. 3.8). Because containment pressure boundary components made from these alloys are normally not exposed to solutions such as ferric sulfate, cupric sulfate, and acids that are required to cause intergranular corrosion, material damage due to this type of metallurgically influenced corrosion is not. considered likely.

Deallovine Corrosion

Dealloying is a corrosion process in which one constituent of an alloy is preferentially removed leaving behind an altered residual structure that is less tolerant to flaws and applied loads (Ref. 3.8). The metal in the affected area becomes porous and loses much of its strength, hardness, and ductility. Medium- and high-carbon steels exposed to oxidizing atmospheres or high-temperature hydrogen, and high-nickel alloys in contact with molten salts are susceptible to dealloying corrosion. Dealloying corrosion of containment pressure boundary steels is not considered likely because they are not exposed to molten salts, and oxidizing atmospheres and high-temperature hydrogen gas are not generally present inside BWR and PWR containment vessels.

3.3.4 Hydrogen Embrittlement

Hydrogen influences the behavior and properties of nearly all ferrous alloys, particularly steels in which the yield strength is close to the ultimate strength. For plain carbon steels, combinations of high temperature and low hydrogen pressure, or low temperature and high hydrogen pressure can contribute to hydrogen attack (Ref. 3.12). Even austenitic stainless steels that were

once thought to be immune from hydrogen embrittlement are susceptible (Ref. 3.13). Factors known to contribute to hydrogen-induced damage include temperature, hydrogen pressure, type alloy, heat treatment, surface condition, and strains from cold work (Ref. 3.12). Damage occurs when atomic hydrogen, which is about one third the size of the crystal cube in a metal lattice, diffuses through the metal and either reacts with the iron carbides in the steel to form methane or accumulates at nonmetallic inclusions to form molecular hydrogen. In both cases, tremendous internal pressures are generated causing the metal to split, fissure, or blister.

Cracking or severe loss of ductility caused by the presence of hydrogen in the metal lattice is called hydrogen embrittlement. There are three categories of damage associated with hydrogen embrittlement — hydrogen environmental embrittlement, hydrogen stress cracking, and loss of tensile ductility. Hydrogen environmental embrittlement occurs when steel is deformed in a hydrogen environment and its mechanical properties are degraded. Hydrogen stress cracking occurs when a steel component is stressed in a hydrogen environment and it fails due to brittle fracture. Additional information about hydrogen stress cracking is presented in Sect. 3.4.4. Loss of tensile ductility occurs in steel when it becomes saturated with atomic hydrogen (Ref. 3 .8). Ductility can be restored, without permanent damage, by heating the metal for a short time at 200°C" (400°F) to drive out the hydrogen.

Under normal operating conditions, the atmosphere inside a containment is controlled such that the pressure, temperature, and chemical makeup are nearly constant (Ref. 3.10). However, during certain unlikely events such as a postulated loss-of-coolant accident (LOCA), hydrogen gas can be generated from the chemical reaction of zircaloy with water or as the result of radiolytic decomposition of water (Ref. 3.14). Two other possible sources of hydrogen in a nuclear power plant are from battery charging operations and impressed-current cathodic protection systems, neither of which produce significant amounts of hydrogen except in localized areas. During normal plant operations, hydrogen embrittlement of pressure-retaining steels is not expected to be a serious problem and therefore should not adversely affect containment integrity.

3.3.5 Neutron Irradiation

Properties of steel can be adversely affected by exposure to neutron irradiation. Damage occurs when neutrons displace metal atoms from their normal lattice positions to form interstitials and vacancies. The effects of neutron irradiation, which include volume increase, hardening, and embrittlement, are primarily associated with high-energy neutrons (greater than 0.1 MeV). However, thermal neutrons such as the ones produced in light-water reactors (energies much less than 1 MeV) can also cause irradiation damage to steel components such as the reactor pressure vessel (Ref. 3.13). Compared to steel reactor pressure vessels, containment steel components are much less susceptible to irradiation damage because biological shielding effectively limits exposure of the materials to levels that are considered safe for occupational workers, and end-of-life fluence of containment components is anticipated to be quite small (Ref. 3.10). Even in the unlikely event of a severe accident, irradiation damage to containment steel components is not expected to be significant.

3.4 PHYSICAL DAMAGE

Physical damage occurs when the geometry of a component is altered by the formation of cracks, fissures, or voids, or its dimensions change due to overload, buckling, corrosion, erosion, or formation of other types of surface flaws. Changes in component geometry, such as wall thinning or pitting caused by corrosion, can affect structural capacity by reducing the net section that is available to resist applied loads. In addition, pits that completely penetrate through the component can compromise the leaktight integrity of the containment. Degradation mechanisms that can

potentially cause‘ physical damage to containment pressure boundary components are listed in Fig. 3.1.

Detection of physical damage is routinely accomplished by visual inspection, nondestructive examination, or destructive testing. However, the effects of physical damage on structural capacity or leaktight integrity must be assessed on a case-by-case basis because its significance is a ‘function of the “magnitude of the damage and the location where the damage has occurred. For example, because stresses in a metal containment vessel vary from one location to another, uniform wall thinning over a relatively large area is more significant at locations where tensile stresses are the highest.

3.4.1 General Corrosion

Corrosion is a chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties (Ref. 3.15). General corrosion of steel is degradation that produces uniform thinning and proceeds without appreciahle localized attack. This type of corrosion is characterized by slow, nearly uniform loss of metal thickness over a wide area. Damage caused by general corrosion is relatively easy to detect and quantify because it affects large areas that can usually be seen at arms length (Ref. 3.8). General corrosion begins at an exposed metal surface and progressively alters the geometry of the affected component without changing the chemical composition of the material or its microstructure. Degradation initiates with the formation of a corrosion product layer and continues as long as at least one of the reactants is able to diffuse through the layer and sustain the reaction. The composition and characteristics of the layer can have a significant influence on the corrosion rate.

Figure 3.2 shows curves that represent three types of time-dependent corrosion behavior. Certain oxide films such as those that form on stainless steel and nickel-chromium alloy surfaces exposed to high-temperature air or passive film layers that form at lower temperatures can effectively decrease the rate of general attack by creating a tough, durable coating that serves as a nearly impermeable barrier between the base metal and the service environment. These film layers tend to inhibit corrosion as long as they remain firmly attached to the metal surface and do not crack. ‘Weathering steels including carbon steels that contain a minimum of 0.2-percent copper also exhibits this type of long-term behavior when exposed to atmospheric conditions. Low-alloy steels including most carbon steels exposed to atmospheric conditions and most aqueous environments tend to form porous corrosion product layers that provide almost no protection for the base metal. Corrosion rates for these materials are generally modeled using a linear model (Ref. 3.11) . This model is particularly appropriate when the corrosion product layer forms and breaks down on a regular basis. Metals exposed to extremely hostile environments can corrode at an ever increasing rate. This behavior is generally associated with high-temperature corrosion phenomenon where the corrosion rate increases continuously with time.

The most significant consequence of general corrosion of steels used to construct containment pressure boundary components is loss of section. This type of physical damage can result in reduced load-carrying capacity and possible containment leakage. Significant physical damage to carbon and low-alloy steel fasteners and pressure-retaining components of the primary system has occurred at a number of PWR plants (Refs. 3.16 and 3.17). The damage was attributed to boric acid (H_3BO_3) attack. In a typical situation, as cooling water from the primary system seeped through leaky seals or gaskets, it flashed to steam leaving behind a sludge or paste consisting of dissolved boric acid and lithium hydroxide (LiOH). The boric acid solution, which had a pH of 3 at 93°C (200°F); caused general corrosion or wastage of carbon and low-alloy steel components and contributed to galvanic corrosion of carbon steel components that were welded to dissimilar metals. Although the physical damage caused by general corrosion of containment steels can be significant, this type of corrosion is thought to have no measurable effect on the mechanical prop-

erties of these metals. Specific forms of general corrosion that could potentially affect containment steel components are identified in Table 3.2. The table also describes the likelihood of physical damage to containment pressure boundary components caused by each form of general corrosion.

Atmospheric Corrosion

Atmospheric corrosion is the gradual degradation or alteration of a material by contact with substances such as oxygen, carbon dioxide, water vapor, and sulfur and chlorine compounds that are present in the. atmosphere (Ref. 3.8). This type of corrosion is characterized by uniform thinning and is probably the most common form of general corrosion. Degradation resulting from immersion in a liquid is considered aqueous corrosion and is discussed later in this section.

In the absence of moisture, most metals corrode very slowly at ambient temperatures. However, iron in the presence of oxygen and water is thermodynamically unstable with respect to its oxides. Consequently, carbon steel exposed to atmospheric conditions will corrode, the only question is at what rate. As the relative humidity increases, the corrosion rate increases very slowly until the humidity level reaches a critical value around 70 percent (about 60 percent for iron). At this level, an invisible film of moisture forms on the surface of the metal and the corrosion rate increases significantly. Because atmospheric corrosion is an electrolytic process, only a very thin adsorbed film of water is required to accelerate the degradation. The critical relative humidity value depends on surface conditions such as cleanliness, corrosion product buildup, and the presence of salts or other contaminants that are hygroscopic and can absorb water at a lower relative humidity. When the relative humidity exceeds the critical value, the surface of the metal becomes wet and the corrosion rate increases due to the formation of water pockets or visible layers of water on the surface of the metal. Under these wet conditions,. the corrosion rate is affected by the solubility of the corrosion products. In building applications, atmospheric corrosion of uncoated steel elements often occurs when warm, moist air from inside the building permeates through the walls and ceilings and condenses on the surfaces of colder steel beams, columns, and fasteners.

Temperature, exposure time, and geographic location have an influence on the atmospheric corrosion process. As the metal surface temperature increases, the corrosion rate rises sharply until the surface becomes dry. After the surface dries, the corrosion rate decreases quickly. When the surface is exposed to alternating wetting and drying, the formation of insoluble corrosion products on the surface may increase the corrosion rate during the dry cycle by absorbing moisture and continually wetting the surface of the metal. Although the rate of atmospheric corrosion of steel depends on humidity, temperature, and the levels of sulfate, chloride, and other atmospheric pollutants, it is usually not constant with time and tends to decrease as the length of exposure increases. The geographic location can also affect the rate of atmospheric corrosion. Rural areas often have less atmospheric pollutants than industrial sites, therefore the corrosion rates in these areas are generally slower. Locations near the ocean usually have the highest rates of atmospheric corrosion because the air often contains wind-blown salt particles that can adhere to exposed metal surfaces and enhance the corrosion process.

The presence of alloys in steel also has an influence on the rate of atmospheric corrosion. Copper, nickel, silicon, chromium, and phosphorus in carbon steel are generally found to be beneficial. Atmospheric corrosion of stainless steels and nickel-chromium alloys is extremely mild expect in very severe industrial or marine environments. Permanent solutions for atmospheric corrosion can be achieved by either replacing the material with one that is more corrosion resistant or applying a coating. Organic, inorganic, and metallic coatings have been used effectively to inhibit corrosion. The main function of the coating is to serve as a barrier to water, oxygen, and ions.

Aqueous Corrosion

Corrosion of metals in aqueous environments occurs when two or more electrochemical reactions take place on the-surface causing the metal or alloy to change from a metallic state to a nonmetallic state (Ref. 3.8). Results may be either dissolved species or solid corrosion products. The driving force behind the corrosion process is the change in energy of the system as the metal converts to a lower energy form. A common example of this phenomenon is rusting in which metal (iron) is converted to a nonmetallic corrosion product (rust).

Aqueous corrosion is similar to atmospheric corrosion except the metal surface is continuously immersed in water. The water may vary from extremely pure to chemically treated, or it may contain high concentrations of chlorides such as those found ii brackish or seawater. Stainless steel valves, fasteners, parts, and equipment usually provide excellent service when immersed in fresh water with chloride levels less than about 600 ppm. However, seawater or other types of severely contaminated water, provide very corrosive environments for. carbon, low-alloy, and stainless steel components. Stainless steels-are particularly susceptible to stress-corrosion cracking in-chloride environments and in high-purity neutral-pH water that contains dissolved oxygen such as the recirculating coolant in a BWR. Carbon steel is severely corroded by waters that contain oxygen, but completely resistant in soft, anaerobic water. The resistance of most low-alloy steels to aqueous corrosion is similar to that of carbon steels.

The corrosion rate. of steel submerged in an aqueous solution depends on the temperature, flow rate, pH, and chemistry. In addition, the effect of one variable can be dependent on the magnitude of another. However the relative acidity of the solution is probably the most important factor. The corrosion rate for iron is very large at very low pH (acidic), independent of pH in the neutral range (pH from 5 to 9) where aeration becomes important, decreases with increasing pH, and finally increases again at very high pH (alkaline). When the corrosion rate is governed completely by the elementary process of metal oxidation, the corrosion rate increases exponentially with an increase in temperature. Flow rate affects the corrosion rate when the rate of transfer, of a species between the surface of the metal and the fluid controls the reaction.

Aqueous corrosion of the external surface of a BWR Mark I metal containment shell in the sand-cushion region of the drywell has occurred (Ref. 3.10). The corrosion caused wall thinning and loss of net. section requiring further evaluation. Degradation occurred after water from the refueling pool leaked through defective gaskets and cracks in the stainless steel fuel pool liner into the air gap between the drywell and the concrete shield, through the gap-forming material, and into the sand cushion adjacent to the uncoated metal shell.. The degradation rate was affected by chlorine, 'bromine, and sulfate ions present in the water. Contamination occurred when the water flowed through the gap-forming material. Similar degradation was found by Electricite de France at the bottom of containment liners at four of its 900-MW PWRs (Ref. 3.18). At these plants, significant corrosion of the steel liner occurred when water entered the space between the liner and adjacent concrete inside the containment. The corrosion was so severe at some locations that it penetrated completely through the 6-mm thick steel liner thereby jeopardizing 'leaktight' mtegnty.

Galvanic Corrosion

Galvanic corrosion is accelerated degradation that occurs when a metal or alloy is electrically coupled to a more noble metal in the same electrolyte (Ref. 3.8). The three requirements for galvanic corrosion are (1) materials possessing different surface potentials, (2) a common electrolyte, and (3) a common electrical path. If one or more of these essential requirements is not met, galvanic corrosion will not occur, For example, a mixed metal system that is electrically isolated will not experience galvanic corrosion even when the metals are immersed in a common electrolyte. However, as soon as the metals are electrically coupled, electrons begin flowing and the anodic (less noble) metal begins to corrode.

The driving force behind the flow of electrons is the difference in potential between the two metals. The direction of flow depends on which metal is more active. The more active (less noble) metal becomes anodic and corrosion occurs while the less active (more noble) metal becomes cathodic. Other factors such as area ratios, distance between electrically connected materials, and geometric shapes also affect galvanic corrosion behavior. Galvanic corrosion has been known to occur in dissimilar-metal, butt-welded piping systems that carry an electrolytic solution. The most severe corrosion occurs adjacent to the weld on the anodic member. In mixed-metal systems containing carbon and stainless steel components, the carbon steel becomes the anode and the stainless steel becomes the cathode. Destruction of weld metal in carbon steel piping systems has also occurred because the welds were anodic to the base metal (Ref. 3.8). Rapid galvanic attack occurs when the anode area is small compared to the cathode area.

Strav-Current Corrosion

Stray-current corrosion is degradation resulting from direct current (DC) flow through paths other than the intended circuit (Ref. 3.8). After the electrical current leaves its intended path, it can pass through the soil, water, or another electrolyte to find a low-resistance path, such as a buried metal pipe or some other metal structure, and flow to and from that structure, causing accelerated corrosion. The corrosion occurs at the point where the stray current leaves the metal structure and enters the surrounding electrolyte. Damage caused by alternating current (AC) is less than that caused by DC and decreases in severity as the frequency increases.

There are many sources of stray electrical current, but mass transit systems, cathodic protection systems, high voltage direct current (HVDC) systems, and DC welding operations are potentially the most significant for nuclear power plant structures (Ref. 3.19). Stray currents originating from these sources usually demonstrate some recognizable pattern that can often be detected by recording instruments. One way to identify a stray-current source is to establish a known pattern by alternately energized and de-energized the suspect equipment.

General Biological Corrosion

General biological corrosion or microbiological-induced corrosion (MIC) as it is sometimes called is deterioration of metal as a result of the metabolic activity of microorganisms (Ref. 3 .8). The corrosion rate of metals in aerated aqueous environments tends to be determined by the rate at which dissolved oxygen can be delivered to the metal surface. Biological organisms present in the environment have the potential to increase or decrease the oxygen transport to the metal surface and influence the corrosion rate. A continuous film of bacteria, algae, or slime can contribute to general corrosion, but the formation of a continuous film over a large area is rare. Consequently, biological corrosion is usually localized because microorganisms tend to settle in discrete colonies rather than uniformly over the surface of a material. Additional information on localized biological corrosion is provided in Sect. 3.4.2.

Molten-Salt Corrosion

Molten-salt corrosion is the oxidation of metals in contact with molten salts (Ref. 3.8). Degradation of containment pressure boundary components by molten-salt corrosion is not considered likely because light-water reactors are cooled with water not molten fluorides, nitrates, sulfates, or chloride salts.

Liauid-Metal Corrosion

Liquid-metal corrosion is the deterioration of materials in contact with liquid metals such as sodium, potassium, and lithium (Ref. 3.8). Degradation of containment pressure boundary com-

ponents by liquid-metal corrosion is not considered likely because light-water reactors are cooled with water not liquid metals like reactors for fast breeder, fusion, and space nuclear power applications.

High-Temperature Corrosion

High-temperature corrosion occurs when metal is exposed to an oxidizing gas at elevated temperature causing the metal to react directly with the gas without the presence of a liquid electrolyte (Ref. 3.8). High-temperature oxidation, sulfidation, and carburization are three types of high-temperature corrosion that affect the surfaces of metals by producing oxide layers, blisters, or scaling. Metals exposed to high-temperature hydrogen can experience a loss in ductility as described in Sect. 3.3.4 or cracking as described in Sect. 3.4.4. Hot corrosion is a term generally used to describe a form of accelerated high-temperature corrosion that affects the blades-of gas turbine engines. Because temperatures in excess of those associated with containment operations are required to cause high-temperature corrosion, degradation of containment pressure boundary component by is mechanism is not considered likely.

3.4.2 Localized Corrosion

Localized corrosion is similar to general corrosion except the rate of attack is usually much faster and the size of the affected area, is significantly smaller. Damage caused by localized corrosion is often difficult to detect and quantify because visible surface flaws tend to be small and often do not provide a good "indication of the extent of damage that has occurred under the surface (Ref. 3.8).

The most significant consequence of localized corrosion of steels used to construct containment pressure boundary components is loss of section caused by crevice or pit formation. This type of physical damage is more likely to result in containment leakage than reduced load-carrying capacity. Pits and crevices caused by localized corrosion are thought to have no measurable effect on the mechanical properties of containment steels. Specific forms of localized corrosion that could potentially affect containment steel components are identified in Table 3.3. The table also describes the likelihood of physical damage to containment pressure boundary components caused by each form of localized corrosion.

Filiform Corrosion

Filiform corrosion is localized surface damage that occurs under thin organic coatings in the form of randomly distributed threadlike filaments that appear as worm like blemishes (Ref. 3.8). The source of initiation is usually a cut, nick, pore, scratch, or disruption in the coating. The corrosion literally tunnels through the substrate, separating the coating from the steel and bulging it out by the expansion of corrosion products. Filiform corrosion generally occurs in coated steels when the relative humidity is between 60 and 95 percent at temperatures that range from 20 to 35°C (70 to 95°F). The constant forward movement of the filament will cease if the tail is not continually aerated and supplied with water vapor condensate. The average width of a filament ranges between 0.05 to 3 mm (0.002 to 0.012 in.), and the depth of attack can be as deep as 15 μm (0.0006 in.). Because filiform corrosion produces very localized distress on coated metal surfaces, its effects on containment integrity is not expected to be significant. However, coating damage caused by filiform corrosion could become a maintenance concern.

Crevice Corrosion

Crevice corrosion is localized attack of a metal surface adjacent to an area that is shielded from full exposure to the environment because of close proximity between the metal and the surface of another material (Ref. 3.8). Narrow openings or spaces between metal-to-metal or

nonmetal-to-metal components, cracks, seams, or other surface flaws can serve as sites for corrosion initiation. Regardless of the material, crevice corrosion is characterized by the development of differences between the local environment and the bulk environment. Crevice geometry is a controlling factor in governing resistance to corrosion. Chances for crevice corrosion increase as the gap decreases (degree of tightness increases) and the depth or distance from the mouth increases. Stainless steels are more prone to crevice corrosion than carbon steels particularly in the presence of chloride solutions.

Pitting Corrosion

Pitting corrosion is localized degradation of a metal surface confined to a point or small area that takes the form of cavities (Ref. 3.8). These cavities are generally irregularly shaped and may or may not become filled with corrosion products. Depth of pitting is sometimes expressed by the term pitting factor. This factor is the ratio of the depth of the deepest pit resulting from corrosion divided by the average metal penetration as determined by the weight loss of the specimen. A pitting factor of unity represents uniform or general corrosion.

Pitting usually affects metals that are covered with a very thin, often invisible, adherent protective surface film. Pits develop at weak spots in the surface film and at sites where the film is damaged mechanically under conditions where self-repair will not occur (Ref. 3.11). The propagation of pits is thought to involve the dissolution of metal and the maintenance of a high degree of acidity at the bottom of the pit by the hydrolysis of the dissolved metal ions making the rate at which pitting corrosion progresses very unpredictable. Pitting corrosion is one of the most common types of localized corrosion encountered in aqueous environments. The significance of pitting depends on the thickness of the component and the penetration rate which usually decreases with time.

Localized Biological Corrosion

Localized biological corrosion, like general biological corrosion described earlier, is deterioration of metal as a result of the metabolic activity of microorganisms (Ref. 3.8). Because microorganisms tend to settle in discrete colonies rather than uniformly over the surface of a material, most biologically induced corrosion tends to be localized. Anaerobic corrosion due to attack by sulfate-reducing bacteria and aerobic corrosion under oxygenated conditions can cause degradation of iron and carbon steel, but localized biological corrosion of stainless steels can also occur.

3.4.3 Mechanically Assisted Degradation

Any type of physical damage that is caused by mechanical action is considered mechanically assisted degradation. Actions that involve both a corrosion mechanism and mechanical wear or fatigue also fall into this category (Ref. 3.8). Under certain conditions, mechanical wear, maintenance and repair activities, and equipment failures can cause loss of net section, wall thinning, discontinuities, stress concentrations, and dimensional changes in component geometry. A list of mechanically assisted degradation mechanisms that could potentially cause physical damage to containment pressure boundary components is presented in Table 3.4.

Erosion, fretting, and cavitation are mechanical actions that can wear away the surface of a component and change its net section. Erosion is the destruction of a material by the abrasive action of moving fluids. Material loss can be accelerated by the presence of solid particles or matter in suspension. Fretting is wear that occurs between tight-fitting surfaces when they are subjected to cyclic motion of extremely small amplitude. Cavitation is loss of material caused by a liquid that experiences rapid and intense pressure changes. Corrosion fatigue is the process in which a metal fractures prematurely under conditions of simultaneous corrosion and repeated cyclic

loading at lower stress levels or fewer cycles than would be required in the absence of the corrosive environment (Ref. 3.8). Steels used to construct containment pressure boundary components are not routinely subjected to wear caused by erosion, fretting, or cavitation, and corrosion fatigue of pressure-retaining components is not expected to be a generic concern (Ref. 3.10).

Steels used to construct metal and concrete containments are ductile materials that generally bulge, stretch, bend, or neck before rupturing. These desirable characteristics can be influenced by the presence of flaws that create stress concentrations. Surface flaws such as notches, cracks, gouges, grooves, dents, and tool marks can be created during routine operations, in-service maintenance, repair activities, or equipment failures that generate missiles or pipe whips. Stress concentrations that are located in critical regions of the containment can affect performance by contributing to premature structural failure at loads well below those permitted in design or loss of leaktight integrity. Flaws located in aqueous environments can also serve as initiation sites for filiform and crevice corrosion. Arc strikes are another type of flaw that can cause loss of ductility in mild and low-alloy steels, hardening of higher carbon and alloy steels, or localized cracking in higher strength, hardenable grades of steel (Ref. 3.20). Arc strikes represent any localized heat-affected zone or change in the surface contour of the finished weld or base metal caused by an arc produced by the passage of electrical current from welding electrodes, magnetic particle inspection electrodes, electrical shorts, or other sources.

Equipment failures, excessive piping loads, and unanticipated thermal expansion or contraction are examples of over-load conditions that can permanently deform, bulge, stretch, bend, buckle, or neck pressure-retaining components. These changes in component geometry can be attributed to plastic deformation of the metal or brittle fracture of the component. The damage caused by over-load conditions can have a detrimental effect on containment structural capacity and leaktight integrity and adversely affect its ability to perform its intended function.

3.4.4 Environmentally Induced Cracking

Environmentally induced cracking is a type of degradation that occurs when cracks are produced in metals as a result of exposure to an environment. Stress-corrosion cracking, hydrogen damage, liquid-metal embrittlement, and solid metal induced embrittlement are four forms of degradation commonly associated with environmentally induced cracking (Ref. 3.8). In general, as the yield strength and stress applied to a metal increase, its resistance to environmentally induced cracking decreases.

For steels in light-water reactor nuclear power plants, only two of these phenomena, stress-corrosion cracking and hydrogen damage, are possible because liquid metals are not present. The likelihood of physical damage to containment pressure boundary components caused by stress-corrosion cracking and hydrogen damage is described in Table 3.5.

Stress-Corrosion Cracking

Stress-corrosion cracking is a material degradation process that requires the simultaneous action of a corrodent and sustained tensile stress to initiate and propagate cracks in metals and alloys. It excludes corrosion-reduced sections that fail by fast fracture as well as intercrystalline or transcrystalline corrosion that can disintegrate an alloy without the presence of either applied or residual stress (Ref. 3.15). Relatively low tensile stresses, often below the yield strength of the material, can cause stress-corrosion cracking. These stresses may be produced by applied loads, residual stresses, or wedging action caused by the growth of corrosion products. Compressive stresses are beneficial in reducing or eliminating stress-corrosion cracking.

Carbon, low-alloy, and stainless steels exposed to various aqueous solutions are susceptible to stress-corrosion cracking. A partial list of aqueous environments that could potentially cause

stress-corrosion cracking of containment steels is identified in Table 3.6. Aqueous solutions that may be present at nuclear power plants and could contribute to stress-corrosion cracking include ground water containing chlorides and sulfates, borated water in PWRs, sodium pentaborate in BWRs, and certain types of decontamination fluids (Ref. 3. 10).

Alloys that are resistant to general corrosion in a particular environment are often susceptible to stress-corrosion cracking. Austenitic stainless steel is a good example. When unstressed samples of this material are exposed to a chloride environment, they exhibit excellent corrosion resistance. However, when stressed, they exhibit premature fracture that can be attributed to stress-corrosion cracking. Other factors such as temperature, degree of aeration, and differences in pH can also influence whether a particular alloy is or is not susceptible to stress-corrosion cracking (Refs. 3.13 and 3.21). Probably one of the most significant instances of stress-corrosion cracking at nuclear power plants occurred in the 1960s and 1970s (Ref. 3.8). Intergranular cracks were discovered in BWR primary piping systems near welds in the heat-affected zone. These cracks resulted when type 304 austenitic stainless steel piping was exposed to high-purity, neutral-pH water containing dissolved oxygen. The problem was resolved by placing controls on the water chemistry, using other types of stainless steels for repairs and replacements, and reducing the residual tensile stresses on the inside surfaces of the pipes.

Material failure caused by stress-corrosion cracking is a time-dependent phenomenon (i.e., an incubation phase precedes the crack initiation and propagation phases). If unmitigated, cracking continues until the applied stress exceeds the strength of the remaining cross section. Standard test methods such as ASTM G 36, G 38, G 39, G 44, and G 49 (Refs. 3.22 to 3.26) are often used to evaluate stress-corrosion cracking. In these tests, smooth metal specimens are subjected to relatively severe environmental conditions such as boiling magnesium chloride while a constant stress is applied to the specimens. Results from these tests are used primarily for material selection purposes. The assumption is that materials that do not crack under these test conditions will be suitable for use at the same stress level in a similar but less severe environment. Occasionally, crack growth rates are established in these tests by periodically measuring the depth of crack propagation.

Hydrogen Stress Cracking

Hydrogen stress cracking or hydrogen-induced cracking as it is sometimes called is one of the three categories of damage associated with hydrogen embrittlement described in Sect. 3.3.4. Hydrogen stress cracking is characterized by the brittle failure of a normally ductile alloy under sustained load in the presence of hydrogen. Cracking, which can be particularly severe for medium- to high-strength steels exposed to hydrogen sulfide, is associated with absorption of hydrogen and a delayed time to failure (incubation time) during which atomic hydrogen diffuses into regions of high triaxial stress (Ref. 3.8). Physical damage to pressure-retaining steels caused by hydrogen attack is not expected to be a serious problem because neither hydrogen at high pressures nor hydrogen at high temperatures are found inside the containment vessel.

3.4.5 Fatigue

Fatigue is the progressive, localized, and permanent structural change that occurs in a material subjected to repeated or fluctuating strains at normal stresses that have maximum values less than the tensile strength of the material (Ref. 3.13). Fatigue failure is a three-step process. During the crack initiation phase, initial fatigue damage leads to crack initiation. During the crack propagation phase, the crack grows to a critical size that depends on various factors including the material, temperature, and stress level. When the crack reaches the critical size and the remaining uncracked section can no longer sustain the load, sudden failure of the remaining cross section occurs. Enhanced fatigue performance can be achieved by eliminating stress concentrations, avoiding the development of discontinuities, reducing residual stresses, and protecting the compo-

nent from corrosion, erosion, or chemical attack. The likelihood of physical damage to containment'pressure boundary components caused by fatigue is summarized in Table 3.5.

In most cases, the factors that cause changes in concrete containment vessel liner stress and strain levels with time (fatigue) occur only a small number of times and produce only minor changes in magnitude. The design of liners for reinforced concrete containments therefore is generally not controlled by fatigue considerations (Ref. 3.1). However, fatigue may be considered a design issue in certain parts or areas of metal containments where thermal stress ratcheting occurs. Combinations of steady state and cyclic loadings that produce a ratcheting action can cause a continuing increase in component deformation eventually leading to component failure. Guidance for performing fatigue evaluations under these conditions is provided in Section III, Division 1 of the Code (Ref. 3.1).

The suitability of a component for cyclic operations can be determined in two ways — using rules presented in the Code, or conducting cyclic load tests. In a fatigue analysis, allowable stress limits and corresponding numbers of permitted stress cycles are evaluated using fatigue design curves presented in Section III, Division 1, Appendix I (Ref. 3.27). These curves reflect actual material performance because they were developed using results from uniaxial strain cycling tests:' Values obtained from these curves include an appropriate safety factor. The fatigue resistance. of a material or component can also be evaluated by cyclic load testing. The test sample should be fabricated using a material having similar properties and composition to that of the prototype. Results of cyclic load testing, however, cannot be used as justification for exceeding the allowable values of primary or primary plus secondary stresses provided by the fatigue design curves contained in Appendix I.

Although design rules for fatigue of steels used to construct containment pressure boundary components are included in the Code, fatigue resulting from cyclic loads such as the ones listed in Table 3.7 is not expected to be a generic concern for either liners of reinforced concrete containments or the shells of metal containments (Ref. 3.10).

3.5 ROOT-CAUSE DETERMINATION

Component degradation can generally be related to a design feature or deficiency, improper material selection, defective base metal, an incorrect fabrication practice or assembly technique, or an excessively severe service condition (Ref. 3.20). Factors to be considered in determining the root cause for component degradation are listed in Fig. 3.3. Under certain conditions, degradation can be attributed to a combination of factors. For example, corrosion of the drywell shell in some Mark I metal containments has occurred near the sand. cushion (Ref. 3.28). The corrosion appears as general wastage of the carbon-steel drywell shell caused by a severe service condition in which water that leaked from a higher elevation within the containment accumulated in the sand. This type of degradation is more likely to occur in containments where the sand cushion is open to the gap between the drywell shell and the surrounding concrete than in containments where the sand cushion is covered with galvanized steel plates that are sealed to the drywell shell and the surrounding concrete. Differences in performance can be attributed to variations in the seal designs 'and the way in which the drainage systems function when a leak develops. Drains connected to the galvanized steel plates remove water before it reaches the sand cushion whereas drains located at the bottom of the sand cushion remove water after it has accumulated in the sand.

Degradation resulting from improper structural design can occur when mechanical or thermal loads are not accurately predicted or when features such as notches or sharp comers are specified. Buckling, necking, cracking, and fracture are examples of physical damage that can be caused by a problem related to design. Occasionally, structural modifications are required to elimi-

nate potentially serious design deficiencies (Ref. 3.29), but, in general, degradation resulting from improper structural design is not a common aging issue.

Material selection plays a significant role in the long-term performance of structural components, especially when they are exposed to corrosive or severe environments. Except in situations where alternative materials are being considered for use in repair or replacement applications, material selection is generally not considered a containment aging issue. Ferrous metals permitted for construction of concrete and metal pressure boundary components are provided in Section III of the Code (Ref. 3.1 and 3.2). These materials, generally characterized as carbon steels, are identified in Sect. 1.3. Carbon steels are excellent structural materials because they are ductile, weldable, and relatively inexpensive. However, without adequate surface or cathodic protection, they will corrode. The only question is at what rate.

Base-metal flaws and differences in microstructure can be introduced during the ingot stage of manufacturing or during subsequent rolling or forming operations. Flaws are usually related to discontinuities or separations in the material whereas differences in metallurgy are influenced by localized heat treatment that produces areas of high hardness adjacent to areas of lower hardness. Terms commonly used to describe base-metal flaws include laminations, laps, slivers, scabs, seams, bark, or cracks. Material specifications often include acceptance criteria and repair procedures for flaws caused by the manufacturing process. However, some of these flaws are difficult, if not impossible, to detect during manufacture or inspection. Differences in the microstructure of a metal can cause variations in its properties from one location to another. These differences can be introduced by the manufacturing process, welding and heat treating operations, or an event such as an electrical short that produces an arc. Rules for inspection and testing of materials used in containment construction are provided in Section III of the Code (Ref. 3.1 and 3.2). However, because all metals contain some type of base-metal flaw, their presence in pressure boundary components can potentially be responsible for in-service containment degradation.

Incorrect fabrication methods or faulty assembly techniques can cause structural failures or be responsible for in-service component degradation. Because of the importance of sound fabrication and construction practices on containment reliability and serviceability, rules for fabrication and construction of concrete and metal containments were established. These rules are provided in Section III of the Code (Ref. 3.1 and 3.2) and address issues that involve welding, bolting, shop forming, hot or cold bending, end preparation for welding, heat treatment, and cleaning operations. Welding operations are particularly important because they can cause both physical and material damage, but, in certain instances, weld flaws may have little or no consequences on containment performance. Terms frequently used to describe weld flaws are listed in Table 3.10. Bolting problems are generally related to torquing or tensioning operations with under tensioning causing problems such as leakage and over tensioning causing possible bolt failure. Heat treatment of containment pressure boundary components is generally not required because the sections are relatively thin. However, when heat treatment is required, it is usually performed to relieve or reduce residual stresses. Improper heat treatment or elimination of heat treatment when it is specified can be a serious concern because of its potential impact on structural performance. After welding and heat treating operations are completed, surface cleaning is often required to remove surface scale or to prepare the surface for coating. Cleaning operations may involve pickling in acid, grinding, or shot or sand blasting. These operations are usually not detrimental unless thinning of the component occurs or cleaning chemicals are not used properly.

Probably the most common cause for component degradation is an excessively severe service condition. When conditions are more severe than anticipated, the design could be inadequate, the materials could be inappropriate, or base-metal flaws could become sites for corrosion or fracture initiation. Conditions involving excessive stresses resulting from overpressurization of the containment, mechanical loads, fatigue, shock, or impact; overheating; leakage of corrosive fluids from the primary system or condensation; or other unanticipated environmental effects can cause

significant component degradation. 'Documented case-histories of degradation caused by exposure to severe environments can sometimes be used to help establish the root cause of the problem, identify other suspect locations, and provide suggested remedies. Detailed descriptions of the affected components and the degradation phenomena are especially valuable, particularly when illustrations or sharp, color photographs of the problem areas are included (Ref. 3.30).

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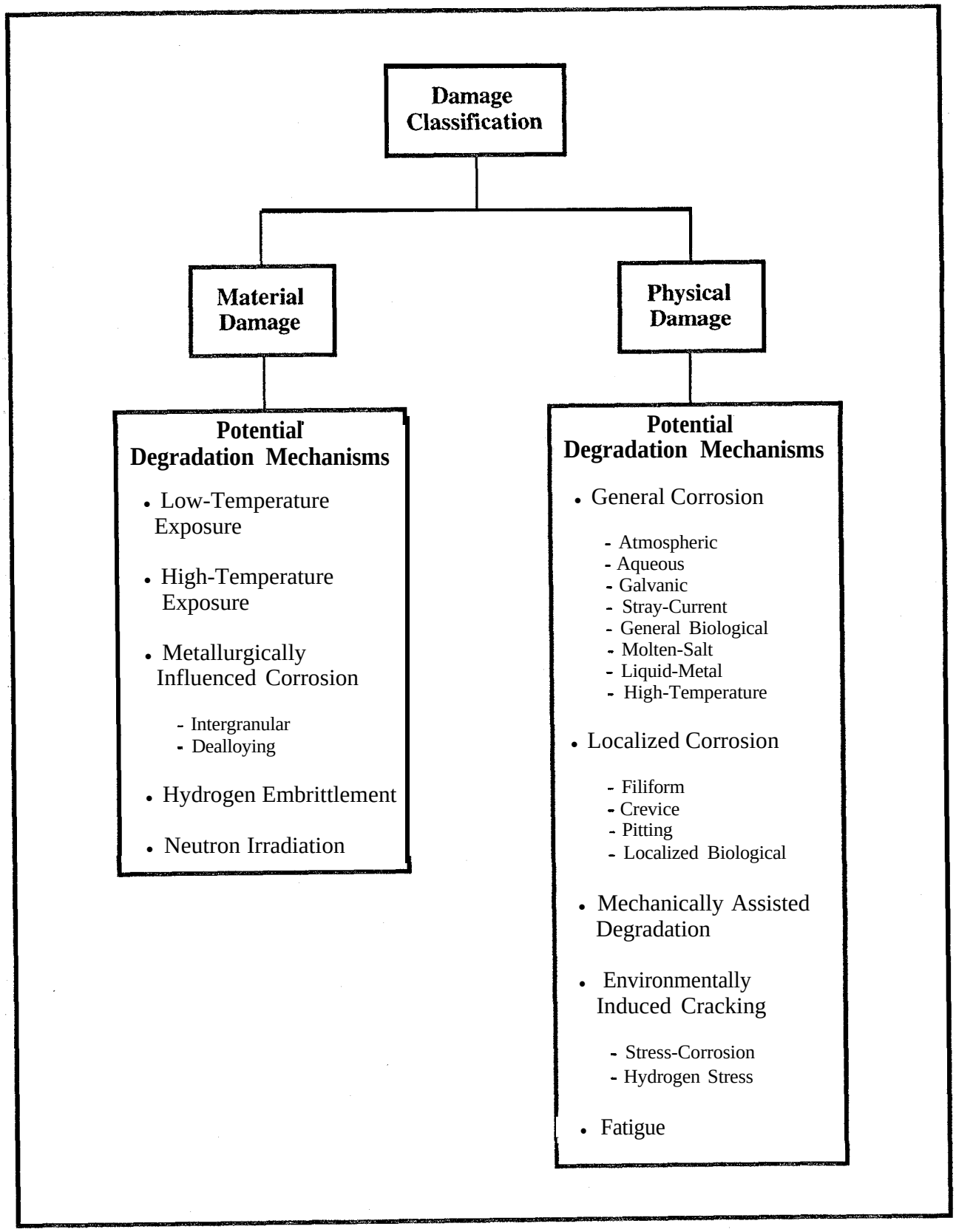

Fig. 3.1 Damage categories and potential degradation mechanisms.

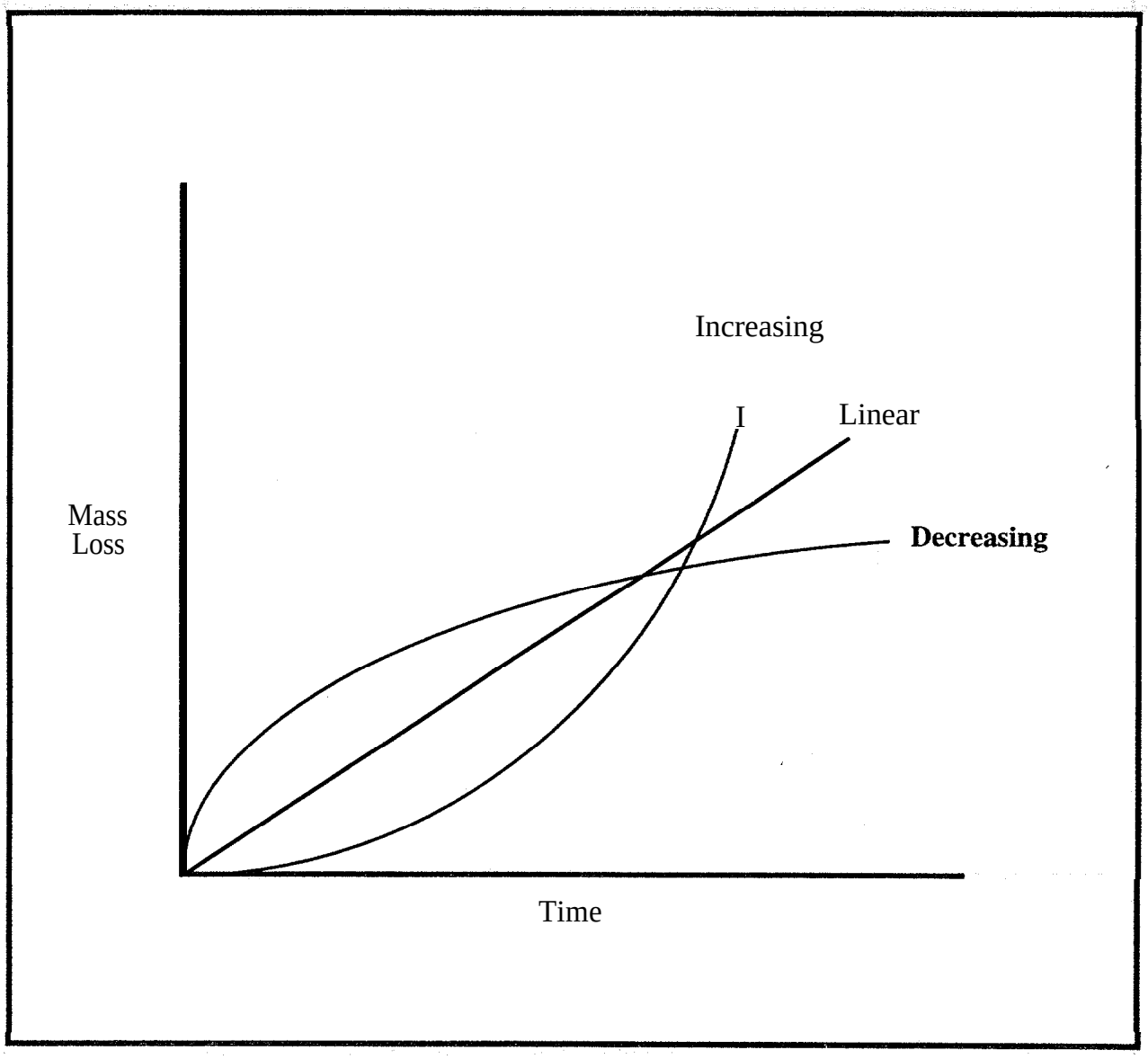

Fig. 3.2 Curves that represent three types of time-dependent corrosion behavior.

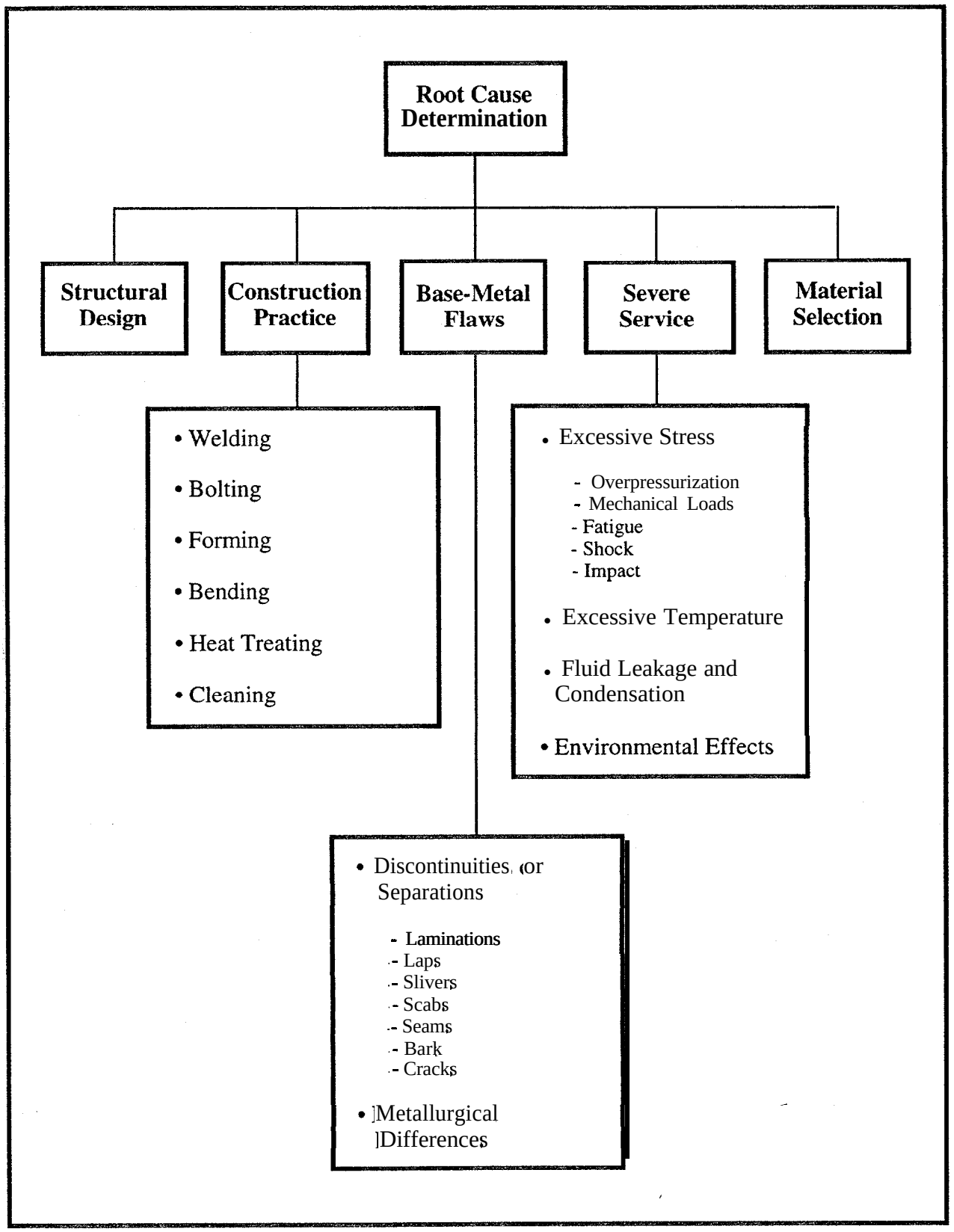

Fig. 3.3 Factors to be considered in determining the root cause for component degradation.

Table 3.1 Degradation mechanisms that can potentially cause material damage to containment steels.

Degradation Mechanism	Likelihood of Causing Material Damage to Containment Steels
Low-Temperature Exposure	Effects of low-temperatures on the properties of containment steels are not considered to be a significant containment issue because low-temperature exposure and fracture toughness are addressed during containment design and because exposure to temperatures low enough to cause brittle fracture is not expected.
High-Temperature Exposure	Temperature-dependent property values for containment steels are provided in Section II, Part D of the Code (Ref. 3.9). Material damage to containment steels due to high-temperature exposure is not expected because temperatures high enough to affect mechanical properties are not likely to occur except in the unlikely even of a severe accident.
Intergranular Corrosion	Intergranular corrosion is a metallurgically influenced corrosion process that takes place when the corrosion rate of the grain-boundary areas of an alloy exceeds that of the grain interiors. Metals that experience intergranular corrosion exhibit time-dependent weight loss that can accelerate with time. Intergranular corrosion of austenitic and ferritic stainless steels and nickel-based alloys used to make containment pressure boundary components is not considered likely. These materials are normally not exposed to solutions such as ferric sulfate, cupric sulfate, and acids that are required to cause this type of degradation.
Dealloying Corrosion	Dealloying is a metallurgically influenced corrosion process in which one constituent of an alloy is preferentially removed leaving behind an altered residual structure that is less tolerant to flaws and applied loads (Ref. 3.8). Material damage to containment steels due to dealloying corrosion is not considered likely because containment steels are not exposed to molten salts, and because oxidizing atmospheres and sufficient hydrogen gas are not generally present inside BWR and PWR containment vessels.
Hydrogen Embrittlement	Hydrogen influences the behavior and properties of nearly all ferrous alloys, particularly steels in which the yield strength is close to the ultimate strength. During normal plant operations, hydrogen embrittlement of containment steels is not expected to be a serious problem because sufficient hydrogen gas is not generally present inside BWR and PWR containment vessels.

Table 3.1 (cont.) Degradation mechanisms that can potentially cause material damage to containment steels.

Degradation Mechanism	Likelihood of Causing Material Damage to Containment Steels
Neutron Irradiation	Metals exposed to neutron irradiation can be damaged when neutrons displace metal atoms from their normal lattice positions to form interstitials and vacancies. Irradiation damage to containment steels is not very likely because biological shielding effectively limits exposure of the materials to levels that are considered safe for occupational workers, and end-of-life fluence of containment components is anticipated to be quite small (Ref. 3.10). Even in the unlikely event of a severe accident, irradiation damage to containment steel components is not expected to be significant.

Table 3.2 Types of general corrosion that can potentially cause physical damage to containment pressure boundary components.

Type of General Corrosion	Likelihood of Causing Physical Damage to Containment Pressure Boundary Components
Atmospheric Corrosion	Atmospheric corrosion is the gradual degradation or alteration of a material by contact with substances such as oxygen, carbon dioxide, water vapor, and sulfur and chlorine compounds that are present in the atmosphere (Ref. 3.8). In buildings, corrosion of uncoated structural steel elements often occurs when warm, moist air from inside the building permeates through the walls and ceilings and condenses on the surfaces of colder steel beams, columns, and fasteners. In nuclear power plants, atmospheric corrosion can be suspected whenever uncoated carbon and low-alloy steel components are exposed to air with a relative humidity that exceeds about 70 percent.
Aqueous Corrosion	Corrosion of metals in aqueous environments occurs when two or more electrochemical reactions take place on the surface causing the metal or alloy to change from a metallic state to a nonmetallic state (Ref. 3.8). A common example of this phenomenon is rusting in which metal (iron) is converted to a nonmetallic corrosion product (rust). Aqueous corrosion of the external surface of a BWR Mark I metal containment shell in the sand-cushion region of the drywell has occurred due to water that leaked from the refueling pool (Ref. 3.10). Physical damage to carbon and low-alloy steel fasteners and pressure-retaining components of the primary system has also occurred at a number of PWR plants due to boric acid (H_3BO_3) attack (Refs. 3.16 and 3.17). Similar types of physical damage caused by aqueous corrosion is possible whenever carbon and low-alloy steel components are in contact with pure, treated, contaminated, or seawater.
Galvanic Corrosion	Galvanic corrosion is accelerated degradation that occurs when a metal or alloy is electrically coupled to a more noble metal in the same electrolyte (Ref. 3.8). The three requirements for galvanic corrosion are (1) materials possessing different surface potentials, (2) a common electrolyte, and (3) a common electrical path. Galvanic corrosion has been known to occur in dissimilar-metal, butt-welded piping systems that carry an electrolytic solution. The most severe corrosion occurs adjacent to the weld on the anodic member, Destruction of weld metal in carbon steel piping systems has also occurred because the welds were anodic to the base metal (Ref. 3.8). Physical damage to welds and base metal in nuclear power plants caused by galvanic corrosion can occur in locations where dissimilar metals are in contact and an electrolytic solution is present.

Table 3.2 (cont.) Types of general corrosion that can potentially cause physical damage to containment pressure boundary components.

Type of General Corrosion	Likelihood of Causing Physical Damage to Containment Pressure Boundary Components
Stray-Current Corrosion	Stray-current corrosion is degradation resulting from direct current flow through paths other than the intended circuit (Ref. 3.8). There are many sources of stray electrical current, but mass transit systems, cathodic protection systems, high voltage direct current systems, and direct current welding operations are potentially the most significant for nuclear power plant structures (Ref. 3.19). Damage caused by alternating current is less than that caused by direct current and decreases in severity as the frequency increases.
General Biological Corrosion	General biological corrosion or microbiological-induced corrosion (MIC) as it is sometimes called is deterioration of metal as a result of the metabolic activity of microorganisms (Ref. 3.8). A continuous film of bacteria, algae, or slime can contribute to general biological corrosion, but the formation of a continuous film over a large area is rare. Consequently, biological corrosion is usually localized because microorganisms tend to settle in discrete colonies rather than uniformly over the surface of a material.
Molten-Salt Corrosion	Molten-salt corrosion is the oxidation of metals in contact with molten salts (Ref. 3.8). Degradation of containment pressure boundary components by molten-salt corrosion is not considered likely because light-water reactors are cooled with water not molten fluorides, nitrates, sulfates, or chloride salts.
Liquid-Metal Corrosion	Liquid-metal corrosion is the deterioration of materials in contact with liquid metals such as sodium, potassium, and lithium (Ref. 3.8). Degradation of containment pressure boundary components by liquid-metal corrosion is not considered likely because light-water reactors are cooled with water not liquid metals like reactors for fast breeder, fusion, and space nuclear power applications.
High-Temperature Corrosion	High-temperature corrosion occurs when metal is exposed to an oxidizing gas at elevated temperature causing the metal to react directly with the gas without the presence of a liquid electrolyte (Ref. 3.8). Because temperatures in excess of those associated with containment operations are required to cause high-temperature corrosion, degradation of containment pressure boundary component by this mechanism is not considered likely.

Table 3.3 Types of localized corrosion that can'potentially cause physical damage to containment pressure boundary components.

Type of Localized Corrosion	Likelihood of Causing Physical Damage to Containment Pressure Boundary Components
Filiform Corrosion	Filiform corrosion occurs under thin organic' coatings in the form of randomly distributed threadlike filaments that appear as worm like blemishes (Ref. 3.8). The source of initiation is usually a cut nick, pore, scratch, or disruption in the coating. Because filiform corrosion produces very localized distress on metal surfaces, its effects on containment integrity is not expected to be significant. However, coating damage may become a maintenance concern.
Crevice Corrosion	Crevice corrosion is localized attack of a metal surface adjacent to an area that is shielded from full exposure to the environment because of close proximity between the metal and the surface of another material (Ref. 3.8). Narrow openings or spaces between metal-to-metal or nonmetal-to-metal components, cracks, seams, or other surface flaws can serve as sites for corrosion initiation. Stainless steels are more prone to crevice corrosion than carbon steels particularly in the presence of chloride solutions, but containment pressure boundary components made from all types of steels can experience this type of localized damage when exposed to aqueous environments.
Pitting Corrosion	Pitting corrosion is degradation of a metal surface confined to a point or small area that takes the form of cavities (Ref. 3.8). Pitting is one of the most common types of localized corrosion encountered in aqueous environments. The propagation of pits is thought to involve the dissolution of metal and the maintenance of a high degree of acidity at the bottom of the pit by the hydrolysis of the dissolved metal ions making the rate at which pitting corrosion progresses very unpredictable. Pitting corrosion of containment pressure boundary components made from all types of steels is possible whenever they are exposed to aqueous environments.
Localized Biological Corrosion	Localized biological corrosion, like general biological corrosion, is deterioration of metal as a result of the metabolic activity of microorganisms (Ref. 3.8). Because microorganisms tend to settle in discrete colonies rather than uniformly over the surface of a material, most biologically induced corrosion tends to be localized. Localized damage to carbon, low-alloy, and even stainless steel components caused by biological corrosion is possible when environmental conditions are favorable for microorganisms.

Table 3.4 Mechanically assisted degradation that can potentially cause physical damage to containment pressure boundary components.

Type of Mechanically Assisted Degradation	Likelihood of Causing Physical Damage to Containment Pressure Boundary Components
Erosion	Erosion is the destruction and removal of a material by the abrasive-action of moving fluids. Material loss can be accelerated by the presence of solid particles or matter in suspension. Except in the torus region of BWR Mark I metal containments, moving water is not usually present inside containment vessels. Therefore, erosion of pressure-retaining components is not expected to be a generic concern (Ref. 3.10).
Fretting	Fretting is wear that occurs between tight-fitting surfaces subjected to cyclic motion of extremely small amplitude. Steels used to construct containment pressure boundary components are not routinely subjected to wear caused by fretting because these components generally remain static.
Cavitation	Cavitation is loss of material caused by a liquid that experiences rapid and intense pressure changes. This action is generally associated with pumps and piping systems and is therefore not considered to be a significant containment degradation mechanism.
Corrosion Fatigue	Corrosion fatigue is the process in which a metal fractures prematurely under conditions of simultaneous corrosion and repeated cyclic loading at lower stress levels or fewer cycles than would be required in the absence of the corrosive environment (Ref. 3.8). Corrosion fatigue of pressure-retaining components is not expected to be a generic concern (Ref. 3.10).
Surface Flaws	Surface flaws such as notches, cracks, gouges, grooves, dents, and tool marks can be created during routine operations, in-service maintenance, repair activities, or equipment failures that generate missiles or pipe whips. Stress concentrations caused by these types of flaws located in critical regions of the containment, can affect performance by contributing to premature structural failure at loads well below those permitted in design or loss of leaktight integrity. Surface flaws located in aqueous environments can also serve as initiation sites for filiform and crevice corrosion.
Arc Strikes	Arc strikes are another type of surface flaw that can cause loss of ductility in mild and low-alloy steels, hardening of higher carbon and alloy steels, or localized cracking in higher strength, hardenable grades of steel (Ref. 3.20). Arc strikes represent any localized heat-affected zone or change in the surface contour of the finished weld or base metal caused by an arc produced by the passage of electrical current from

Table 3.4 (cont.) Mechanically assisted degradation mechanisms that can potentially cause physical damage to containment pressure boundary components.

Type of Mechanically Assisted Degradation	Likelihood of Causing Physical Damage to Containment Pressure Boundary Components
Arc Strikes (cont.)	welding electrodes, magnetic particle inspection electrodes, electrical shorts, or other sources.
Over-Load Conditions	Equipment failures, excessive piping loads, and movements caused by thermal expansion or contraction due to extreme-temperature exposure are examples of over-load conditions that can permanently deform, bulge, stretch, bend, buckle, or neck pressure-retaining components. These changes in component geometry can be attributed to plastic deformation of the metal or brittle fracture of the component. The damage caused by over-load conditions can have a detrimental effect on containment structural capacity and leaktight integrity and adversely affecting its ability to perform its intended function.

Table 3.5 Degradation mechanisms that can potentially cause cracking of containment pressure boundary components.

Degradation Mechanism	Likelihood of Causing Physical Damage to Containment Pressure Boundary Components
Stress-Corrosion Cracking	Stress-corrosion cracking is a material degradation process that requires the simultaneous action of a corrodent and sustained tensile stress to initiate and propagate cracks in metals and alloys. Carbon, low-alloy, and stainless steels exposed to various aqueous environments are susceptible to stress-corrosion cracking. Aqueous solutions that may be present at nuclear power plants and could contribute to stress-corrosion cracking include ground water containing chlorides and sulfates, borated water in PWRs, sodium pentaborate in BWRs, and certain types of decontamination fluids (Ref. 3.10).
Hydrogen Stress Cracking	Hydrogen stress cracking is one of the three categories of damage associated with hydrogen embrittlement described in Table 3.1. Hydrogen stress cracking is characterized by the brittle failure of a normally ductile alloy under sustained load in the presence of hydrogen. Physical damage to pressure-retaining steels by hydrogen is not expected to be a serious problem because neither hydrogen at high pressures nor hydrogen at high temperatures are found inside the containment vessel.
Fatigue	Fatigue is the progressive, localized, and permanent structural change that occurs in a material subjected to repeated or fluctuating strains at normal stresses that have maximum values less than the tensile strength of the material (Ref. 3.13). Guidance for performing fatigue evaluations is provided in Section III, Division 1 of the Code (Ref. 3.1). Although design rules for fatigue of steels used to construct containment pressure boundary components are included in the Code, fatigue resulting from cyclic loads such as the ones listed in Table 3.7 is not expected to be a generic concern for either liners of reinforced concrete containments or the shells of metal containments (Ref. 3.10).

Table 3.6 Aqueous environments that can potentially cause stress-corrosion cracking of containment steels.

Low-Carbon and Low-Alloy Ferritic Steels	Austenitic Stainless Steels
Nitrites	Chlorides
Phosphates	Hydroxides
Sulfates	Fluorides
Carbonates	Bromides
Carbon monoxide	Water/oxygen
Carbon dioxide	Sulfates
Hydrogen sulfide	Thiocyanates
Ferric chloride	Thiosulfates
Ammonia	Tetrathionates
Organic liquids	Polythionates
Water/oxygen	Sulfur dioxide
Cyanides	Sulfurous acid
Hydroxides	

Source: Ref. 3.13

Table 3.7 Possible cyclic loads on containment pressure boundary components.

Startup and shutdown cycles (temperature transients)
Pipe reactions (at penetrations)
Crane loads
Leakage rate test pressures
Safety relief valve discharge tests
Refueling loads
Loads resulting from repair and replacement activities

Source: Ref. 3.10

Table 3.8 Terms frequently used to describe weld flaws.

Arc strikes
Bum through
Centerline crevice
Cracks
Hot cracking
Cold cracking
Microfissuring
Base-metal cracking
Crater pits
Hi-low
Incomplete fusion
Lack of penetration
Overlap
Porosity
Sink or concavity
Slag inclusion
Slugging
Tungsten inclusion
Undercut
Wagon tracks
Weld reinforcement
Weld splatter

Source: Ref. 3.20

4. DAMAGE MEASUREMENT

4.1 MEASUREMENT CONSIDERATIONS

One way to evaluate the significance of containment pressure boundary component degradation on structural capacity and leaktight integrity is by comparing its preservice condition to its condition after degradation has occurred. Condition assessment accuracy depends on the availability of quantifiable evidence such as dimensions of corroded surface areas, depths of corrosion penetration, or changes in material properties that indicate the extent and magnitude of the degradation. Methods for quantifying component degradation involve either nondestructive examination or destructive testing. Results from these investigations provide a measure of the extent of degradation at the time the component was examined. Techniques for establishing time-dependent change such as corrosion and wear rates involve periodic examination or testing. In-service monitoring provides a way to measure time-dependent changes in component geometry or material properties and to detect undesirable changes in operating conditions that can affect useful service life.

Discussions in this section focus on information that can be obtained from nondestructive examinations, destructive testing, and in-service monitoring for use in assessing the condition of degraded containment pressure boundary components. Issues related to damage measurement are identified in Fig. 4.1. Details about specific examination procedures, test methods, and inspection techniques are not included in this report. These subjects are discussed in a state-of-the-art report (Ref. 4.1) and other information sources including some of the references cited in this section (Refs. 4.2 to 4.4).

4.2 NONDESTRUCTIVE EXAMINATION

Nondestructive examination (NDE) is the development and application of technical methods to examine materials or components in ways that do not impair future usefulness and serviceability in order to detect, locate, measure, and evaluate discontinuities, defects, and other imperfections; to assess integrity, properties, and composition; and to measure geometrical characters (Ref. 4.5). Terms such as nondestructive testing, nondestructive evaluation, and nondestructive inspection are synonymous with nondestructive examination. Issues related to nondestructive examinations are identified in Fig. 4.1.

The objective of a nondestructive examination is to identify indications or evidence of a discontinuity that requires interpretation to determine its significance. Discontinuities are interruptions that may be either intentional or unintentional in the physical structure or configuration of a component (Ref. 4.5). The diagram in Fig. 4.2 shows interpretations that can be made when a nondestructive examination produces an indication. A false indication is interpreted to be caused by a discontinuity at a location where no discontinuity exists. Nonrelevant indications are caused by a condition or discontinuity that is not rejectable. False indications are considered nonrelevant. Relevant indications are caused by a condition or discontinuity that requires evaluation resulting in a decision to either accept or reject the material or component. Flaws are imperfections or unintentional discontinuities that are detectable by a nondestructive examination (Ref. 4.6). A defect is a flaw, discontinuity, or group of discontinuities whose indications do not meet specified acceptance criteria (Ref. 4.5).

Rules for preoperational and in-service examination of pressure retaining components are provided in Section XI, Division 1, Subsection IWA of the Boiler and Pressure Vessel Code (Ref. 4.6). These rules include standards for evaluation, significant digits for limiting values, flaw characterization, and linear flaws detected by surface or volumetric examinations. According

to these standards, flaw dimensions are determined by the size of a rectangle or square that fully contains the area of the flaw. Requirements for component thickness and flaw dimensioning are also provided in the standard.

4.2.1 Flaw Detection

Flaw detection is one of the most important objectives of a nondestructive examination. Some of the techniques that have been used to detect flaws include visual inspection, replication microscopy, liquid penetrant, magnetic particle, magnetic field, eddy current, ultrasonic, radiography, X-ray computed tomography, neutron radiography, thermography, optical holography, speckle metrology, digital image enhancement, electric current perturbation, magabsorption, and acoustic emission. Selection of a suitable flaw detection technique depends on its anticipated size, shape, orientation, and location and whether it is expected to be a volumetric or planar flaw. Practical and effective flaw detection often requires use of a variety of techniques that yield complementary information (Ref. 4.7).

Visual inspection is a nondestructive examination technique that is frequently used to detect discontinuities and imperfections on containment pressure boundary component surfaces including corrosion, cracks, wear, and erosion. This inspection method usually involves direct examination with the eye placed within about 600 mm (24 in.) of the surface to be inspected. In situations where access is limited or normal visual acuity is not sufficient, examination may require the use of visual aids such as the equipment listed in Table 4.1. Rules for three visual examination categories are provided in Section XI, Division 1, Subsection IWA of the Code (Ref. 4.6). These categories are designated as VT-l, VT-2, and VT-3 examinations. VT-l examinations are conducted to detect discontinuities and imperfections on component surfaces, VT-2 examinations are conducted to detect evidence of leakage from pressure retaining components, and VT-3 examinations are conducted to determine the general mechanical and structural condition of components and their supports. Subsection IWA also provides rules for remote visual examinations and examinations using surface replication methods.

Rules for surface examinations of containment pressure boundary components using magnetic particle and liquid penetrant techniques and rules for volumetric examinations using radiographic, ultrasonic, and eddy current techniques are also provided in Subsection IWA. Alternative techniques, combinations of techniques, and newly developed techniques are permitted provided the results are considered to be equivalent or superior to those of the specified technique.

4.2.2 Leak Detection

Leak detection is a nondestructive examination technique that can be used to detect special types of flaws such as through-wall discontinuities or passages through which fluid flows or permeates. These flaws allow liquids or gases to escape from pressurized (or into evacuated) components or systems intended to contain these fluids. Leak testing is generally performed to locate a leak, determine the leakage rate, or monitor for leakage. Leakage rate is the amount of fluid that flows through a flaw per unit of time under a prescribed set of conditions.

"In nuclear power plants; leakage rate testing is conducted at prescribed intervals to verify that the containment system can prevent the release of radioactive fission products into the environment in the unlikely event of a severe accident. Current requirements for preoperational and periodic leakage rate testing are described in Sect. 2.5.

4.2.3 Metrology

Metrology is the measurement of dimensions. It is a widely used nondestructive examination technique for establishing the size and shape of objects including flaws and

discontinuities. Tools-for dimensional measurements include conventional hand-held devices such as rulers, gages, and micrometers as well as coordinate- measurmg machines and sophisticated systems based on laser technology.

According to rules provided in Section XI, Division 1, Subsection IWA of the Code (Ref. 4.6) dimensions of component thickness and flaws detected by nondestructive exarnmations are expressed to the nearest 2.54 mm (0.1 in.) for dimensions 25.4 mm (1 in.) and greater, and to the nearest. 1.27 mm (0.05 in.) for dimensions less than 25.4 mm (1 in.). These dimensions are an important part of a-condition assessment because they provide an accurate description of the size of an affected areas or the length and depth of flaws. Precise flaw dimensions are vital to fracture mechanics evaluations.

4.2.4 Location Detection

Location detection is a nondestructive examination technique that is occasionally used to verify that an assembly actually contains the required parts. This technique is particularly useful when the parts are not accessible for visual examination. In nuclear power plants, it could be necessary to use location detection techniques to verify the presence or determine the location of liner anchors or attachments embedded in a concrete containment. Some of the techniques that have been used for location detection include X-ray radiography, X-ray computed tomography, and neutron radiography (Ref. 4.2).

4.2.5 Structure or Microstructure Characterization

Field replication microscopy is a nondestructive examination technique that was developed for use in characterizing the structure or microstructure of a material while it remains in service (Ref. 4.8). This technique does not involve removal of material for laboratory examination but records and preserves the topography of a metallographic specimen as a negative relief on a plastic film. A suitable replica, which is at least 12 by 18 mm (0.5 by 0.75 in.), should accurately record all of the microstructural features present on the surface that was replicated. The resolution should exceed 0.1 μm to permit examination by scanning electron microscope at high magnification (up to 5,000x). The replica should also be sufficiently durable so that it can be transported to a light microscope or scanning electron microscope for subsequent analysis. When properly performed, field replication microscopy should yield the same results as the metallographic examination process described in Sect., 4.3.3. However, caution should be exercised when selecting a method for preparing the surface of the material for examination. The method used should not result in either physical damage caused by sandblasting, wire wheels, or abrasive disks or material damage caused by acid etches or electropolishing.

Results from field replication microscopy can be used to accurately characterize the microstructure of damaged material and to help establish the root cause for the, degradation. For example, a replica can provide evidence that a crack originated from a manufacturing imperfection or that it was caused by service conditions or damage (Ref. 4.2). It can also be used to determine whether the crack resulted from creep, fatigue, or corrosion. On a microstructural level these cracks have different characteristics. Transgranular cracks such 'as those caused by stress corrosion extend across grain boundaries forming an interconnected random pattern. Cracks caused by creep begin as small holes or cavities at, the grain boundaries and eventually link up to cause failure. Fatigue cracks are generally singular defects that extend across, many grain boundaries. Intergranular cracking tends to follow the grain boundaries.

4.2.6 Estimation of Mechanical and Physical Properties

Material properties can potentially be estimated using results from nondestructive examination techniques provided the results are influenced by material microstructure (Ref. 4.2).

Eddy current, ultrasonic, X-ray and neutron radiography, computed tomography, thermography, and acoustic microscopy phenomena are likely candidates because the results can be related to some mechanical or physical properties. However, these techniques are more suited for locating areas where the microstructure is different by comparison.

4.2.7 Stress-Strain and Dynamic Response Determination

The response of a component to a specific set of loading conditions can be determined using strain sensing techniques such as photoelastic coatings, brittle coatings, and strain gages or displacement transducers. Resulting strain or displacement values combined with known applied stresses can be used to establish the stress-strain characteristics of the material. Strain sensing and displacement measuring techniques can also be used to characterize the dynamic response of a component subjected to shock, impact, or vibration. One potential use for this type of testing is described in Sect. 4.2.8.

Residual stresses in metallic materials can be determined using nondestructive and "semi-destructive" examination techniques. Near-surface residual 'stresses can be measured using" nondestructive examination techniques that involve either X-ray diffraction or electromagnetic methods (Ref. 4.2). Residual stresses just below the surface can be measured using the hole-drilling strain gage technique (Ref. 4.9). This technique is often described as "semi-destructive" because the damage that it causes is very localized and in any cases does not significantly affect the usefulness of the component.

4.2.8 Signature Analysis

The dynamic response of a component is called a signature (Ref. 4.2). Accelerometers, acoustic and displacement transducers, and strain gages can be used to establish the signature of a component produced by a specified set of loading conditions. Analysis of the signature can be correlated with machine noise, shock, vibrations, or structural instability such as buckling **or** cracking. Time-dependent signature differences may indicate that its geometry has changed as a result of cracking, fracture, or buckling or that its mass has changed due to corrosion or erosion. Changes in elastic properties can also affect the signature because the structural stiffness of a component is a function of the modulus of elasticity of the material.

4.2.9 Chemical Composition Determination

The chemical composition of a metal can be determined using a sample of the metal obtained during the pouring of the heat (heat analysis) or a sample of the finished product (product analysis). Chemical requirements for heat and product analyses are provided in the material specification. In general, acceptance standards for product analyses are more liberal than for heat analyses because of a lack of homogeneity in the composition of steel particularly rimmed or capped steels (Ref. 4.10).

4.2.10 Corrosion Characterization

Damage caused by general and localized corrosion can often be detected using the same nondestructive examination techniques that are used to detect flaws. However, the amount of corrosion that has occurred can be difficult to characterize or quantify depending on the specific type of corrosion involved. The types of general and localized corrosion that can potentially affect containment pressure boundary components are identified and described in Tables 3.2 and 3.3.

General Corrosion

General corrosion, which is one of the most common forms of corrosion, is characterized by uniform thinning. Thickness variations caused by corrosion and the size of the affected area can generally be measured using equipment described in Sect. 4.2.3. However, when access is limited, other techniques such as ultrasonics may be required (Ref. 4.11). The rate at which general corrosion attacks metal is often expressed in units of length per unit of time such as millimeters per year (mm/y) or mils* per year (mpy) , but a variety of other units may also be used. Equations for determining average corrosion rates from test specimen data have been developed (Ref. 4.12). These equations factor in exposure time, surface area, material density, and mass loss of the specimen. However, corrosion rates calculated from. mass loss can be misleading especially when deterioration is highly localized, as in pitting or crevice corrosion.

A means for quantifying the amount of rust present on a painted steel surface has also been developed (Ref. 4.13). This test method covers the evaluation of the degree of rusting using visual standards and descriptions of 11 rust grades. In this method, Rust Grade 10 corresponds to no rust or less than 0.01 percent of surface rusted, Rust Grade 4 corresponds to rusting to the extent' of 10 percent of surface rusted, and Rust Grade 0 corresponds to approximately 100 percent of surface rusted.

Pitting Corrosion

Pitting corrosion is localized corrosion of a metal surface, confined to a point or small area, that takes the form of cavities (Ref. 4.14). The extent of pitting corrosion can be determined while the affected component remains in service or in a laboratory using representative samples of the pitted metal. Pits may be round, elongated, or irregularly shaped and have cross-sectional variations such as those illustrated in Ref. 4.14. The shapes in these illustrations are described as "narrow or deep, elliptical; wide or' shallow, subsurface, undercutting, horizontal, and vertical.

Whenever possible, visual inspection is performed to establish the location and density of pits and to identify affected areas. Nondestructive examinations based on radiographic, electromagnetic, ultrasonic, and penetrant techniques can also be used to detect pitting and to establish pit shapes and densities, but these techniques may not be as effective as visual inspections combined with metallographic examinations that use representative portions of the affected metal. Results from metallographic examinations can be particularly important because they can be used to determine whether there is a relationship between pits and inclusions or microstructure, or whether the cavities are true pits or might have resulted from metal dropout caused by intergranular corrosion, dealloying, etc. The extent of pitting is not usually related to mass loss unless general corrosion is slight and pitting is fairly severe. Under these conditions, mass loss data can be valuable, particularly in a laboratory investigation.

Pit depth can be determined by metallographic examination of a pitted region of metal removed from the affected component or by machining operations that gradually remove layers of metal exposing the pitted cross section. Nondestructive examination techniques involving metrology and microscopy can also be effective in determining pit depth as long as the base or bottom of the pit can be established. Pitting can be described or quantified using standard rating charts, depth measurements, statistical methods, and changes in mechanical properties. Standard rating charts (Ref. 4.14) are used to rate pits in terms of density (A), size (B), and depth (C). A typical rating might be A-3, B-2, C-3, representing a density of 5×10^4 pits/m^2, an average pit opening of 2.0 mm^2, and an average pit depth of 1.6 mm. The ratings offer an effective means for reporting data for comparison with other test result, but measurements required to establish the ratings are time consuming and tedious to obtain. Depth measurements of the deepest pits are

* One mil equals 0.001 in.

particularly important when the affected component is part of the containment pressure boundary because a through-thickness hole could lead to loss of leaktight integrity. Metal penetration can be expressed in terms of a pitting factor (Ref. 4.14) which can be determined using the following equation:

$$\text{Pitting Factor} = \frac{\text{deepest metal penetration}}{\text{average metal penetration}} \qquad (1)$$

A pitting factor of one represents uniform corrosion, but extremely small or large values are considered meaningless. When sufficient test data on pitting corrosion are available, the probability (P) that pits will initiate on a metal surface can be established using the following equation:

$$P = \frac{\text{number of specimens that pit}}{\text{total number of specimens}} \times 100 \text{ percent} \qquad (2)$$

The probability is influenced by many factors including the pitting tendency of the metal, corrosivity of the exposure conditions, specimen area, and time of exposure. Other relationships between maximum pit depth and surface area or exposure time can also be developed using field data and laboratory test results.

Effects of pitting can be established by performing mechanical properties tests using corroded and uncorroded replicate specimens. Test methods intended for use in measuring tensile strength, elongation, impact resistance, and fatigue strength can be used for this purpose. In these tests, differences in properties can be attributed to corrosion. However, the erratic nature of pitting and the location of pits on the test specimens can affect the results, and in some cases, the changes in mechanical properties may be too small to be meaningful or significant.

Crevice Corrosion

Crevice corrosion is localized corrosion of a metal surface at, or immediately adjacent to, an area that is shielded from full exposure to the environment because of close proximity between the metal and the surface of another material (Ref. 4.15). Visual detection of crevice corrosion can be difficult or impossible because locations where it occurs are often inaccessible. Crevices can generally be classified as either naturally occurring or man made. Naturally occurring cervices are created by biofouling, sediment, debris, deposits, etc. Man-made crevices are created during manufacturing, fabrication, assembly or service. The geometry of a crevice can be described by the dimensions of the crevice gap and crevice depth (Ref. 4.16). Crevice gap is the width or space between the metal surface and the crevice former. The distance from the mouth to the center, or base of the crevice is the crevice depth.

4.3 DESTRUCTIVE TESTING

Tests that alter the shape, form, size, or structure of the material being tested are considered destructive tests (Ref. 4.4). These test may be performed to determine mechanical, physical, chemical, thermal, or other properties of the material or to examine the material for microstructural imperfections, voids, or inclusions. Destructive tests commonly used to determine mechanical properties of metallic materials involve tension, compression, ductility, shear, torsion, bend,

creep, stress-relaxation, hardness, fatigue, or fracture testing. These tests are usually conducted in room-temperature air but they can also be performed at higher or lower temperatures or under other environmental conditions. Test methods that require the removal and testing of representative portions of material from a' component are also considered destructive tests when the affected component is rendered useless or unfit for future service. The following sections describe the types of results that can be obtained from tension, hardness, and metallographic testing performed on-samples of materials removed from degraded containment pressure boundary components.

4.3.1 Tension Testing

Tension testing involves the gradual application of increasing uniaxial elongation to a test specimen until failure occurs (Ref. 4.17). Specimen geometry and loading conditions generally depend on the size, shape, and type of material being tested. Measurements obtained during tension testing can be used to develop stress-strain curves and to establish mechanical property values such as the modulus of elasticity, ultimate tensile elongation, ultimate tensile strength, yield strength, yield point, and reduction of area.

Property values obtained from tension testing 'are generally used to determine conformance or nonconformance with material specifications. However, test results can also be used to compare the performance and properties of replicate specimens tested under a variety of exposure conditions or using different testing methods. Replicate specimen results can provide a basis for establishing limits on environmental exposure, working stresses, or operating temperatures.

4.3.2 Hardness Testing

Hardness testing is widely used for determining the relative quality of a metallic component and to establish the uniformity of its material properties. It is relatively easy to perform, requires very little material or surface preparation, and usually causes minimal surface damage to the material or component. Testing usually involves an indention hardness tester that uses small diamond points or hardened round steel balls to produce permanent indentations or deformations in the surface of the material being tested. Because a hardness test does not measure a well-defined property, caution should be exercised when hardness indications or numbers obtained using one test method are converted to those obtained using another (Ref. 4.18) or when hardness test results are used to approximate material property values such as tensile strength (Ref. 4.4). Numerous hardness test methods have been developed, but the Brine11 and the Rockwell hardness tests are commonly used (Ref. 4.4).

The Brine11 hardness test is an indention hardness test using calibrated machines to force a hard ball, under specified conditions. into the surface of the material under test and to measure the diameter of the resulting impression' after removal of the load. Hardness, which is reported as a Brine11 hardness number, is related to the applied load and to the surface area of the permanent impression made by the ball indenter and computed using a simple mathematical expression. A Brine11 hardness number followed by the symbol I-IB without any suffix numbers, such as 65 HB, denotes use of a 10-mm diameter ball, a 3,000-kgf load, and a 10- to 15-second loading duration. A complete Brinell hardness number, such as 65 HB 10/500/30, denotes use of a 10-mm diameter ball, a 500-kgf load, and a 30-second loading duration (Ref. 4.19).

The Rockwell hardness test is similar to the Brine11 hardness test except the indenter, which can be either a diamond spheroconical indenter or a hard steel ball indenter, is forced into the surface of the test material using a two-step process. Hardness is represented by a Rockwell hardness number derived using the difference in penetration depth between the two loading steps. Rockwell hardness numbers are always quoted with a scale symbol representing the indenter and forces used followed by the symbol HR and the scale designation. For example, 64 HRC is Rockwell hardness number 64 on the Rockwell C scale (Ref. 4.20).

4.3.3 Metallography

Metallography is the branch of science that relates to the constitution and structure, and their relation to the properties of metals and alloys (Ref. 4.21). Testing is usually performed in a laboratory set up to prepare metallic specimens for microscopic examination. These examinations are conducted to reveal the constituents and structure of the material. Metallography is probably the most useful destructive testing method available for identifying differences in material microstructure caused by exposure to high temperatures or severe environments. Other types of information that can be obtained from microstructural analysis are described in Sect. 4.2.5.

Metallographic testing begins with the selection of material for examination. This is an important activity that should take into consideration the purpose for the examination, especially if the results are to be representative of the material being studied. After the sample is selected and removed, it is firmly mounted for grinding and polishing (Ref. 4.22). The polished surface is examined visually using a microscope to reveal imperfections such as cracks, voids, or entrapped nonmetallics. The specimen is then treated with an etchant such as a two-percent solution of nitric acid in alcohol and the polished surface is reexamined. A photograph of the polished surface showing the observed microstructure is usually prepared to serve as a record of the examination.

Extensive ultrasonic thickness measurements of the Oyster Creek BWR drywell metal containment shell were performed in the 1980s to determine if wall thinning had occurred as a result of corrosion. The measurements were made from inside the containment. Results indicated that wall thinning had occurred adjacent to the sand cushion. Cores were removed from the shell at seven locations to verify the ultrasonic thickness measurements. One of the cores had an actual thickness of 29.7 mm (1.17 in.) when the ultrasonic thickness measurement indicated a thickness of 12.7 mm (0.49 in.). A metallographic examination of the core was performed to determine the cause for the discrepancy. Examination results revealed a difference in the density of the microstructure sufficient to produced a reflection in the ultrasound signal, and the inclusion depth correlated with the ultrasonic thickness measurement (Ref. 4.11).

4.4 IN-SERVICE MONITORING

In-service monitoring involves periodic examination of a containment pressure boundary component while it remains in service. This type of examination is different from the preservice inspection that is conducted before a containment is placed into service and the in-service inspections that are performed on a regular basis over the operating life of the plant. In-service monitoring generally involves repeated examination of a flawed component or suspect area using one or more nondestructive examination, techniques. Data collection can be performed on a case-by-case basis at irregular intervals or at prescribed times using a computer-controlled data acquisition system. Results from in-service monitoring can provide valuable information for assessing the condition of a degraded component, estimating its remaining useful service life, and making informed aging-management decisions.

Selection of nondestructive examination techniques for in-service monitoring requires an understanding of the capabilities and limitations of the various examination options, the types of data that are needed, the frequency and accuracy with which the data are to be collected, and the configuration of the component being monitored. For example, periodic dimensional measurements can be used to establish the crack growth rate of a defective component or the time-dependent change in its thickness caused by wear, erosion, or corrosion. However, adequate space must be available to accommodate the necessary instrumentation and the measurement technique must be sufficiently sensitive to detect the changes that are anticipated. On-line electrochemical measurements can be used to establish the average degradation rate of a component

caused by corrosion (Ref. 4.23) or the cumulative metal loss or the instantaneous corrosion rate of a component under actual service conditions (Ref. 4.24). For these results to be reliable, the sensing probe must be installed in an area that is representative of the corrosive environment to which the component is exposed.

Results obtained from individual in-service examinations can be 'used to determine the status of a degraded component and to accurately 'assess its current condition. Time-dependent results can be used to establish instantaneous. or average degradation rates for use in estimating remaining service life. As an aging-management tool, results obtained from in-service monitoring can be used to guide the selection of appropriate examination techniques, specify testing methods, and establish the frequency of subsequent inspections. One of the most important potential benefits from in-service, monitoring is the detection of undesirable changes in the operating conditions that can adversely affect the performance and useful life of containment pressure boundary components.

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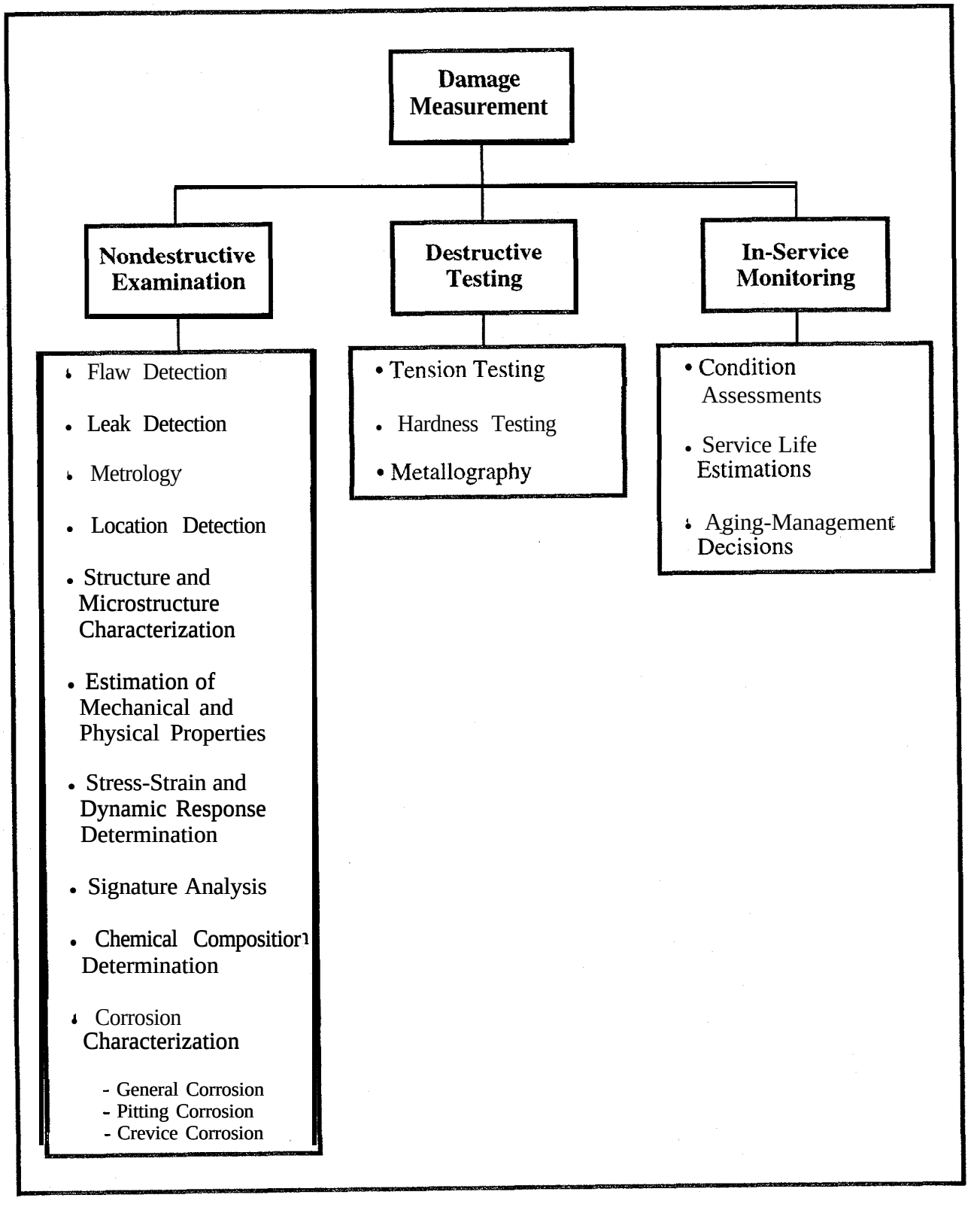

Fig. 4.1 Issues related to the measurement of containment pressure boundary component damage.

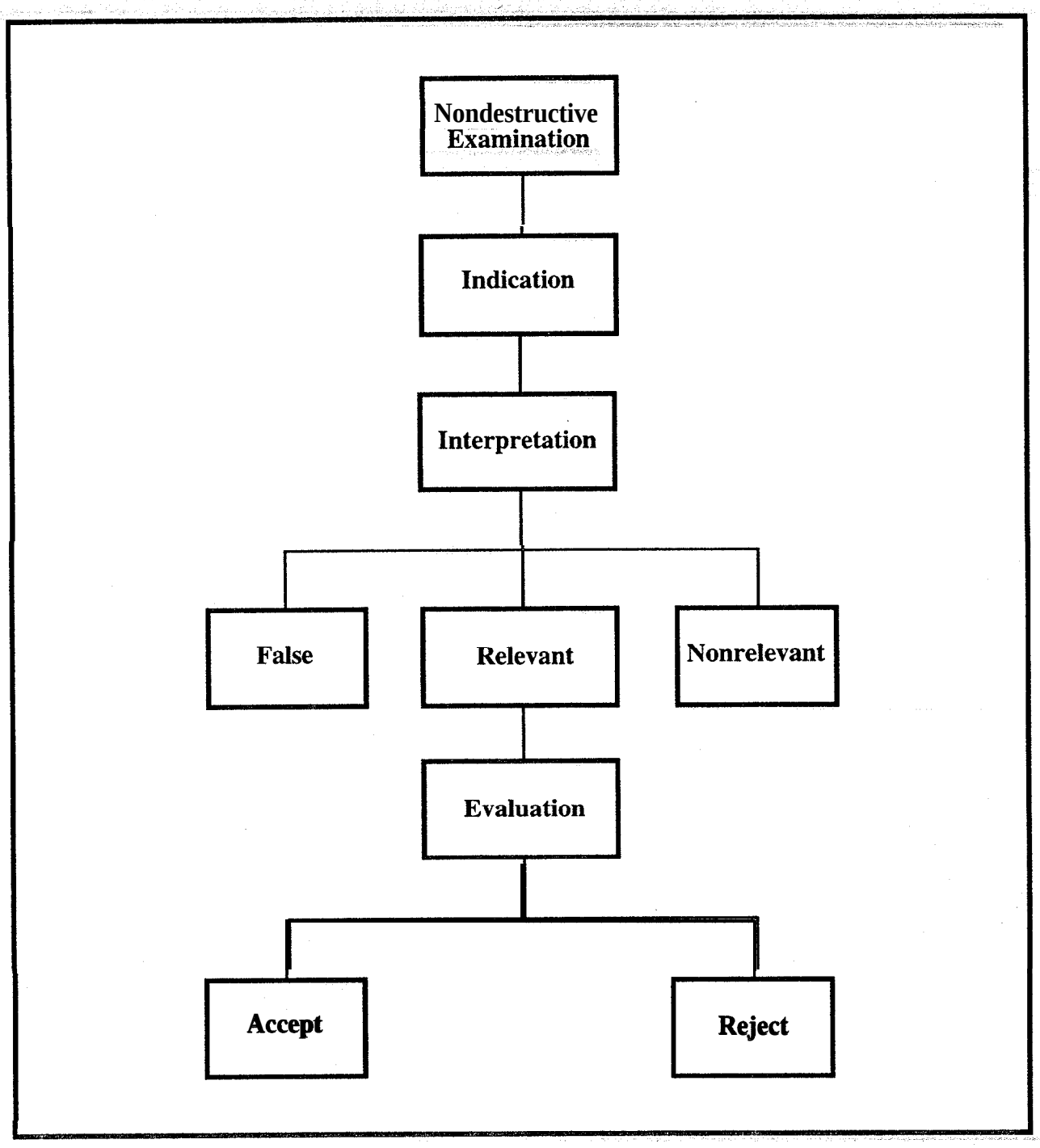

Fig. 4.2 Interpretation that could be made. when a nondestructive examination produces an indication. Source: Ref. 4.5

Table 4.1 Equipment used to aid visual inspection.

Flexible or rigid borescopes for illuminating and observing internal closed or inaccessible areas
Image sensors for remote sensing or for the development of permanent visual records in the form of photographs, video tapes, or computer-enhanced images
Magnifying systems for evaluating surface finish, surface shape, and surface microstructure
Dye and fluorescent penetrants and magnetic particles for enhancing the observation of cracks

Source: Ref. 4.2

5. SUMMARY

5.1 DEGRADATION ASSESSMENT METHODOLOGY

This report describes a degradation assessment methodology intended for use in characterizing the in-service condition of degraded metal and concrete containment pressure boundary components and in quantifying the amount of damage that is present. In-service condition assessments play an important part in the aging management of nuclear power plants by providing vital information for continued service evaluations and service life estimations. Knowledge gained from condition assessments can serve as a baseline for evaluating the safety significance of any damage that may be present and defining in-service inspection programs and maintenance strategies. Assessment results can also be used in estimating future performance and remaining service life.

Condition assessments involve detecting damage in areas of the containment pressure boundary that are potentially vulnerable to in-service deterioration or attack, classifying the types of damage that may be present, determining the root cause of the problem, and quantifying the extent of degradation that may have occurred. Degradation is considered to be any phenomenon that decreases the load-carrying capacity of a pressure-retaining component, limits its ability to contain a fluid medium, or reduces its service life. Because information required to characterize and quantify the condition of degraded components must be established on a case-by-case basis taking into consideration unique containment design features and plant operating constraints, this report provides general, non-prescriptive guidance on performing in-service condition assessments and conducting continued service evaluations. The four elements of an in-service condition assessment are identified and briefly described below.

- **Damage Detection**

  Damage detection is the first and most important step in the condition assessment process. Routine observation, general visual inspections, leakage rate testing, and nondestructive examinations are techniques frequently used to identify areas of the containment that have experienced degradation. However, damage such as wall thinning caused by corrosion can occur in inaccessible locations making detection difficult or impossible. Knowing where to inspect and what type of damage to anticipate often requires information about the design features of the containment and the materials used to construct its pressure-retaining components.

- **Damage Classification**

  Damage occurs when the microstructure of a material is modified by exposure to a severe environment or when the geometry of a component is altered. Determining whether material or physical damage has occurred often requires information about the service conditions to which the component was exposed and an understanding of the degradation mechanisms that could cause such damage.

- **Root-Cause Determination**

  The root cause for component degradation can generally be linked to a design or construction problem, inappropriate material application, a base-metal flaw, or an excessively severe service condition. Determining what caused the degradation can help in identifying the type of damage that has occurred and defining appropriate actions to be taken to reduce or eliminate further deterioration.

- **Damage Measurement**

One way to evaluate the significance of containment pressure boundary component degradation on structural capacity and leaktight integrity is by comparing its preservice condition to its condition after degradation has occurred. Condition assessment accuracy depends on the availability of quantifiable evidence such as dimensions of corroded surface areas, depths of corrosion penetration, or changes in material properties that indicate the extent and magnitude of the degradation. Methods for quantifying component degradation involve either nondestructive examination or destructive testing. Results from these investigations provide a measure of the extent of degradation at the time the component was examined. Techniques for establishing time-dependent change such as corrosion and wear rates involve periodic examination or testing. In-service monitoring provides a way to measure time-dependent changes in component geometry or material properties and to detect undesirable changes in operating conditions that could affect useful service life.

5.2 CONTINUED SERVICE REQUIREMENTS

Current requirements for in-service condition assessments and continued service evaluations of metal and concrete containment structures and components in nuclear power plants are provided in 10 CFR 50, Appendix J (Refs. 5.1 and 5.2). According to these regulations, a general inspection of accessible containment surfaces must be performed prior to each Type A leakage rate test and at two other refueling outages before the next Type A test if the interval for the Type A test has been extended to 10 years (Ref. 5.3) to uncover any evidence of structural deterioration that may affect either the containment structural integrity or leaktightness. When evidence of degradation is detected, corrective actions involving either repair, nondestructive examination, or testing must be taken before the containment can be returned to service. The regulations, which are limited in scope, do not

- define structural deterioration,
- address inspection of inaccessible areas,
- include prescriptive rules for determining acceptable levels of degradation, or
- establish conditions appropriate for continued service.

More detailed inspection requirements, acceptance standards, and evaluation criteria for use in determining the acceptability of degraded components for continued service are provided in Section XI, Division 1, Subsection IWE of the Code (Refs. 5.4 and 5.5). According to these rules, components that are not damaged can be considered acceptable for continued service but damaged components must be evaluated. Evaluations are performed to determine whether the damage is significant enough to adversely affect structural capacity, leaktight integrity, or remaining service life. Components without significant damage are allowed to remain in service, but components with significant damage must be evaluated further to determine whether repairs, replacements, or retrofits are needed. These requirements are not currently being imposed upon licensees because they have not yet been approved by the NRC.

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