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A Survey of Repair Practices for Nuclear Power Plant Containment Metallic Pressure Boundaries

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Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

The Nuclear Regulatory Commission has initiated a program at the Oak Ridge National Laboratory to provide assistance in their assessment of the effects of potential degradation on the structural integrity and leaktightness of metal containment vessels and steel liners of concrete containments in nuclear power plants. One of the program objectives is to identify repair practices for restoring metallic containment pressure boundary components that have been damaged or degraded in service. This report presents issues associated with inservice condition assessments and continued service evaluations and identifies the rules and requirements for the repair and replacement of nonconforming containment pressure boundary components by welding or metal removal. Discussion topics include base and welding materials, welding procedure and performance qualifications, inspection techniques, testing methods, acceptance criteria, and documentation requirements necessary for making acceptable repairs and replacements so that the plant can be returned to a safe operating condition.

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ABBREVIATIONS

AC	alternating current
ACI	American Concrete Institute
ALARA	as low as reasonably achievable
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASNT	American Society for Nondestructive Testing
ASTM	American Society for Testing and Materials
AWS	American Welding Society
BWR	boiling water reactor
CFR	*Code of Federal Regulations*
DC	direct current
DCEN	direct current electrode negative
DCEP	direct current electrode positive
ECCS	emergency core cooling system
FCAW	flux cored are welding
GKN	Neckar I Nuclear Power Plant, Germany
GMAW	gas metal-arc welding
GTAW	gas tungsten-arc welding
HAZ	heat affected zone
KWO	Obrigheim Nuclear Power Plant, Germany
MIC	microbiological induced corrosion
NDE	nondestructive examination
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PAW	plasma-arc welding
PQR	procedure qualification record
PWHT	postweld heat treatment
PWR	pressurized water reactor
RILEM	The International Union of Testing and Research Laboratories for Materials and Structures
SMAW	shielded metal-arc welding
UT	ultrasonic testing
WPQ	welder/welding operator performance qualification
WPS	welding procedure specification

1. INTRODUCTION

1.1 Background

There are 109 light-water reactor nuclear power plants in the United States that have been licensed by the Nuclear Regulatory Commission (NRC) for commercial operation. In some cases, two or more plants are located at a particular site. Each boiling-water reactor (BWR) or pressurized-water reactor (PWR) is located inside a much larger metal or concrete containment vessel that houses and supports the primary coolant system components. These metal and concrete containment systems are designed to provide an essentially leaktight barrier against the uncontrolled release of radioactivity to the environment and to assure that the containment design conditions important to safety are not exceeded for as long as postulated accident conditions require (Ref. 1.1).

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. Although some of these components can be replaced if necessary, most are intended to remain in service for the entire operating life of the plant.

1.2 Scope and Objective

The NRC has initiated a program at the Oak Ridge National Laboratory (ORNL) to provide assistance in their assessment of the effects of potential degradation on structural integrity and leaktightness of metal containment vessels and steel liners of concrete containments in nuclear power plants. One of the program objectives is to identify repair practices for restoring metallic containment pressure boundary components that have been damaged or degraded in service so that the plant can be returned to a safe operating condition. Components of interest are those that are intended to remain in service for as long as the plant is operating such as the ones identified in Sect. 1.1.

Rules and requirements for repair and replacement of damaged or degraded steel pressure boundary components are described in this report. Options that involve welding are frequently considered for these applications because welding provides an effective means for making the types of high-quality repairs and replacements that are required by utility owners, jurisdictional authorities, and regulatory agencies. For this reason, discussions focus primarily on base and welding materials, welding procedure and performance qualifications, inspection techniques, testing methods, acceptance criteria, and documentation that satisfy the requirements of enforcement, regulatory, and jurisdictional authorities, including the NRC. A repair in this context is the process of restoring a nonconforming component by welding or metal removal. Replacement includes the addition of components (modifications) and system changes such as rerouting of piping.

Other topics that may be of importance in the development of a well planned and executed repair or replacement program are also discussed. These topics include:

- underwater welding;
- welding with concrete backing;
- welding repair alternatives involving:

  a. replacement plate welding repairs,
  b. doubler plate welding repairs,
  c. stiffener plate welding repairs, and
  d. overlay welding repairs;

- temporary non-code repairs that are acceptable to the NRC; and
- options for restoring damaged bellows.

In addition, issues pertaining to protective coating repairs and cathodic protection systems are presented.

Maintenance activities involving metallic and non-metallic components such as seals and gaskets that are designed to be routinely repaired or periodically replaced as part of normal plant operations are not addressed.

1.3 Performance History

Since nuclear power plants have been in operation, inservice performance of metal and concrete containments has generally been very good. However, instances of wall thinning, coating degradation, moisture barrier deterioration, and component damage have been reported (Refs. 1.2 to 1.6). 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 (Ref. 1.7). Past experience also suggests that degradation of metal containment shells can occur on the inside as well as the outside of the containment vessel. Potential locations for corrosion of steel liners in concrete containments include the junction of the containment cylinder and intermediate floors and basemat concrete for PWR and BWR Mark III containments, the junction of the drywell and the base or intermediate concrete floors for BWR Mark I and II containments, surfaces adjacent to crane girder rails and supports attached to the liner plate of concrete containments, water-soaked areas where carbon steel liner plate is used in BWR Mark I and II containments, and surfaces behind insulation and ice condenser baskets (Ref. 1.6).

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 is detected and containment integrity is jeopardized, defective areas are either evaluated, repaired, or replaced before the plant is returned to service. Under certain conditions, inservice inspection programs have even been initiated to periodically examine suspect areas or to monitor the long-term performance of degraded components. Requirements for monitoring the effectiveness of maintenance at nuclear power plants have been issued by the NRC (Ref. 1.8).

1.4 Inservice Condition Assessments

Inservice condition assessments play an important part in the aging management of nuclear power plants by providing vital information for continued service evaluations. Knowledge gained from condition assessments can serve as a baseline for evaluating the safety significance of any damage that may be present and defining inservice inspection programs and maintenance strategies.

Condition assessments involve detecting damage in areas of the containment pressure boundary that are potentially vulnerable to inservice 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, non-prescriptive guidance on performing inservice condition assessments and conducting continued service evaluations has been prepared (Ref. 1.7). The four elements of an inservice condition assessment and the topics associated with each are shown in Fig. 1.1 and discussed below.

1.4.1 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.

1.4.2 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.

1.4.3 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.

1.4.4 Damage Measurement

One way to evaluate the significance of containment pressure boundary component degradation on structural integrity and leaktightness 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. Inservice 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.

1.5 Continued Service Evaluations

From an aging management viewpoint, metal and concrete containment pressure boundary components that exhibit satisfactory long-term performance and do not experience inservice degradation can be considered acceptable for continued service. However, components found by routine examination or inservice inspection to be deteriorated or damaged must be evaluated to determine whether continued service is appropriate or whether repairs or replacements are needed. Damage is considered significant when it adversely affects structural integrity, leaktightness, or remaining service life.

Current requirements for inservice 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. 1.1 and 1.9). According to these regulations, a visual examination of accessible interior and exterior containment surfaces should be conducted prior to initiating a Type A leakage-rate 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. 1.10). The purpose for these examinations is to uncover any evidence of structural deterioration that may affect either the containment structural integrity or leaktightness. When evidence of degradation is detected, the condition must be corrected or evaluated before the containment can be returned to service. Continued service is permitted after one or more of the following actions have been taken.

1. Unacceptable flaws, discontinuities, or areas of degradation have been removed to the extent necessary to meet the acceptance standards.

2. A repair involving welding has been completed such that existing design requirements are met.

3. Replacement of the component or portion of the component containing the unacceptable flaws or areas of degradation has been accomplished.

4. An engineering evaluation has been performed revealing that the flaws, discontinuities, or areas of degradation have no effect on structural integrity or leaktightness.

Rules and requirements for removing defects and for making acceptable repairs and replacements are well established in codes and standards that have been adopted by the NRC (Ref. 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. 1.11). The decision-making process begins with an understanding of the inservice condition of each containment component (Ref. 1.12 and 1.13). A diagram that illustrates the continued service evaluation process is shown in Fig. 1.2.

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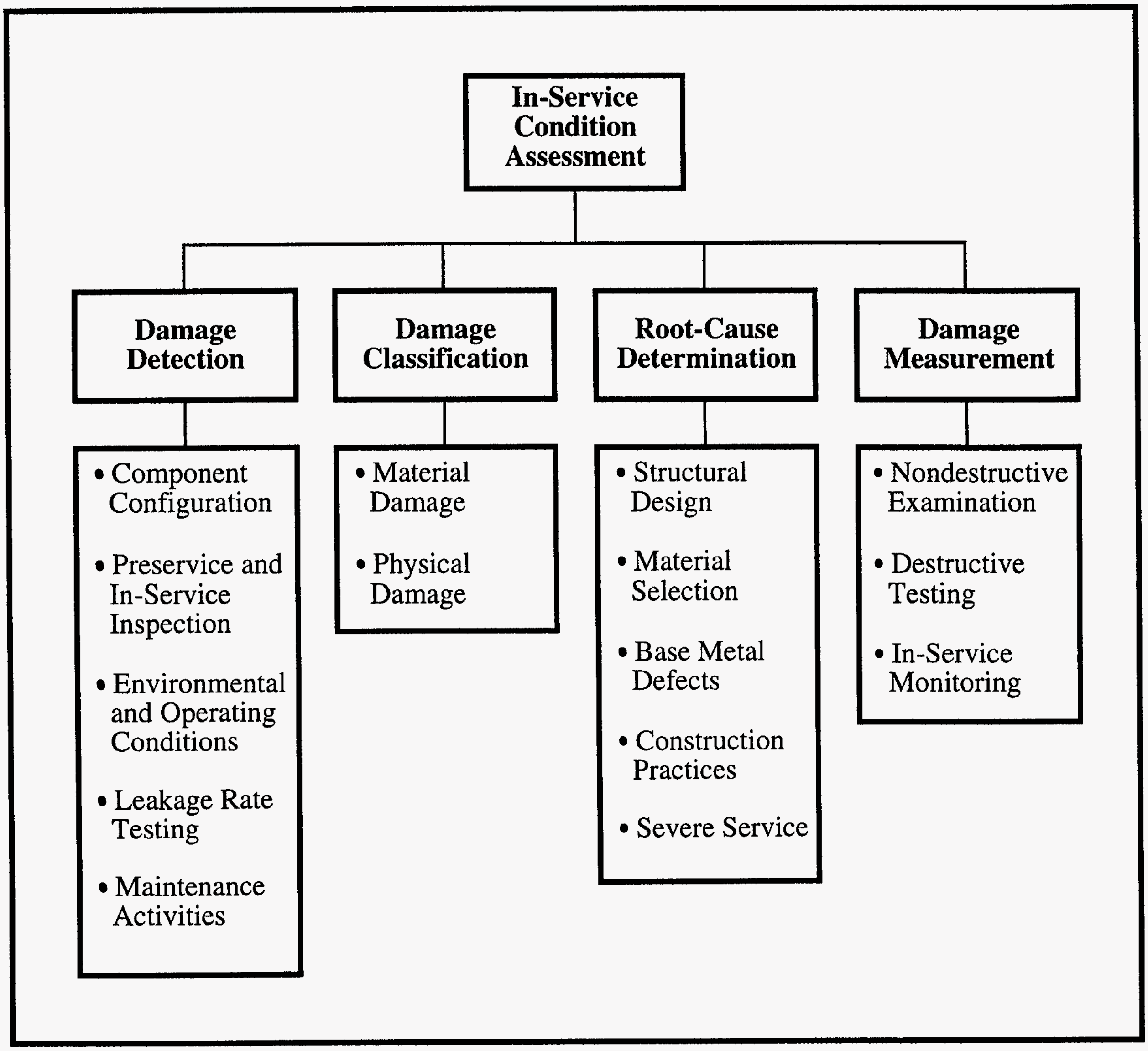

Fig. 1.1 Major topics pertaining to inservice condition assessments.

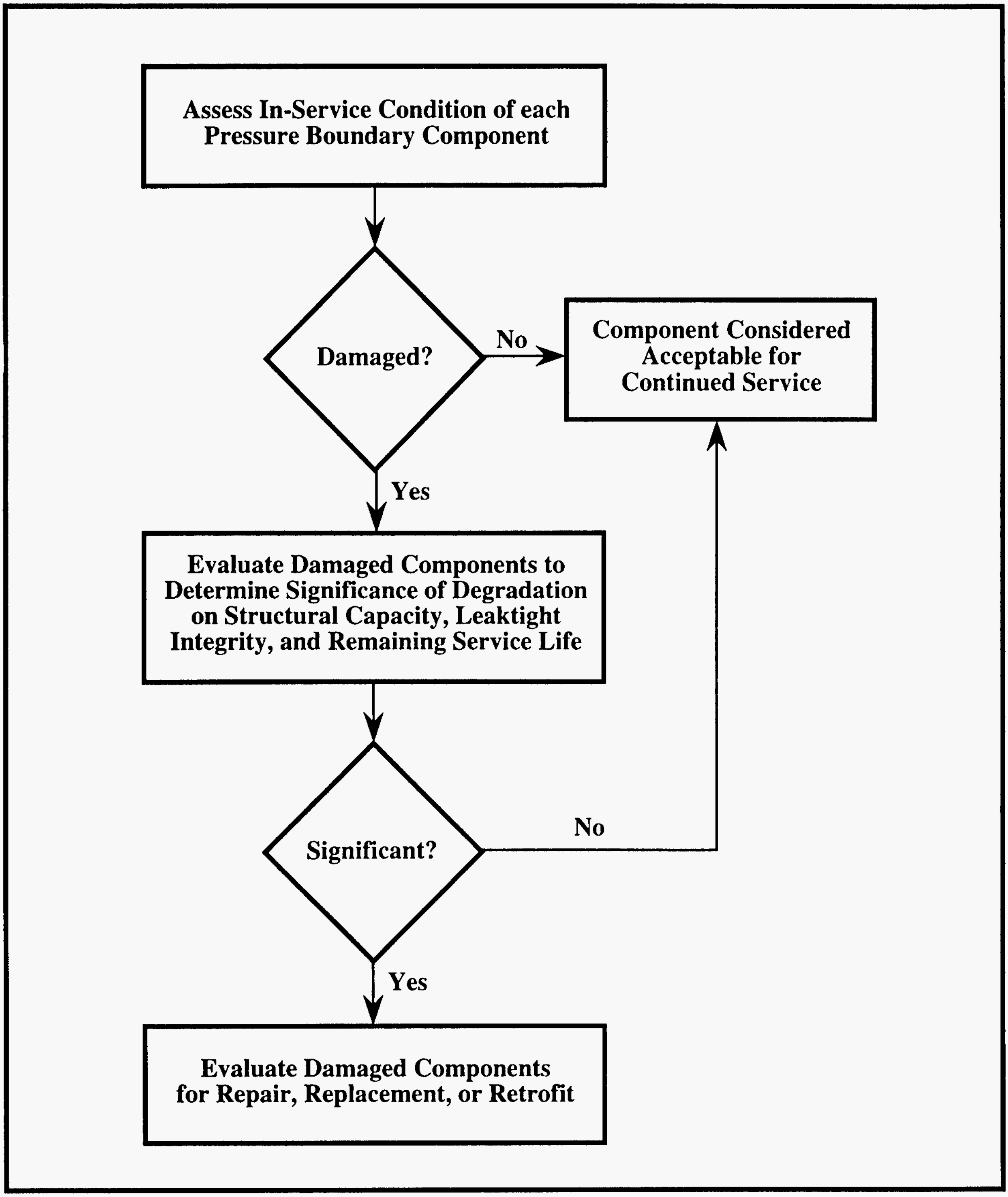

Fig. 1.2 Continued service evaluation process for containment pressure boundary components.

2. RULES AND REQUIREMENTS

2.1 Construction

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. The Code is written, revised, and interpreted by the committee process. All members are volunteers who are supported by their employers. Committee meetings are held regularly to consider revisions of the rules, new rules as dictated by technological development, code cases, and requests for interpretations. The entire Code system consists of several volumes that have been subdivided into sections. In order to avoid duplication of requirements, the various volumes have been organized into construction codes and reference codes. Construction codes provide rules and requirements for component manufacturing. Reference codes are used only when referenced by the construction code and only as specified. New editions of the Code are issued every three years on July 1, but addenda, which contain updated information and revisions, are published annually in the winter. Errata are issued when necessary to correct printer's or typographical errors and are normally retroactive to the issue date of the addenda. Code cases are issued to provide alternative or new rules to the Code. Although code cases are never mandatory, they are issued on a case-by-case basis and are only applicable to the Code specified. Interpretations are official opinions by the ASME which clarify the intent of the Code based on the question asked. Interpretations can be made only by ASME in writing and must be signed by the secretary of the applicable subcommittee.

Construction rules for nuclear power plant components are contained in Section III (Refs. 2.1 and 2.2) of the Code. Current rules for material, design, fabrication, examination, inspection, testing, and preparation of reports for Class MC (metal) containment vessels for nuclear power plants are provided in Section III, Division 1, Subsection NE (Ref. 2.1) of the Code. Corresponding rules for Class CC (prestressed or reinforced) concrete containments are provided in Section III, Division 2, Subsection CC (Ref. 2.2) of the Code. Rules for preservice and inservice examination, testing, and inspection of components and systems in nuclear power plants including Class MC components and metallic liners of Class CC components are provided in Section XI, Division I, Subsection IWE (Ref. 2.3) of the Code. The jurisdiction of Section XI covers individual components that have met all the requirements of the construction code.

Reference codes cited in the construction codes include Sections II, V, and IX. Section II – Materials (Ref. 2.4) is subdivided into four parts. Part A – Ferrous Material Specifications and Part B – Nonferrous Material Specifications contains base metal specifications that have been adopted by the American Society for Testing and Materials (ASTM). Material specifications for welding rods, electrodes, and filler metals that have been adopted by the American Welding Society (AWS) are contained in Part C. Part D provides tables of property values for the ferrous and nonferrous metals included in Parts A and B. Nondestructive examination (NDE) requirements and methods specified in the construction codes are provided in Section V – Nondestructive Examination (Ref. 2.5). The NDE methods are intended to detect surface and internal discontinuities in materials, welds, and fabricated parts and components. They include radiographic examination, ultrasonic examination, liquid penetrant examination, magnetic particle examination, eddy current examination, visual examination, leak testing, and acoustic emission examination. The NDE methods are described in Subsection A. Subsection B contains consensus standards that cover each NDE method. Personnel performing nondestructive examinations must be qualified and certified using a written practice prepared in accordance with ANSI/ASNT CP-189, *Standard for Qualification and Certification of Nondestructive Testing Personnel* (Ref. 2.6). Qualification for welders, welding operators, brazers, and brazing operators, and the procedures employed in welding or brazing in accordance with construction code requirements are provided in Section IX – Welding and Brazing Qualifications (Ref. 2.7).

Requirements that have been adopted by the NRC pertaining to applicable codes and standards for nuclear power plant construction are provided in Title 10, Part 50 of the *Code of Federal Regulations* (Ref. 2.8).

2.2 Repairs and Replacements

A repair is the process of restoring a nonconforming component by welding, brazing, or metal removal such that existing design requirements are met (Ref. 2.9). The nonconformance may be the result of material damage caused when the microstructure of a material was modified by exposure to a hostile environment or physical damage caused when the geometry of a component was altered. Potential causes for these two damage categories are identified in Fig. 2.1 (Ref. 2.10). Examples of repair activities include:

- removing weld or material defects,
- reducing the size of defects to a size acceptable to the applicable flaw evaluation criteria, and
- addition of weld or braze material.

Defects are flaws, discontinuities, or groups of discontinuities whose indications do not meet specified acceptance criteria (Ref. 2.11). Components found to contain defects that do not meet acceptance standards may be acceptable for continued service without the removal or repair of the defect or replacement if an engineering evaluation indicates that the defect is nonstructural in nature or has no effect on the structural integrity of the containment. Components containing defects that are not acceptable based on an engineering evaluation may not be returned to service until the defect has been either removed by mechanical methods or repaired, or the component or portion of the component containing the defect is replaced (Ref. 2.3).

Replacement includes the addition of components, such as valves, and system changes, such as rerouting of piping. Possible reasons for replacing nuclear power plant components are listed in Table 2.1.

Current rules and requirements for repair of pressure-retaining components by welding, brazing, or metal removal; specification and construction of items to be used for replacement; and installation of replacement items are provided in Section XI, Division 1, Article IWA-4000 (Ref. 2.9) of the Code and in Code Case N-236-1 (Ref. 2.12). Additional requirements that have been adopted by the NRC pertaining to applicable codes and standards are provided in Title 10, Part 50 of the *Code of Federal Regulations* (Ref. 2.8). Regulations in paragraph 50.55a impose limitations on specific editions and addenda of Section XI, Division 1 of the Code dealing with Class MC and Class CC components up through and including the 1992 Edition and the 1992 Addenda. These regulations adopt requirements in Subsections IWE and IWL (Refs. 2.13 and 2.14) of the Code with modifications that address examination of concrete containments and examination of metal containment and liners of concrete containments. Revisions made to Section XI, Division 1 of the Code since 1992 have not yet been approved by the NRC and, therefore, are not currently being imposed upon licensees.

Guidelines for determining whether an activity is considered a repair or a replacement are provided in Section XI, Division 1, Nonmandatory Appendix J (Ref. 2.15) of the Code in the form of a decision tree. The decision tree is also useful for distinguishing repair and replacement activities (including modifications) from maintenance which is considered a separate activity. Examples of maintenance activities include:

- adjustment of packing, removal of bonnet, stem, or actuator, or disconnecting hydraulic or electrical lines on valves;
- changing oil, flushing the cooling system, adding packing rings or mechanical seal maintenance on pumps;
- grinding or machining on valve disk seating surfaces;
- removing arc strikes or weld spatter in the area of previous preservice or inservice surface examinations; and
- preparing welds for nondestructive examinations (Ref. 2.15).

2.3 Responsibility

Whenever a repair or replacement is considered necessary, it is the Owner's responsibility to provide a Repair/Replacement Program and Plans as required by Section XI, Division 1, Article IWA-4000 (Ref. 2.9) of the Code. The Owner must also determine the applicable construction code edition, addenda, and code cases used for the item being repaired or replaced and provide specifications for the repair or replacement (Ref. 2.16).

The organization responsible for the repair or replacement must have an established quality assurance program that complies with applicable quality assurance program criteria provided in 10 CFR 50, Appendix B (Ref. 2.8). The quality assurance documentation should include written policies, procedures, or instructions that control the activities addressed in the Repair/Replacement Program and Plans. When the responsibility for repair or replacement is split between the Owner and a repair organization, it is the Owner's responsibility to assure that the combination of the two quality assurance programs cover all activities prescribed in the Repair/Replacement Program and Plans.

2.4 Repair/Replacement Program and Plans

The Repair/Replacement Program is a document that defines the managerial and administrative control for the repair and replacement of items. Items are considered to be material, parts, appurtenances, piping subassemblies, components, or component supports (Ref. 2.9). This program also includes Repair/Replacement Plans that contain essential requirements for completion of the repair or replacement. A list of topics that should be identified in the Repair/Replacement Plans is presented in Table 2.2. After the Repair/Replacement Program, Repair/Replacement Plans, and required evaluations of acceptability have been prepared, they should be submitted for review to enforcement and regulatory authorities, including the NRC, having jurisdiction at the plant site.

2.5 Evaluation of Acceptability

If an item is considered unsatisfactory and a repair or replacement is determined to be necessary, the Owner should establish the cause of the unacceptability and evaluate the suitability of the repair or replacement prior to returning the item to service. Deficiencies resulting from a design or construction problem, inappropriate material application, a base-metal flaw, or an excessively severe service condition should be considered as the specification for the repair or replacement item is being prepared. Corrective provisions included in the specification should also be consistent with the relevant Owner's requirements and either the construction code or Section III of the Code in effect at the time of the specification revision.

2.6 Inspection

Repairs and replacements must be inspected and accepted before the containment can be returned to service (Ref. 2.9). These inspections may involve the following:

- Authorized Inspection Agency
- National Board of Boiler and Pressure Vessel Inspectors
- Certificate of Competency
- Certificates of Authorization
- Certificate Holders
- Authorized Nuclear Inspectors

2.6.1 Authorized Inspection Agency

The services of an Authorized Inspection Agency must be used when making repairs and replacements (Ref. 2.9). An Authorized Inspection Agency is either a jurisdiction that has adopted and administers Section XI, Division 1 (Ref. 2.1) of the Code as a legal requirement and is qualified to be represented on the ASME Code Conference Committee, or an insurance company authorized to write boiler and pressure vessel insurance within a particular jurisdiction in the United States or a Province of Canada. The Owner is responsible for notifying the Authorized Inspection Agency before work is initiated and for keeping the appropriate Authorized Inspector informed of the progress so that necessary inspections can be performed.

The Authorized Inspection Agency must be accredited by ASME in accordance with the provisions set forth in ASME N626-1990, "Qualifications and Duties for Authorized Inspection Agencies and Personnel" (Ref. 2.17). Some of the more important duties of the Authorized Inspection Agency are listed in Table 2.3.

2.6.2 The National Board

The National Board of Boiler and Pressure Vessel Inspectors (also known as the National Board) is an organization made up of the officials charged with the enforcement of boiler and pressure vessel laws within a jurisdiction in the United States or Province of Canada. The objectives of the National Board are to promote:

- uniform administration and enforcement of boiler and pressure vessel laws;
- standardization of construction and operation;
- standardization of inspector qualifications; and
- testing of safety valves built in accordance with ASME Boiler and Pressure Vessel Code requirements.

In order for an individual to be an Authorized Inspector, the individual must obtain a commission issued by the National Board. A commission is issued based on a written examination and must be renewed annually. Various endorsements may be obtained after further training and examination. Examples of these are the N, S, I, and Is qualifications for an Authorized Nuclear Inspector, Authorized Nuclear Inspector Supervisor, Authorized Nuclear Inservice Inspector, and Authorized Nuclear Inservice Inspector Supervisor, respectively. Authorized Nuclear Inspectors and Supervisors monitor construction in accordance with Section III, Division 1 (Ref. 2.1) of the Code. Authorized Nuclear Inservice Inspectors and Supervisors monitor inservice examinations, tests, repairs, and replacements in accordance with Section XI (Ref. 2.3) of the Code. Qualifications and duties for each type of inspector are presented in Sect. 2.6.5. The endorsements to which an individual has been qualified are clearly printed on a commission card provided by the National Board. A National Board Commission may be revoked for:

- falsification of any information on the application,
- neglect of duties spelled out in the ASME Boiler and Pressure Vessel Code, and
- falsification of any data report.

2.6.3 Certificate of Competency

A Certificate of Competency is a "work card" or commission issued by a jurisdiction. This certificate is generally required to perform inservice inspections within the jurisdiction. However, some jurisdictions also require it to perform shop inspections. The commission is generally reciprocal among jurisdictions and is issued based on the successful completion of the National Board examination. Some jurisdictions have additional requirements such as an oral examination on their specific laws.

2.6.4 Certificate of Authorization

A Certificate of Authorization is a document that is issued by ASME authorizing the use of an ASME Code Symbol Stamp for a specified time and for a specified scope of Code activities. A Certificate Holder is an organization holding a valid Certificate of Authorization. Various types of Certificates of Authorization may be issued to a Certificate Holder depending on the type of Code-related work that is involved. Organizations that perform nuclear-related construction in accordance with Section III (Ref. 2.1) of the Code may hold either an N, NV, NPT, or NA Certificate of Authorization.

Responsibilities and authorizations for N, NV, NPT, and NA Certificate Holders are provided in Section III, Articles NCA-3000 and NCA-8000 (Ref. 2.18) of the Code. Basically an N Certificate of Authorization must be obtained for the construction of any item intended to be in compliance with the requirements of Section III (Refs. 2.1 and 2.2) of the Code and to be stamped with the N Code Symbol. The N Code Symbol Stamp corresponds to construction of nuclear vessels including metal and concrete containments, pumps, pressure relief valves, line valves, storage tanks, piping systems, and core support structures. An N Certificate Holder may do all of the work of the NPT or NA Certificate Holder at the location shown on the Certificate of Authorization provided that the scope of work is included in the certificate. NV Certificate Holders may only perform work involving pressure relief valves that require the NV Code Symbol Stamp. NPT Certificate Holders may only perform construction involving tubular products welded with filler metal, parts, appurtenances, piping subassemblies, and component supports that require the NPT Code Symbol Stamp. NA Certificate Holders may only perform construction involving placing and attaching of components to support structures that require a NA Code Symbol Stamp.

A Certificate of Authorization is issued to an organization after a joint review of the quality assurance program and its implementation is performed by ASME and the Authorized Inspection Agency, and the ASME Accreditation Committee has voted its approval. Prior to application for a Certificate of Authorization, the organization should have the following:

- properly trained and qualified personnel who have knowledge and thorough understanding of the applicable ASME Codes and referenced standards,
- facilities adequate to handle the scope of work, and
- a contract with an Authorized Inspection Agency.

A Certificate of Authorization that is issued by the ASME is granted for a three-year period.

Organizations including N Certificate Holders that perform repairs, replacements, or modifications of nuclear components may be required to obtain a National Board Certificate of Authorization to use the NR Symbol Stamp. Repairs, replacements, or modifications performed under the NR Certificate of Authorization must be in accordance with the provisions of the National Board Inspection Code, Section XI (Ref. 2.3) of the Code, and the rules of the jurisdiction. Before the National Board of Boiler and Pressure Vessel Inspectors will issue an NR certificate, the organization must have the following:

- an inspection agreement with an Authorized Nuclear Inspector,
- a written quality system program,
- a current edition of the National Board Inspection Code (Ref. 2.19), and
- copies of the original code of construction appropriate to the intended scope of work and ASME Section XI.

A Certificate of Authorization that is issued by the National Board of Boiler and Pressure Vessel Inspectors is granted for a three-year period.

2.6.5 Authorized Inspector Qualifications and Duties

Authorized Nuclear Inspectors (N), Authorized Nuclear Inspector Supervisors (S), Authorized Nuclear Inservice Inspectors (I), and Authorized Nuclear Inservice Inspector Supervisors (Is) are employees of an Authorized Inspection Agency that meet the qualification requirements provided in ASME N626-1990 (Ref. 2.17) and summarized in Tables 2.4 and 2.5.

Authorized Nuclear Inspectors and Authorized Nuclear Inspector Supervisors are responsible for performing inspections required by Section III (Refs. 2.1 and 2.2) of the Code. Duties of an Authorized Nuclear Inspector include, but are not necessarily limited to those listed in Table 2.6.

Authorized Nuclear Inservice Inspectors and Authorized Nuclear Inservice Inspector Supervisors are responsible for verifying that examinations, tests, and repairs (that do not include welding or brazing) are performed in accordance with Section XI (Ref. 2.3) of the Code. Other duties of an Authorized Nuclear Inservice Inspector include, but are not necessarily limited to those listed in Table 2.7.

2.7 Code Applicability

The Owner is responsible for determining the applicable construction code edition, addenda, and code cases used for the item being repaired or replaced and provides specifications for the repair or replacement. The repair or replacement must be performed in accordance with the Owner's Design Specification and the original construction code of the component or system. However, later editions and addenda of the construction code or applicable portions of Section III (Refs. 2.1 and 2.2) of the Code and code cases may be used (Ref. 2.16).

The edition and addenda of Section XI used for the Repair/Replacement Program should correspond to the edition and addenda identified in the inservice inspection program applicable to the inspection interval. Later editions and addenda, either in their entirety or portions thereof, may be used for the Repair/Replacement Program provided these editions and addenda at the time of the planned repair or replacement have been incorporated by reference in amended regulations of the regulatory authority having jurisdiction at the plant site. If repair welding cannot be performed in accordance with these requirements, the applicable alternative requirements provided in Section XI, Article IWA-4000 (Ref. 2.9) of the Code may be used.

References

2.1 "Rules for Construction of Nuclear Power Plant Components," *ASME Boiler and Pressure Vessel Code*, Section III, Division 1, Subsection NE, Class MC Components, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

2.2 "Rules for Construction of Nuclear Power Plant Components," *ASME Boiler and Pressure Vessel Code*, Section III, Division 2, Code for Concrete Reactor Vessels and Containments, Subsection CC, Concrete Containments (Prestressed or Reinforced), American Society of Mechanical Engineers, New York, New York, July 1, 1995.

2.3 "Rules for Inservice Inspection of Nuclear Power Plant Components," *ASME Boiler and Pressure Vessel Code*, Section XI, Division 1, Subsection IWE, Requirements for Class MC and Metallic Liners of Class CC Components of Light-Water Cooled Plants, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

2.4 "Materials," *ASME Boiler and Pressure Vessel Code*, Section II, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

2.5 "Nondestructive Examination," *ASME Boiler and Pressure Vessel Code*, Section V, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

2.6 *Standard for Qualification and Certification of Nondestructive Testing Personnel*, ANSI/ASNT CP-189, American Society for Nondestructive Testing, Inc., Columbus, Ohio, 1991.

2.7 "Qualification Standards for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators," *ASME Boiler and Pressure Vessel Code*, Section IX, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

2.8 "Domestic Licensing of Production and Utilization Facilities," *Code of Federal Regulations*, Title 10, Part 50, January 1, 1997.

2.9 "Rules for Inservice Inspection of Nuclear Power Plant Components," *ASME Boiler and Pressure Vessel Code*, Section XI, Division 1, Subsection IWA, General Requirements, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

2.10 Oland, C. B. and Naus, D. J., "Degradation Assessment Methodology for Application to Steel Containments and Liners of Reinforced Concrete Structures in Nuclear Power Plants," ORNL/NRC/LTR-95/29, Oak Ridge National Laboratory, Oak Ridge, Tennessee, January 1996.

2.11 "Standard Terminology for Nondestructive Examinations," ASTM Designation: E 1316-91b, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1991.

2.12 "Repair and Replacement of Class MC Vessels," Case N-236-1, *ASME Boiler and Pressure Vessel Code*, 1995 Code Cases, Nuclear Components, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

2.13 "Rules for Inservice Inspection of Nuclear Power Plant Components," *ASME Boiler and Pressure Vessel Code*, Section XI, Division 1, Subsection IWE, Requirements for Class MC and Metallic Liners of Class CC Components of Light-Water Cooled Plants, American Society of Mechanical Engineers, New York, New York, July 1, 1992.

2.14 "Rules for Inservice Inspection of Nuclear Power Plant Components," *ASME Boiler and Pressure Vessel Code*, Section XI, Division 1, Subsection IWL, Requirements for Class CC Components of Light-Water Cooled Plants, American Society of Mechanical Engineers, New York, New York, July 1, 1992.

2.15 "Rules for Inservice Inspection of Nuclear Power Plant Components," *ASME Boiler and Pressure Vessel Code*, Section XI, Division 1, Nonmandatory Appendix J, Guide to Plant Maintenance Activities and Section XI Repair/Replacements, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

2.16 "Alternative Rules for Repairs, Replacements, or Modifications," Case N-389-1, *ASME Boiler and Pressure Vessel Code*, 1995 Code Cases, Nuclear Components, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

2.17 "Qualifications and Duties for Authorized Inspection Agencies and Personnel," ASME N262-1990, American Society of Mechanical Engineers, New York, New York, September 4, 1990.

2.18 "Rules for Construction of Nuclear Power Plant Components," *ASME Boiler and Pressure Vessel Code*, Section III, Subsection NCA, General Requirements for Division 1 and Division 2, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

2.19 *National Board Inspection Code*, 1995 Edition, The National Board of Boiler and Pressure Vessel Inspectors, Columbus, Ohio, 1995.

2.20 "Recommended Practice for Nondestructive Testing Personnel Qualification and Certification," SNT-TC-1A, 1984 Edition, American Society for Nondestructive Testing, Inc., Columbus, Ohio, 1984.

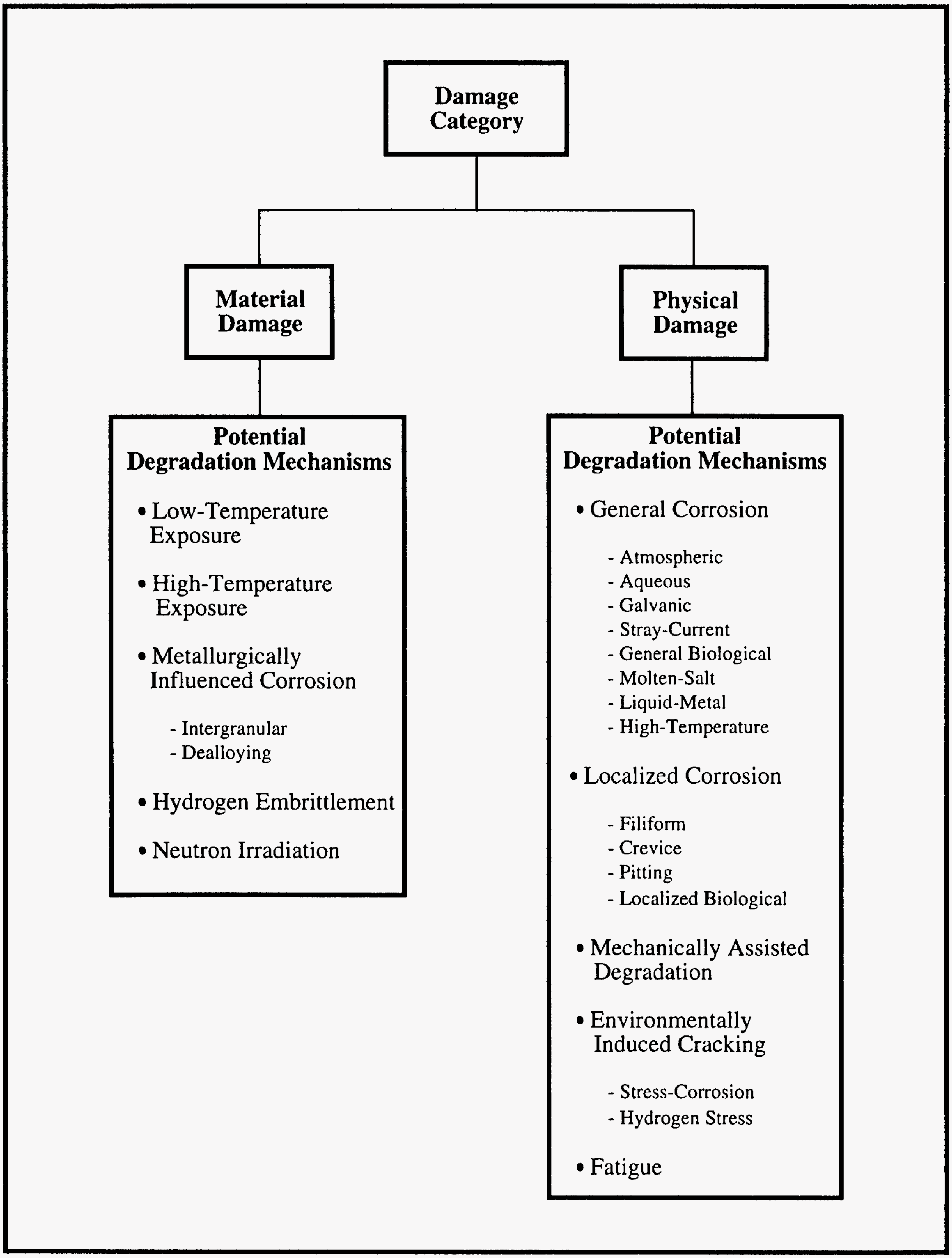

Fig. 2.1 Damage categories and potential degradation mechanisms.

Table 2.1 Reasons for replacement of nuclear power plant components.

- Discrepancies detected during inservice inspection
- Regulatory requirements change
- Design changes to improve equipment service
- Changes to improve reliability
- Damage
- Failure during service
- Personnel exposure
- Economics
- End of service life
- Discrepancies detected during maintenance

Table 2.2 Topics to be identified in the Repair/Replacement Plan.

- Applicable edition, addenda, and code cases of Section XI
- Construction code edition, addenda, code cases and Owner's requirements for the following:
  1. construction of the item to be repaired or replaced
  2. construction of the item to be used for replacement
  3. performance of the repair
- For a repair, description of the flaw and the nondestructive examination method used to detect the flaw
- For a repair, the flaw removal method, method of measurement of the cavity created by removing the flaw; and, when required, requirements for recording reference points during and after repair
- Description of work to be performed on the item
- Applicable weld procedure, heat treatment, nondestructive examination, tests, and material requirements
- Applicable examination, test, and acceptance criteria to be used to verify acceptability
- Intended life of the repair or the item to be used for replacement, when less than the remainder of the design life of the item
- For replacement, whether application of the ASME Code Symbol Stamp is required
- Documentation requirements

Table 2.3 Some of the more important duties of the Authorized Inspection Agency.

- Participate in joint reviews of the quality control manual for adequacy and audit to verify proper implementation
- Provide qualified Authorized Nuclear Inservice Inspectors to monitor repair and replacement activities in accordance with Section XI, Division 1 requirements
- Maintain qualified Authorized Nuclear Inservice Inspector Supervisors to monitor the performance of the Authorized Nuclear Inservice Inspectors and to audit the activities at nuclear shops and field sites for which inspection agreements have been made
- Provide all Authorized Nuclear Inservice Inspectors with the name, office and home addresses, and telephone numbers of the respective supervisor
- Assure proper execution of responsibilities by providing written instructions to Authorized Nuclear Inservice Inspectors and Authorized Nuclear Inservice Inspector Supervisors outlining their duties and responsibilities including instructions to inspectors telling them to contact their supervisor when Code problems cannot be resolved and when new Code requirements may affect them
- Provide certification for each Authorized Nuclear Inservice Inspector and Supervisor
- Submit to the National Board of Boiler and Pressure Vessel Inspectors an application for a special endorsement for each Authorized Nuclear Inservice Inspector and Authorized Nuclear Inservice Inspector Supervisor applicant, certifying that the individual has the required experience and training

Table 2.4 Summary of Authorized Nuclear Inspector and Authorized Nuclear Inspector Supervisor qualifications.

Qualification	Authorized Nuclear Inspector (N)	Authorized Nuclear Inspector Supervisor (S)
Hold a valid state Certification of Competency (where required) and a valid National Board Commission.	√	
Have a minimum of one year of diversified shop inspection experience in the construction of Section I or Section VIII pressure vessels, or one year of diversified experience as an inspector trainee of nuclear items under the direct supervision of an Authorized Nuclear Inspector.	√	
Have demonstrated the ability to perform shop and field (on-site) inspections to the satisfaction of the Authorized Inspection Agency.	√	
Have a satisfactory degree of expertise, experience, and background for the inspection of nuclear items, according to the complexity of the assignment.	√	
Have knowledge of applicable sections of the ASME Code and code cases.	√	
Have knowledge of quality assurance manuals and shop and field procedures.	√	
Have knowledge and ability to evaluate and monitor shop and field procedures.	√	
Have knowledge of the requirements for maintenance and retention of in-transit and permanent records.	√	
Achieve a passing grade on an examination in the methods of welding and nondestructive examinations for Authorized Nuclear Inspectors, given by the National Board, covering knowledge of, and familiarization with, the ASME Code.	√	
Have qualified as an Authorized Nuclear Inspector (N).		√
Have passed an examination developed, promulgated, and administered by the National Board that focuses on the ability of the individual to ascertain the validity and quality of nondestructive examination and quality assurance requirements of Section III of the Code.		√
Have knowledge of basic fundamentals of health physics, insofar as permissible exposure to radiation is concerned and have the ability and means to properly administer affected personnel schedules so as to maintain individual radiation exposure within permissible limits.		√
Satisfy one of the following requirements: (a) graduate of a four-year engineering college, plus five years experience in quality assurance, including testing or inspection of equivalent manufacturing, construction, or installation activities; (b) high school graduation, plus ten years experience in quality assurance, including testing or inspection of equivalent construction and installation activities; (c) at least five years of ASME Code related work to include inspection under the provisions of Sections I, III, or VIII; supervision of such work; administration of shop inspection service; or experience in applicable Code related manufacturing or construction activities.		√
Have knowledge of ASME nuclear survey procedures including service with at least three nuclear survey teams as a member or observer.		√
Have experience assisting in the preparation of applicants for ASME Nuclear Accreditation including reviews of quality assurance programs.		√
Have knowledge of the requirements of applicable Code sections.		√

Table 2.5 Summary of Authorized Nuclear Inservice Inspector and Authorized Nuclear Inservice Inspector Supervisor qualifications.

Qualification	Authorized Nuclear Inservice Inspector (I)	Authorized Nuclear Inspector Inservice Supervisor (Is)
Hold a valid state Certification of Competency (where required) and a valid National Board Commission, and have been qualified as an Authorized Nuclear Inspector (N).	√	
Have a minimum of one year of diversified Code inspection experience of Section I, Section III, Division I and/or Section VIII pressure vessels, or one year of diversified experience as an inspector trainee of nuclear items under the direct supervision of an Authorized Nuclear Inservice Inspector.	√	
Have demonstrated the ability to perform monitoring of nuclear inservice inspections to the satisfaction of the Authorized Inspection Agency.	√	
Have a satisfactory degree of expertise, experience, and background for the inspection of nuclear items, according to the complexity of the assignment.	√	
Have knowledge of Section XI of the Code and applicable code cases, including the requirements for maintenance and retention of records.	√	
Achieve a passing grade on an examination in the methods of nondestructive examinations for Authorized Nuclear Inservice Inspectors, prepared by the National Board and monitored by a representative of the National Board, covering knowledge of, and familiarization with, Section XI of the Code and requirements equivalent to SNT-TC-1A (Ref. 2.20) supplements for Level II NDE personnel.	√	
Have knowledge of basic fundamentals of health physics, including purpose and working principles of the film badge, dosimeter, and radiation monitoring devices.	√	
Have qualified as an Authorized Nuclear Inspector Supervisor (S) and be qualified as an Authorized Nuclear Inservice Inspector (I).		√
Have knowledge of basic fundamentals of health physics, insofar as permissible exposure to radiation is concerned and have the ability and means to properly administer affected personnel schedules so as to maintain individual radiation exposure within permissible limits.		√
Have been actively engaged as an Authorized Nuclear Inservice Inspector for a minimum of one year and have at least one year of experience in nondestructive examination methods.		√
Have passed an examination developed, promulgated, and administered by the National Board that focuses on the ability of the individual to ascertain the validity and quality of nondestructive examination and quality assurance requirements of Section XI of the Code, except for individuals who qualified for Authorized Nuclear Inservice Inspector Supervisors prior to September 15, 1985, and who were also qualified as Authorized Nuclear Inspector Supervisors and as Authorized Nuclear Inservice Inspectors.		√

Table 2.6 Duties of an Authorized Nuclear Inspector.

- Verify that the manufacturer has a valid Certificate of Authorization
- Verify that the manufacturer has the appropriate ASME Boiler and Pressure Vessel Codes, addenda, and applicable code cases
- Monitor the implementation of the quality control system and accept changes to that system
- Verify that the applicable design calculations are available
- Verify that all materials meet ASME Boiler and Pressure Vessel Code requirements
- Verify material identification
- Verify that all cut edges are examined
- Verify that the Welding Procedure Specification (WPS) and Procedure Qualification Report (PQR) meet ASME Boiler and Pressure Vessel Code requirements
- Verify that all welders are properly qualified
- Verify that only qualified welders and procedures are used
- Verify that any weld repairs are made using qualified procedures and welders
- Verify that required heat treatments meet the ASME Boiler and Pressure Vessel Code and are recorded properly
- Verify that required nondestructive examination is performed properly by qualified personnel and recorded as required
- Perform an internal inspection prior to closure
- Witness the pressure test, if required
- Verify that all ASME Boiler and Pressure Vessel Code nonconformances are properly resolved
- Verify that the nameplate data is correct and attached to the proper vessel
- Review the data report for clarity and correctness and, if acceptable, sign the report; (1) after the Certificate Holder, and (2) after being satisfied that the vessel meets all ASME Boiler and Pressure Vessel Code requirements
- Maintain a daily record of activities

Table 2.7 Duties of an Authorized Nuclear Inservice Inspector.

- Verify that the Owner or User has the appropriate ASME Codes, addenda, and applicable code cases
- Verify that all materials used for nondestructive examinations comply with Section XI requirements
- Verify that required nondestructive examinations and tests have been performed by qualified personnel
- Verify that the Design Specification and Design Report for the repairs and replacements, when required, are available
- Verify that all welding procedures conform to Section IX and Section XI requirements
- Verify that all welders and welding operators are properly qualified to use the required procedures
- Verify that all material and replacement parts comply with Section XI requirements
- Verify that all heat treatments required by Section XI for repairs and replacements have been performed and are properly documented
- Verify that the Owner's reports for inservice inspections have been signed by the Owner's representative and that they are correct before signing
- Maintain a bound record or diary of daily activities and inspections made

3. CONTAINMENT PRESSURE BOUNDARY RESTORATION

3.1 Conditions for Continued Service

According to requirements provided in 10 CFR 50, Appendix J (Ref. 3.1), evidence of structural deterioration that could affect the structural integrity or leaktightness of metal and concrete containments must be corrected before the containment can be returned to service. Corrective actions that are taken must be performed in accordance with the repair procedures, nondestructive examinations, and testing specified in applicable codes including those editions and addenda of Section XI that have been adopted by the NRC. The Owner is responsible for preparing Repair/Replacement Plans that list all editions, addenda, and code cases that are applicable to a particular repair or replacement.

Current requirements contained in Section XI, Subsection IWA-4000 (Ref. 3.2) of the Code state that containment pressure boundary components with flaws, discontinuities, or areas of degradation that do not meet acceptance standards may not be returned to service unless:

1. the unacceptable flaws, discontinuities, or areas of degradation are removed to the extent necessary to meet the acceptance standards,

2. a repair involving welding is performed such that existing design requirements are met, or

3. the component or portion of the component containing the unacceptable flaws or areas of degradation is replaced.

These three conditions are intended to ensure that metal and concrete containment pressure boundary components remain free from defects during their entire service life. A less prescriptive condition for continued service has been developed and included in requirements provided in Section XI, Subsection IWE-3000 (Ref. 3.3) of the Code. These requirements, which were recently adopted by the NRC, state that containments with pressure boundary components that contain flaws, discontinuities, or areas of degradation that do not meet acceptance standards may be permitted to remain in service provided an engineering evaluation reveals that the flaws, discontinuities, or areas of degradation have no effect on structural capacity or leaktight integrity. Issues related to these four continued-service conditions are discussed in the following subsections.

3.1.1 Defect Removal

According to requirements provided in Section XI, Subsection IWA-4300 (Ref. 3.2) and Subsection IWE-3000 (Ref. 3.3) of the Code, containment pressure boundary components that contain defects may be returned to service provided the unacceptable flaw or discontinuity is removed or reduced to an acceptable size and the resultant section thickness created by the removal process is equal to or greater than the minimum design thickness. If the affected component has been reduced below the minimum design thickness, the component must either be repaired, replaced, or evaluated before being returned to service. Defects may be removed or reduced to an acceptable size using the mechanical removal process described in Sect. 3.4.

3.1.2 Welding Repairs

Containment pressure boundary components that have been reduced below the minimum design thickness either by degradation or defect removal may be repaired by welding and returned to service. Requirements for welding repairs of similar materials, cladding, and dissimilar materials are provided in Section XI, Subsection IWA-4500 (Ref. 3.2) of the Code. All welding repairs must be completed and documented in accordance with the requirements of the Repair/Replacement Program. Issues pertaining to repair materials, welding methods, and repair welding requirements are included in Sects. 3.2, 3.3, and 3.5, respectively.

3.1.3 Replacements

As an alternative to defect removal or repair, items or portions of containment pressure boundary components that contain flaws, discontinuities, or areas of degradation may be replaced with items that meet the acceptance standards. Items used as replacements must be constructed, installed, and documented in accordance with the requirements of the Repair/Replacement Program.

3.1.4 Engineering Evaluation

Engineering evaluations are performed on a case-by-case basis by qualified engineers and authorized personnel who determine the adequacy of damaged or degraded components for their intended use. Acceptance criteria are generally established so that components with flaws, discontinuities, or areas of degradation that adversely affects the structural capacity, leaktight integrity, or remaining service life of the containment are not considered acceptable for continued service.

According to requirements provided in Section XI, Subsection IWE-3122 (Ref. 3.3) of the Code, *containments that contain pressure boundary* components with flaws, discontinuities, or areas of degradation that are found by engineering evaluation to have no effect on structural capacity or leaktight integrity may be returned to service without removing the defect or repairing or replacing the defective component. Damaged components are considered acceptable for continued service if either the thickness of the base material is reduced by no more than 10 percent of the nominal thickness or it can be demonstrated by analysis that the reduced thickness satisfies the requirements of the design specification.

3.2 Materials

The leaktightness of BWR and PWR containment vessels 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 nonstructural attachments, embedment anchors, pipes, tubes, fittings, fasteners, and bolting items that are used to join other pressure-retaining components. Material specifications permitted for construction of metal and concrete containment pressure boundary components are listed in Section III, Division 1, Subsection NE (Ref. 3.4) and Section III, Division 2, Subsection CC (Ref. 3.5) of the Code.

3.2.1 Base Materials

Ferrous materials permitted for use as base materials in containment pressure boundary component construction, repairs, and replacements must conform to the material specifications provided in Section II, Part A (Ref. 3.6) of the Code. These specifications, which were developed by the 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-516/SA-516M (Ref. 3.6) and ASTM A 516/A 516M-86 (Ref. 3.7) are identical. 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. 3.6) and ASTM A 738/A 738M (Ref. 3.8) 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 permitted material specifications 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 material specifications and to adopt new ones.

Section II, Part D (Ref. 3.9) of the Code contains tabulated maximum allowable stress values, design stress intensity values, and thermal properties for all ferrous materials cited in the Code. The tables are organized so that materials with similar compositions and characteristics are grouped together. The ASME specification designations are used to distinguish one material from another. 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 than the corresponding heat analysis results. Base materials used for the construction of containment pressure boundary components must be certified, and a Certified Material Test Report must be available. A Certified Material Test Report is a document attesting that the material is in accordance with specified requirements, including the actual results of all required chemical analyses, tests, and examinations Each piece of metal that is used must also carry identification markings that remain distinguishable until the component is assembled or installed.

Each grade, class, and type of ferrous base material listed in Section II, Part D (Ref. 3.9) of the Code is assigned a P-Number and a Group Number. P-Numbers are based essentially on comparable base material characteristics such as composition, weldability, brazeability, and mechanical properties. Group Numbers are assigned to subdivide ferrous base materials with the same P-Number based on specific impact test requirements. The P-Number and Group Number assignments are intended to reduce the number of welding procedure qualifications required for the construction and repair of metal and concrete containment pressure boundary components. The assignments do not imply that base materials may be indiscriminately substituted for a base material that was used in a qualification test without consideration of the compatibility from the standpoint of metallurgical properties, postweld heat treatment, design, mechanical properties, and service requirements. P-Number and Group Number assignments are listed in certain tables that appear in Section II, Part D (Ref. 3.9), in Section IX, Table QW/QB-422 (Ref. 3.10), and in Section IX, Nonmandatory Appendix D (Ref. 3.10) of the Code.

3.2.2 Welding Materials

Material specifications for welding rods, electrodes, and filler metals permitted for use in repair welding of containment pressure boundary components are provided in Section II, Part C (Ref. 3.11) of the Code. With few exceptions, these specifications are identical to corresponding specifications published by the American Welding Society. AWS specifications that have been adopted by ASME are identified by the prefix "SF" followed by the appropriate AWS designation. For example, ASME specification SFA-5.1 (Ref. 3.11) and ANSI/AWS specification A5.1-91 (Ref. 3.12) are identical. Table 3.1 lists the welding rod, electrode, and filler metal specifications that are permitted for use in construction and repair of containment pressure boundary components.

The American Welding Society has established a system for identifying and classifying welding rods and electrodes. The AWS classification system is represented by a string of alphanumeric characters consisting of mandatory classification designators and optional supplemental designators. Although the exact meaning of each character in the string varies from one specification to another, the classification system for each specification is unique even though there is overlap among several specifications. Guidelines for classification interpretation are provided in the appendix included with each specification. In most cases the first character in the classification is either an "E" for welding electrode or an "R" for welding rod. However, an "ER" is occasionally used when the product can be used either as a welding electrode or a welding rod. A welding electrode is a component of an electrical circuit through which current is conducted and that terminates at the arc, molten conductive slag, or base material. Welding rods are a form of welding filler metal that do not conduct electricity. The last column in Table 3.1 shows the order of typical AWS classifications for various ASME specifications. The following paragraph summarizes the AWS classifications for carbon steel electrodes.

AWS classifications for carbon steel electrodes for shielded metal-arc welding are provided in ASME specification SFA-5.1 (Ref. 3.11). As Table 3.1 shows, the order of the AWS classification for welding electrodes that conform to this specification is "EXXXX-X." Welding electrodes covered by this specification have mandatory classification designations that begin with the prefix letter "E." The two characters that follow the "E" represent the tensile strength of the deposited weld metal. For example, E60XX electrodes produce weld metal with a minimum tensile strength of 414 MPa (60 ksi) and E70XX electrodes produce weld metal with a minimum tensile strength of 482 MPa (70 ksi). The fourth character in the classification is used to designate position usability that will allow satisfactory welds to be produced with the electrode. A "1" indicates that the electrode is usable in all positions including flat (F), horizontal (H), vertical (V), and overhead (OH). A "2" indicates that the electrode is only suitable for use in flat positions (F) or for making fillet welds in the horizontal position (H-fillets). A "4" indicates that the electrode is suitable for use in vertical welding with downward progression

(V-down) and for other specified positions. The fourth- and fifth-character combination designates the type of current to be used with the electrode and the type of covering on the electrode. Table 1 in ASME specification SFA-5.1 (Ref. 3.11) lists the mandatory classification designations for the eight E60XX and the nine E70XX electrodes covered by the specification. Up to four optional designators may also be included in the classification to identify those electrodes that also meet certain supplementary requirements for notch toughness, improved elongation, absorbed moisture, and diffusible hydrogen (low hydrogen). Complete descriptions of optional supplemental designators are provided in figures, tables, and notes included in the specification. According to ASME specification SFA-5.1 (Ref. 3.11), a welding electrode with an AWS classification of "E7018-1H4R" would have the following properties and characteristics.

- 482 MPa (70 ksi) weld metal tensile strength (minimum)
- suitable for welding in all positions (F, V, OH, and H)
- suitable for use with arc welding machines that produce either alternating current or direct current electrode positive
- low hydrogen potassium, iron powder covering
- elongation of 22 percent (minimum)
- 27 J at -46°C (20 ft-lb at -50°F) average Charpy V-notch impact requirements (minimum)
- four percent average diffusible hydrogen content
- meets the requirements of the absorbed moisture test

Packages containing welding electrodes that conform to ASME specification SFA-5.1 (Ref. 3.11) are marked on the outside with the AWS specification and classification designations; supplier's name and trade designation; size and net weight; and lot, control, or heat number. The classification plus any optional designations are also printed on the covering of each electrode within 65 mm (2.5 in.) of the grip end. By affixing the AWS specification and classification designations to the package, or the classification to the product, the manufacturer certifies that the product meets the requirements of the specification. Because absorption of moisture by the electrode covering can adversely affect weld quality, storage and handling precautions and recommendations of the electrode manufacturer should be followed.

Welding electrodes and rods with similar usability characteristics are grouped together and assigned the same F-Number. F-Number assignments and corresponding AWS classifications for seven metal categories are listed in Section IX, Table QW-432 (Ref. 3.10) of the Code. These assignments are made to reduce the number of welding procedure and performance qualifications. However, it should not be implied that base materials or filler metals within the same group may be indiscriminately substituted for metal that was used in a qualification test without consideration of the compatibility of the base and filler metals from the standpoint of metallurgical properties, postweld heat treatment, design, mechanical properties, and service requirements.

A system for classifying deposited ferrous weld metals is also provided in Section IX (Ref. 3.10) of the Code. This system uses A-Numbers that are assigned based on a comparison between the chemical requirements provided in Table QW-442 and the results of a chemical analysis of the deposited weld metal. A-Numbers are used in welding procedure qualification.

3.3 Welding Methods

Repairs to containment pressure boundary component base material and welds can be categorized as those involving welding of similar materials, dissimilar materials, or austenitic stainless steel and nickel-base cladding. According to the repair and replacement requirements found in Section XI, Subsection IWA-4000 (Ref. 3.2) of the Code, these three categories of repairs may only be performed using either the shielded metal-arc welding (SMAW) or the gas tungsten-arc welding (GTAW) process. Requirements for welding procedure and welding performance qualifications using these methods are provided in Section IX (Ref. 3.10) of the Code. These topics are the subject of discussions provided in Sects. 4 and 5. Exceptions and modifications to these requirements as well as repair welding requirements are provided in the construction codes and in Section XI, Subsection IWA-4000 (Ref. 3.2) of the Code.

3.3.1 Shielded Metal-Arc Welding (SMAW)

Shielded metal-arc welding is a manual welding process that uses heat generated by an arc between a covered metal electrode and the work to produce a coalescence of metals. Gas (normally carbon dioxide) that shields the arc and weld zone from the atmosphere is produced by the decomposition of the electrode covering. Filler metal that becomes part of the weld is obtained from the consumable electrode. Welding electrodes for SMAW may have many different compositions of core wire and a wide range of coverings. The filler metal may consist of a bare electrode or metal-cored electrode to which a covering sufficient to provide a slag layer on the deposited weld metal has been applied. The covering may contain materials that provide such functions as shielding from the atmosphere, deoxidization, and arc stabilization. In certain applications, the covering can also serve as a source of metallic additions to the weld (Ref. 3.10).

Prior to welding, items being joined by the SMAW process are placed beside or in contact with each other. Holding or clamping pressure is normally not required. Welding begins when the welder momentarily touches the electrode on the base material to initiate an arc. The arc melts both the base material and the tip of the welding electrode creating a molten pool of metal. As the welder manipulates the electrode, molten electrode metal is continuously transferred to the base material until the electrode metal is consumed or the arc is extinguished. The resulting weld is covered by a slag layer produced by the decomposition of the electrode covering. Removal of this slag layer and any spatter that may be present is essential to the production of high-quality welds. The quality of welds deposited by the SMAW process depends on the design of the joint, selection of the electrode, technique and accessibility, and skill level of the welder. Welder skill is developed through training and experience. Despite the need for skilled welders, SMAW is the most widely used welding process for the following reasons.

- SMAW can be used in all positions (flat, vertical, horizontal, and overhead).
- SMAW can be used with virtually all base-metal thickness of 1.6 mm (0.06 in.) and greater.
- SMAW can be used in areas of limited accessibility.
- Welding electrodes are readily available for almost all manufacturing, construction, and maintenance and repair applications involving low-carbon, mild, low-alloy, high-strength, quenched and tempered, high-alloy, and stainless steels (see Table 3.1 for a list of applicable ASME welding rod, electrode, and filler metal specifications).
- SMAW requires a relatively small investment in rather simple equipment.
- Cladding and hard surfacing layers can be applied using the SMAW process.

Equipment required to perform SMAW consists of an electrical power source, or welding machine, that produces constant current and voltage to maintain a controllable and stable arc; an electrode holder that is held by the welder and used to manipulate the electrode; and electrical cables that connect the power source, the electrode holder, and the work piece. Electrodes operate within a range of 25 to 500 amperes depending on the electrode size, rate of deposition, and heat transfer characteristics of the base materials. The constant current provided by the electrical power source can either be alternating current (AC), direct current electrode negative (DCEN or straight polarity), or direct current electrode positive (DCEP or reverse polarity). Power supply selection depends on the electrode covering characteristics. Operating arc voltage varies between 15 and 35 volts.

3.3.2 Gas Tungsten-Arc Welding (GTAW)

Gas tungsten-arc welding is a high-temperature metal-joining process that uses heat generated by an arc between a nonconsumable tungsten alloy electrode and the work. Weld pool temperatures can approach 2,500°C (4,530°F). An inert gas (normally argon, helium, or a mixture of argon and helium) sustains the arc and protects the molten metal from atmospheric contamination. Gas tungsten-arc welds can be made with or without filler metal depending on the thickness of the materials being joined. When required, filler metal can be added manually in straight lengths or automatically from rolls or coils (Ref. 3.10).

The GTAW process can be used to weld almost all types of metals ranging in thickness from a few thousandths of a millimeter to many millimeters. Although carbon and low-alloy steels can be welded using this process, it is used primarily for joining dissimilar metals, stainless steels, aluminum, magnesium, and reactive materials and for root-pass welding of carbon and low-alloy steels. Welds produced using this process are generally high-quality, low-distortion welds that are free of spatter. During the welding operation, the welder can maintain precise control of heat input, and vision is not impaired because fumes and smoke are not produced as in certain other arc welding processes. However, welders who use the GTAW process must have a relatively high level of skill and slightly more dexterity and coordination than welders who use the SMAW process.

Equipment required to perform GTAW involves a power supply, a welding torch, inerting gas, filler metal (when required), cables, hoses, gas regulators, and cooling water (if needed). The power supply, which may produce either AC, DCEN, or DCEP, is usually of the constant-current type with a drooping (negative) volt-ampere curve. Because DCEN results in maximum application of heat to the work, this type of constant-current power source is most often used. The welding torch consists of a holder for the tungsten electrode, a handle for the welder, and a nozzle for dispensing the inert gas. The nonconsumable electrode may be either almost pure tungsten or a tungsten alloy. Requirements for these electrodes are provided in ASME specification SFA-5.12 (Ref. 3.11). Cables, hoses, and gas regulators are used to deliver electricity, inert gas, and water (when supplementary electrode cooling is required) to the welding torch. When filler metal is required, it can be supplied either manually or automatically using a continuous wire feed system. Table 3.1 lists ASME welding rod, electrode, and filler metal specifications that pertain to GTAW.

3.4 Defect Removal

Indications of flaws, discontinuities, or areas of degradation that are detected in containment pressure boundary components can be removed or reduced to an acceptable size by mechanical methods such as grinding. Grinding is a process whereby metal fragments are removed from the surface of an item as it comes into contact with an abrasive substance such as a rotating aluminum oxide grinding wheel. In most defect removal applications, the grinding wheel is manipulated manually.

Requirements for defect removal are provided in Section XI, Subsection IWA-4300 (Ref. 3.2) of the Code. According to these requirements, in areas where repair welding is not required, the affected area must be faired into the surrounding area so that all sharp notches and severe discontinuities are eliminated. When repair welding is required, the cavity produced by the defect removal process must be finished smooth with beveled sides and rounded edges so that suitable access for welding is provided. To ensure that the indications have been removed or reduced to an acceptable size by the defect removal procedure, the affected surfaces must be examined by the magnetic particle or liquid penetrant method. In those instances when repair welding of similar materials is to be performed or when repair welding of cladding or dissimilar materials is required and the defect penetrates the base material, the original defect must be completely removed.

Liquid penetrant and magnetic particle testing are common nondestructive examination techniques typically used to detect surface-breaking flaws and discontinuities in materials such as steel. Liquid penetrant testing provides a means for enhancing the visibility of surface-breaking flaws such as cracks. In this method, a colored liquid is applied to the surface of the material being examined and allowed to penetrate surface-breaking cracks and crevices. After about 15 minutes, the liquid is removed and a white powder developer is applied to the surface. The penetrant in the cracks and crevices is drawn into the developer by a reverse-capillary action revealing the locations of the flaws. Magnetic particle testing is the preferred method for detecting surface-breaking and near-surface flaws in situations where a test material can be magnetized. The method depends on the disruption of a magnetic flux by a surface-breaking or near-surface flaw or discontinuity. The magnetic flux can be generated along the surface of the material by a permanent magnet or an electromagnet or by electric current carrying electrodes and cables. Flux leakage from the material creates magnetic poles that attract magnetic particles creating a clearly visible image of the flaw (Ref. 3.13).

3.5 Repair Welding Requirements

Requirements for repair welding are provided in the original construction code or Section III, Division 1, Subsection NE (Ref. 3.4) of the Code. With certain exceptions, all welds in P-No. 1 materials, including repair welds, must be postweld heat treated. In new construction, where fabrication activities can be staged and properly sequenced, postweld heat treatment (PWHT) is normally not a problem. However, PWHT of repair welds in existing containment pressure boundary components is not always feasible especially when the size and configuration of the repair leads to highly restrained weld joints and when factors such as water backing make preheat and PWHT impractical.

For these reasons, alternative repair welding methods are provided in Section XI, Subsection IWA-4500 (Ref. 3.2) of the Code. These requirements permit repairs to base material and welds of similar materials, cladding, and dissimilar materials without the required PWHT provided:

1. the neutron fluence in the repair area is taken into account when weld metal composition limits are established,

2. the welding procedure and the welders are qualified in accordance with the requirements of Section IX (Ref. 3.10) of the Code and the additional requirements provided in Subsection IWA-4500, and

3. the welding procedure includes weld preparation and specified preheat provisions.

Additional alternative repair welding method requirements for repairs to similar materials, cladding, and dissimilar materials are summarized below. Also included are requirements for butter bead—temper bead repairs of metal and concrete containment pressure boundary components.

3.5.1 Similar Metals

Repairs to P-Nos. 1, 3, 12A, 12B, and 12C* base materials and associated welds may be made without the specified PWHT based on requirements provided in Section XI, Subsection IWA-4510 (Ref. 3.2) of the Code. These requirements only apply to repairs that have a maximum finished surface area of 64,500 sq. mm (100 sq. in.) and a depth of repair that is no greater than one-half the base material thickness. For these repairs, peening may be used except on the initial and final weld layers.

In addition, the test assembly base material, weld metal, and heat affected zone (HAZ) for the welding procedure qualification test must meet the impact test requirements for the construction code and Owner's requirements. Requirements that must be included in the repair welding procedure specification for shielded metal-arc and gas tungsten-arc welding are listed in Tables 3.2 and 3.3, respectively. During the repair welding operation, the initial layer must be ground or machined and then examined by the magnetic particle method. Each subsequent layer must also be examined by the magnetic particle method unless a final volumetric examination is to be performed. The completed repair area must be nondestructively examined after the weld has been at ambient temperature for at least 48 hours. The examination must include a surface examination and a volumetric examination unless each layer was examined by the magnetic particle method.

An experimental effort to evaluate the technical acceptability of making welding repairs to thick-section P-No. 1 steels without PWHT has been undertaken (Ref. 3.14). In this study, four test assemblies were prepared using steel plates that conformed to ASTM A 516, Grade 70 (Ref. 3.7) requirements and E7018 covered electrodes. The assemblies were welded in the flat position using the SMAW process. Each assembly was prepared using a different set of preheat and interpass temperatures. Charpy data, metallographic examination results from broken Charpy specimens, tensile data, microhardness data, and microstructure examination results from the weldments were compared to those obtained from companion test specimens that had been subjected to PWHT. Based on this comparison, the optimum preheat/interpass temperature range for weld repairs in ASTM A 516, Grade 70 steel is 93-149°C (200-300°F).

3.5.2 Cladding

When the ferritic material is within 3.18 mm (0.125 in.) of being exposed, repairs to austenitic stainless steel and nickel-base cladding on P-Nos. 1, 3, 12A, 12B, and 12C base materials can

*P-Nos. 12A, 12B, and 12C are material classifications originally identified in Section III and later reclassified and included in Section IX.

be made without PWHT based on requirements provided in Section XI, Subsection IWA-4520 (Ref. 3.2) of the Code. When the repair involves two different P-Number or Group Number materials, the welding qualification test assembly must duplicate the combination. Dimensions of the test assembly base material must be at least 305 mm by 305 mm by 51 mm (12 in. by 12 in. by 2 in.) with a clad surface area of at least 203 mm by 203 mm (8 in. by 8 in.) in the region from which the bend test specimens will be taken. The guided bend test acceptance standards in Section IX for cladding must also be applicable to the HAZ of the base material. Requirements that must be included in the repair welding procedure for shielded metal-arc and gas tungsten-arc welding are listed in Tables 3.4 and 3.5, respectively.

After the completed weld has been at ambient temperature for at least 48 hours, the weld repair and the adjacent preheated band must be examined by the liquid penetrant method and deposited weld metal and HAZ must be examined by the ultrasonic method.

3.5.3 Dissimilar Metals

Repairs to welds that join P-No. 8 or P-No. 43 material to P-Nos. 1, 3, 12A, 12B, and 12C base material can be made without the specified PWHT based on requirements provided in Section XI, Subsection IWA-4530 (Ref. 3.2) of the Code. These requirements are only applicable to repairs made along the fusion line of a nonferritic weld to ferritic base material where 3.18 mm (0.125 in.) or less of nonferritic weld deposit exists above the original fusion line after defect removal. If the defect penetrates into the ferritic base material, repair of the base material may be performed provided the depth of the repair in the base material does not exceed 9.53 mm (3/8 in.). Repairs to a completed joint must not exceed one-half the joint thickness, and the surface of the completed repair may not exceed 64,500 sq. mm (100 sq. in.).

The depth of the cavity in the welding qualification test assembly must be a minimum of one-half the depth of the actual repair but not less than 25.4 mm (1 in.). The test assembly thickness must also be a minimum of twice the depth of the cavity in the test assembly, and the test assembly must be large enough to permit removal of the required test specimens. To simulate the restraint that the weld metal will experience in the repaired section of the component, the test assembly dimensions surrounding the cavity must be equal to the test assembly thickness but not less than 152 mm (6 in.). Layout requirements for the qualification test plate are shown in Fig. IWA-4531.1-1 (Ref. 3.2). The ferritic base material and HAZ must meet the same requirements as those described in Sect. 3.5.1 for similar materials. Requirements that must be included in the repair welding procedure for shielded metal-arc and gas tungsten-arc welding are listed in Tables 3.6 and 3.7, respectively.

After the completed weld has been at ambient temperature for at least 48 hours, the weld repair and the adjacent preheated band must be examined by the liquid penetrant method, the radiographic method, and, if practical, the ultrasonic method.

3.5.4 Butter Bead—Temper Bead Repairs

An alternative welding technique that is intended for use in the repair of metal and concrete containment pressure boundary components where preheat and PWHT are impractical has been developed. This technique is known as butter bead—temper bead welding. Butter bead—temper bead welding is suitable for use when the size or configuration of the repair leads to highly restrained weld joints or the repair area is backed by water. Requirements for this technique are provided in Section XI, Subsection IWA-4540 (Ref. 3.2) of the Code. Butter bead—temper bead welding involves application of a butter layer of surfacing weld metal followed by the application of temper beads or a temper bead layer. This welding sequence eliminates the need for PWHT. General butter bead—temper bead repair welding requirements are summarized in Table 3.8.

To help ensure the quality of repairs made using butter bead—temper bead welding, the welding procedure and welders must be qualified in accordance with requirements provided in Section IX (Ref. 3.10) of the Code as well as applicable requirements provided in Section III, Division 1, Subsection NE-4000 (Ref. 3.4), Section III, Division 2, Subsection CC-4000 (Ref. 3.5), and Section XI, Subsection IWA-4540 (Ref. 3.2). Welder qualification involves a performance qualification test and a production test prior to any repair welding. In the performance qualification test, the welder prepares a groove weld test specimen that is then examined radiographically in accordance with Section IX requirements. The production test involves the preparation of a production test assembly that may consist of one or more production tests. Production tests are intended to simulate the repair welding using the welding variables contained in Section IX as well as those listed in Table 3.9. Any physical obstructions associated with the actual repair must be simulated in the production test. Production test assemblies are evaluated according to:

1. a nondestructive visual examination to determine compliance with the welding procedure specification;

2. a nondestructive surface examination of the welds to detect cracks and other surface discontinuities;

3. a destructive examination at 10x magnification of two polished and etched cross sections for each production test; and

4. a destructive test in which a minimum of two microhardness traverses with no less than ten indentations are taken from one cross section for each production test.

Prior to butter bead—temper bead welding of the production test or the actual work, areas to be welded must be examined by magnetic particle or liquid penetrant methods, and all surrounding surface areas must be clean and free of scale, rust, moisture, or other surface contaminants. The minimum preheat temperature specified in the welding procedure specification and the production test must be maintained during tack welding and until completion of the weld. However, the maximum interpass temperature may not exceed 260°C (500°F). As the welding progresses, the welder must apply a butter bead layer followed by temper beads or a temper bead layer. Improper application of the temper bead or defects in the butter bead or temper bead must be repaired by application of a new butter bead and temper bead. After the welding is completed, no postweld heat treatment is required.

3.6 Installation of Replacements

Replacement items that involve installation by welding are required to be installed using the appropriate welding requirements described in Sect. 3.5. Repaired areas and welded joints made for installation of replacement items must be examined in accordance with the requirements of the construction code identified by the Owner in the Repair/Replacement Plan.

Application of the ASME NA Symbol Stamp is neither required nor prohibited for installation of an item to be used for replacement. When stamping is performed, it may be performed by either the Owner, provided the Owner is in possession of the appropriate Certificate of Authorization, or the Owner's designee, provided the designee is in possession of the appropriate Certificate of Authorization.

3.7 Pressure Tests

According to the special testing requirements for containment modifications provided in 10 CFR 50, Appendix J (Ref. 3.1), repairs or major modifications to containment pressure boundary components or replacement of these components must be followed by a Type A, Type B, or Type C leakage-rate test, as applicable to the affected area.

3.8 Documentation

The Owner is responsible for the preparation and maintenance of the reports and records that are required for all repairs and replacements. The types of documents that may be involved are listed below.

- Certified Design Specification
- Certified Design Report
- Design Report
- Overpressure Protection Report
- Manufacturer's Data Report
- Material Certification
- Evaluation Report (required by Section XI, Subsection IWA-4150)

The Owner is also responsible for the preparation of the Owner's Report for Repairs or Replacements, Form NIS-2, as required in Section XI, Subsections IWA-4910 and IWA-6210 (Ref. 3.2) of the Code. The types of information that must be included on this form are listed in Table 3.10.

Alternative documentation requirements to those just described are provided in Code Case N-532 (Ref. 3.15). This code case permits the use of a Repair/Replacement Certification Record, Form NIS-2A, which references a unique Repair/Replacement Plan identification number that is assigned by the Owner. Certification of the repair or replacement is achieved when Form NIS-2A is signed and dated by the Authorized Nuclear Inservice Inspector.

References

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3.3 "Rules for Inservice Inspection of Nuclear Power Plant Components," *ASME Boiler and Pressure Vessel Code*, Section XI, Division 1, Subsection IWE, Requirements for Class MC and Metallic Liners of Class CC Components of Light-Water Cooled Plants, American Society of Mechanical Engineers, New York, New York, July 1, 1992.

3.4 "Rules for Construction of Nuclear Power Plant Components," *ASME Boiler and Pressure Vessel Code*, Section III, Division 1, Subsection NE, Class MC Components, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

3.5 "Rules for Construction of Nuclear Power Plant Components," *ASME Boiler and Pressure Vessel Code*, Section III, Division 2, Code for Concrete Reactor Vessels and Containments, Subsection CC, Concrete Containments (Prestressed or Reinforced), American Society of Mechanical Engineers, New York, New York, July 1, 1995.

3.6 "Materials," *ASME Boiler and Pressure Vessel Code*, Section II, Part A, Ferrous Material Specifications, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

3.7 "Standard Specification for Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service," ASTM Designation: A 516/A 516M-90, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1990.

3.8 "Standard Specification for Pressure Vessel Plates, Heat-Treated, Carbon-Manganese-Silicon Steel, for Moderate and Lower Temperature Service," ASTM Designation: A 738/A 738M-90, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1990.

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3.10 "Qualification Standards for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators," *ASME Boiler and Pressure Vessel Code*, Section IX, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

3.11 "Materials," *ASME Boiler and Pressure Vessel Code*, Section II, Part C, Specifications for Welding Rods, Electrodes, and Filler Metals, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

3.12 "Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding," ANSI/AWS A5.1-91, American Welding Society, Miami, Florida, 1991.

3.13 "Volume 17 — Nondestructive Evaluation and Quality Control," *ASM Handbook*, formerly ninth edition, *Metals Handbook*, ASM International, Materials Park, Ohio, 1989.

3.14 Friedman, L. M., "Weld Repair Without Postweld Heat Treatment of Thick-Section Carbon Steel Components," EWI-MR9402, Edison Welding Institute, Columbus, Ohio, February 1994.

3.15 "Alternative Requirements to Repair and Replacement Documentation Requirements and Inservice Summary Report Preparation and Submission as Required by IWA-4000 and IWA-6000," Case N-532, *ASME Boiler and Pressure Vessel Code*, 1995 Code Cases, Nuclear Components, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

Table 3.1 Welding rod, electrode, and filler metal specifications permitted for use in repair of containment pressure boundary components.

ASME Specification Number	Specification for	Welding method[1]	Order of typical AWS Classification[2]
SFA-5.1	Carbon Steel Electrodes for Shielded Metal Arc Welding	SMAW	EXXXX-X
SFA-5.4	Stainless Steel Electrodes for Shielded Metal Arc Welding	SMAW	EXXX(X)-XX
SFA-5.5	Low Alloy Steel Covered Arc Welding Electrodes	SMAW	EXXXX-XX
SFA-5.9	Bare Stainless Steel Welding Electrodes and Rods	GTAW	ERXXX(X)
SFA-5.11	Nickel and Nickel Alloy Welding Electrodes for Shielded Metal Arc Welding	SMAW	ENiXXXX-X
SFA-5.12	Tungsten and Tungsten Alloy Electrodes for Arc Welding and Cutting	GTAW	EWXX-XX
SFA-5.13	Solid Surfacing Welding Rods and Electrodes	SMAW GTAW	EXXX-X, RXXX-X, or ERXXX-X
SFA-5.14	Nickel and Nickel Alloy Bare Welding Electrodes and Rods	GTAW	ENiXXXX-X
SFA-5.18	Carbon Steel Filler Metals for Gas Shielded Arc Welding	GTAW	ERXXX-X
SFA-5.21	Composite Surfacing Welding Rods and Electrodes	SMAW GTAW	EXXX-X, or RXXX-X,
SFA-5.28	Low Alloy Steel Filler Metals	GTAW	EXXX-X, or ERXXX-X

(1) Shielded Metal-Arc Welding (SMAW); Gas Tungsten-Arc Welding (GTAW)

(2) E = electrode; X = alphanumeric character as prescribed in specification (the number of characters represented by the X's and the exact order of the designation may vary from one AWS classification to another); R = rod; ER = either electrode or rod; Ni = nickel; W = tungsten

Table 3.2 Similar material repair welding procedure specification requirements for shielded metal-arc welding.

- Low hydrogen type welding electrodes must be used.
- The maximum bead width must be no more than four times the welding electrode core diameter.
- Covered welding electrodes must be baked and maintained in accordance with the manufacturer's recommendations.
- After baking but before being allowed to cool below 107°C (225°F), the welding electrodes must be transferred to holding or drying ovens operated between 107 and 177°C (225 and 350°F).
- During the repair, welding electrodes removed from the holding ovens for more than eight hours for E70XX electrodes or four hours for E80XX electrodes must be reprocessed as described above.
- Welding electrodes must not be rebaked more than once.
- Weld repair cavities must be completely buttered using a 2.38-mm (3/32 in.) diameter welding electrode.
- The weld bead crown in the butter layer must be removed by grinding or machining before the second layer is deposited.
- The second layer must be deposited with a 3.18-mm (1/8 in.) diameter welding electrode.
- Subsequent layers must be deposited with welding electrodes that are no larger in diameter than 3.97-mm (5/32 in.).
- At least one layer of weld reinforcement must be deposited over the entire weld repair surface.
- The weld reinforcement must be removed by mechanical methods making the finished surface of the repair substantially flush with the surface surrounding the repair.
- Repair weld areas must be maintained at a temperature of 232 to 288°C (450 to 550°F) for a minimum of two hours after completion of the weld repair in P-No. 1 materials and for a minimum of four hours in P-No. 3 materials.

Table 3.3 Similar material repair welding procedure specification requirements for gas tungsten-arc welding.

- Weld metal must be deposited by the automatic or machine gas tungsten-arc welding process using cold wire feed.
- Weld repair cavities must be buttered with the first six layers of weld metal with the weld heat input for each layer controlled to within ±10 percent of that used in the procedure qualification test.
- Subsequent layers must be deposited with a heat input equal to or less than that used for layers beyond the sixth in the procedure qualification.
- At least one layer of weld reinforcement must be deposited over the entire surface.
- The weld reinforcement must be removed by mechanical methods making the finished surface of the repair substantially flush with the surface surrounding the repair.
- Repair weld areas must be maintained at a minimum temperature of 149°C (300°F) for a minimum of two hours after completion of the weld repair in P-No. 1 materials and four hours for P-No. 3 materials.

Table 3.4 Cladding repair welding procedure requirements for shielded metal-arc welding.

- A-No. 8 weld metal must be used for austenitic stainless steel cladding or F-No. 43 weld metal for either stainless steel or nickel-base cladding.
- The maximum bead width must be no more than four times the welding electrode core diameter.
- Covered welding electrodes used for the qualification test and repair welding must be from freshly opened, hermetically sealed packages or heated ovens maintained between 107 and 177°C (225 and 350°F).
- Welding electrodes withdrawn from hermetically sealed packages or heated ovens for longer than eight hours must be discarded.
- During the repair, the welding electrodes may be stored in heated ovens in the repair area provided the ovens are maintained between 107 and 177°C (225 and 350°F).
- All areas of the base material on which weld metal is to be deposited must be covered with a single layer of weld deposit using a 2.38-mm (3/32 in.) diameter welding electrode.
- The weld bead crown of the first layer must be removed by grinding or machining before the second layer is deposited.
- The second layer must be deposited with a 3.18-mm (1/8 in.) diameter welding electrode.
- Subsequent layers must be deposited with welding electrodes that are no larger in diameter than 3.97-mm (5/32 in.).
- After completion of welding or when at least 4.76 mm (3/16 in.) of weld metal has been deposited, the weld area must be maintained at a temperature of 232 to 288°C (450 to 550°F) for a minimum of two hours in P-No. 1 materials and for a minimum of four hours in P-No. 3 materials.
- Subsequent to the heat treatment described above, the balance of the welding, if any, may be performed at a maximum interpass temperature of 177°C (350°F).

Table 3.5 Cladding repair welding procedure requirements for gas tungsten-arc welding.

- A-No. 8 weld metal must be used for austenitic stainless steel cladding or F-No. 43 weld metal for either stainless steel or nickel-base cladding.
- Weld metal must be deposited by the automatic or machine gas tungsten-arc welding process using cold wire feed.
- Weld repair cavities must be buttered with the first six layers of weld metal with the weld heat input for each layer controlled to within ±10 percent of that used in the procedure qualification test.
- Subsequent layers must be deposited with a heat input equal to or less than that used for layers beyond the sixth in the procedure qualification.
- After completion of welding or when at least 4.76 mm (3/16 in.) of weld metal has been deposited, the weld area must be maintained at a temperature of 232 to 288°C (450 to 550°F) for a minimum of two hours in P-No. 1 materials and for a minimum of four hours in P-No. 3 materials.
- Subsequent to the heat treatment described above, the balance of the welding, if any, may be performed at a maximum interpass temperature of 177°C (350°F).

Table 3.6 Dissimilar material repair welding procedure requirements for shielded metal-arc welding.

- Weld metal shall be deposited using A-No. 8 or F-No. 43 weld metal. A-No. 8 weld metal is used for P-No. 8 to P-No. 1 or P-No. 8 to P-No. 3 weld joints. F-No. 43 weld metal is used for either P-No. 8 or P-No. 43 to P-No. 1 or P-No. 3 weld joints.
- The maximum bead width must be no more than four times the welding electrode core diameter.
- Covered welding electrodes used for the qualification test and repair welding must be from freshly opened, hermetically sealed packages or heated ovens maintained between 107 and 177°C (225 and 350°F).
- Welding electrodes withdrawn from hermetically sealed packages or heated ovens for longer than eight hours must be discarded.
- During the repair, the welding electrodes may be stored in heated ovens in the repair area provided the ovens are maintained between 107 and 177°C (225 and 350°F).
- All areas of the ferritic base material, exposed or not, on which weld metal is to be deposited must be covered with a single layer of weld deposit using 2.38-mm (3/32 in.) diameter welding electrodes.
- The weld bead crown of the first layer must be removed by grinding or machining before the second layer is deposited.
- The second layer must be deposited with a 3.18-mm (1/8 in.) diameter welding electrode.
- Subsequent layers must be deposited with welding electrodes that are no larger in diameter than 3.97-mm (5/32 in.).
- After completion of welding or when at least 4.76 mm (3/16 in.) of weld metal has been deposited, the weld area must be maintained at a temperature of 232 to 288°C (450 to 550°F) for a minimum of four hours.
- Subsequent to the heat treatment described above, the balance of the welding, if any, may be performed at a maximum interpass temperature of 177°C (350°F).

Table 3.7 Dissimilar material repair welding procedure requirements for gas tungsten-arc welding.

- Weld metal shall be deposited using A-No. 8 or F-No. 43 weld metal. A-No. 8 weld metal is used for P-No. 8 to P-No. 1 or P-No. 8 to P-No. 3 weld joints. F-No. 43 weld metal is used for either P-No. 8 or P-No. 43 to P-No. 1 or P-No. 3 weld joints.
- Weld metal must be deposited by the automatic or machine gas tungsten-arc welding process using cold wire feed.
- The weld repair cavity must be buttered with the first six layers of weld metal with the weld heat input for each layer controlled to within ±10 percent of that used in the procedure qualification test.
- Subsequent layers must be deposited with a heat input equal to or less than that used for layers beyond the sixth in the procedure qualification.
- At least one layer of weld reinforcement must be deposited over the entire weld repair surface.
- The weld reinforcement must be removed by mechanical methods making the finished surface of the repair substantially flush with the surface surrounding the repair.
- After completion of welding or when at least 4.76 mm (3/16 in.) of weld metal has been deposited, the weld area must be maintained at a temperature of 232 to 288°C (450 to 550°F) for a minimum of two hours in P-No. 1 materials and for a minimum of four hours in P-No. 3 materials.
- Subsequent to the heat treatment described above, the balance of the welding, if any, may be performed at a maximum interpass temperature of 177°C (350°F).

Table 3.8 General requirements for butter bead—temper bead repair welding.

- The butter bead—temper bead repair technique is only applicable to P-No. 1, Group No. 1 and P-No. 1, Group No. 2 pressure boundary materials using the shielded metal-arc welding process with low hydrogen welding electrodes.
- After receipt from the manufacturer and before use, all covered welding electrodes must be subjected to the following conditioning.
  1. The welding electrodes must be baked at the manufacturer's recommended baking temperature, but in no case at a temperature less than 343°C (650°F) or greater than 454°C to (850°F).
  2. The temperature of the baking oven must not exceed 300°F when the welding electrodes are inserted for the baking cycle.
  3. The baking oven temperature may not be raised more than 167°C/hr (300°F/hr).
  4. The total time above 260°C (500°F), including the holding time, may not exceed five hours.
  5. After baking and before cooling below 107°C (225°F), the welding electrodes must be transferred to holding or drying ovens that are maintained within the temperature range of 107 to 177°C (225 to 350°F).
- During repair welding, the welding electrodes must be subjected to the following care.
  1. The welding electrodes must be maintained in holding or drying ovens or heated portable containers in the repair area until they are used.
  2. The holding or drying ovens and the heated portable containers must be maintained within the temperature range of 107 to 177°C (225 to 350°F).
  3. Welding electrodes must be used within two hours after they are removed from the holding or drying ovens or the heated portable containers.
  4. Welding electrodes removed from heated ovens for more than two hours, but less than four hours, must be returned to a holding oven and maintained within the temperature range of 107 to 177°C (225 to 350°F) for at least eight hours before use.
  5. Welding electrodes removed from heated ovens or heated portable containers for a period in excess of four hours must be rebaked as described above before use.
  6. Welding electrodes may not be rebaked more than once.
- Welding materials used in the repair must be controlled during repair so that they are identified as acceptable material until consumed.
- Welding material contaminated with oil, grease, water, or other foreign material may not be used.
- All welding material must conform to the applicable material testing requirements provided in Section III, Divisions 1 and 2 (Refs. 3.4 and 3.5).
- The component base material to be repaired must comply with the impact test requirements and acceptance criteria provided in the construction code and the Owner's requirements.
- Controlled peening of welds may be performed to minimize distortion, provided it is also used on the welds made to qualify the repair procedure and the production test assembly.
- Peening must not be used on the initial layer of the weld metal or on the final layer.
- If peening is used, it must be considered as an essential variable in the welding procedure.
- Fabrication and welding must be sequenced to minimize the effects of restraint.

Table 3.9 Production test variables.

- Base material used in the production test to represent the pressure boundary should be of the same material specification, type, class, group number, or grade as the pressure boundary material to be repaired by welding.
- All other material should be of the same P-Number as those to be used in the repair.
- When the original material is no longer manufactured, material similar to the original material specification may be substituted.
- Welding electrodes used for the production test must be the same specification and classification as those used for the weld repair and must be treated as described in Table 3.8.
- The production test must simulate the repair, and the following parameters must be recorded.

1. All essential and supplementary essential variables listed for the process in Section IX
2. Nominal pressure boundary base material thickness
3. Maximum nominal attachment base material thickness
4. Weld joint geometry (including joint design and fit up tolerances) and the maximum nominal weld thickness (for fillet welds, the nominal thickness is the throat thickness, and for groove welds, the nominal thickness is the depth of the weld groove)
5. Restraint on the weld joint (restraint must be maintained on the production test assembly for a minimum of 48 hours after the completed weld has reached ambient temperature)
6. Weld sequencing (both fabrication steps and order of bead sequence)
7. Weld position
8. Water backing and water temperature within specified tolerances, as applicable
9. Actual welding electrode size to be used for the butter bead layer and the temper bead layer
10. Range of welding electrode sizes to be used to complete the weld joint;
11. Preheat and preheat maintenance within tolerances specified in the welding procedure specification
12. Peening, as applicable
13. Guides, templates, and fixtures used for weld placement, as applicable
14. Maximum temper bead edge clearance and the minimum temper bead edge clearances
15. Maximum weave width for the butter bead layer

Table 3.10 Types of information reported on an Owner's Report for Repair or Replacement, Form NIS-2.

- The name and address of the Owner of the nuclear power plant.
- The date Form NIS-2 was prepared.
- The name and address of the nuclear power plant where the repair or replacement activity was performed.
- The Owner's designated unit identification number.
- A unique identification of the repair or replacement enabling the work to be identified.
- The name and address of the organization responsible for completing the repair or replacement activity.
- The symbol representing the Certificate of Authorization (e.g., N, NPT, NA).
- The number from the Certificate of Authorization held by the organization responsible for completing the repair or replacement.
- The expiration date of the Certificate of Authorization taken from the certificate held by the organization responsible for completing the repair or replacement.
- The unique designation of the system in the nuclear power plant, by name, including the ASME Class of system.
- The Section of the ASME Code that the item was manufactured in accordance with, including the year of publication, the designation of the addenda of the standard in effect, and any applicable code cases identified by number.
- The Edition and Addenda of Section XI used for the repair or replacement.
- The name of the item repaired or replaced taken from the Data Report provided by the manufacturer or from plant records when no Data Report exists for the item.
- The name of the manufacturer of the item repaired or replaced.
- The serial number of the item.
- The National Board Number assigned to the item by the manufacturer.
- Other appropriate identification taken from drawings or other records.
- The year the item was manufactured.
- Indicate the action taken on the item: repaired, replaced, or replacement.
- Indicate if the item bears an ASME Code Symbol Stamp.
- A brief narrative of the work performed.
- Indicate the appropriate pressure test completed following the repair or replacement, or denote exemption.
- Additional information necessary to describe the repair or replacement not otherwise covered in the Form NIS-2.
- Indicate if the activity performed is repair or replacement.
- The type of ASME Code Symbol Stamp held by the Owner or the Owner's designee, if applicable.

Table 3.10 (Cont'd) Types of information reported on an Owner's Report for Repair or Replacement, Form NIS-2.

- The number taken from the ASME Certificate of Authorization that granted authority to possess the ASME Code Symbol Stamp, if applicable.
- The signature of the individual and title representing the Owner who certified the accuracy of the contents of the Form NIS-2 and its attachments.
- The name of the jurisdiction where the repairs or replacements were performed.
- The name of the Inspector's employer, the Authorized Inspection Agency.
- The address of the Authorized Inspection Agency.
- The date the Authorized Nuclear Inservice Inspector began verifications that the activities represented by the Form NIS-2 were completed.
- The last date the Authorized Nuclear Inservice Inspector verified the activities represented by the Form NIS-2.
- The Authorized Nuclear Inservice Inspector's signature.
- The Authorized Nuclear Inservice Inspector's National Board Commission Number, including endorsements, and if applicable, the jurisdiction name and Certificate of Competency number held in the State or Province where inspections represented by the Form NIS-2 were performed.
- The date the Authorized Nuclear Inservice Inspector signed the Form NIS-2.

4. WELDING PROCEDURE AND PERFORMANCE QUALIFICATION

4.1 Overview of Qualification Requirements

Basic criteria for the qualification of welders and welding procedures used in ASME Code construction are provided in Section IX (Ref. 4.1). To minimize duplication, these requirements are referenced by Section XI (Ref. 4.2) of the Code and the various construction codes including Section III (Refs. 4.3 and 4.4). Because these codes apply to specific types of fabrication and assembly practices, they sometimes impose additional requirements or exemptions such as those described in Sect. 3.5 for repair welding of containment pressure boundary components. It is the Owner's responsibility to prepare a Repair/Replacement Plan that defines the managerial and administrative control for completion of the repair or replacement and identifies which specific editions, addenda, and code cases are applicable to a particular repair or replacement.

Requirements in Section IX (Ref. 4.1) of the Code focus on two separate but related activities. One involves the development of a welding procedure that can be used to determine whether the weldment proposed for construction is capable of providing the required properties for its intended application. The second involves the performance qualification of welders who perform manual or semiautomatic welding, and welding operators who operate welding machines and automatic equipment. Each contractor or manufacturer that is responsible for welding performed in accordance with code requirements is required to conduct tests to qualify the welding procedures use in the construction and to verify the performance of the welders and welding operators who apply these procedures. Documentation from welding procedure and performance qualification testing must be certified by the contractor or manufacture, maintained in accordance with quality assurance program requirements, and made accessible upon demand to the Authorized Nuclear Inspector. Issues pertaining to welding procedure and performance qualification requirements are discussed in the following sections.

4.2 Welding Procedure Qualification

A qualified welding procedure specification (WPS) is a written document that provides direction for making production welds in accordance with code requirements. It is also useful in directing the welder or welding operator to assure code compliance. A completed WPS defines the acceptable ranges for all welding variables identified in the WPS and includes reference to a procedure qualification record (PQR). The PQR is a record of the welding data collected during the welding of a test coupon and includes properties of the completed weldment. Depending on the qualification and documentation requirements, a WPS may require the support of more than a single PQR, and a PQR may support more than one WPS.

4.2.1 Welding Variables (Procedure)

Essential, nonessential, and supplementary essential welding variables applicable to WPS qualification are defined in Section IX (Ref. 4.1) of the Code. Essential variables are those in which a change will affect the mechanical properties of the weldment, and therefore, require requalification of the WPS. Nonessential variables are those in which a change may be made in the WPS without requalification of the WPS. Supplementary essential variables are required for metals that must be tested for compliance with specified notch-toughness requirements. Changes may be made in the nonessential variables in a WPS without requalification provided such changes are documented. However, when an essential or supplementary essential variable is changed, the WPS must be requalified and new or additional PQRs must be prepared to support the changes. A change from one welding process to another is considered an essential variable and requires requalification.

More than one WPS having different essential or nonessential variables may be used in a single production joint. Each procedure may include one or more welding processes, filler metals, or other variables. Rules for determining the range of base metal thicknesses qualified and the maximum thickness of deposited weld metal qualified for each process or procedure are provided in Section IX (Ref. 4.1) of the Code.

There are nine categories of welding variables that are applicable as either essential, nonessential, or supplementary essential for WPS qualification. The category designations are listed below.

1. Joints
2. Base metals
3. Filler metals
4. Position
5. Preheat
6. Postweld heat treatment (PWHT)
7. Gas
8. Electrical characteristics
9. Technique

Although each category may include a number of variables, only certain ones apply to a particular welding process. For example, the essential, nonessential, and supplementary essential welding variables specified in Section IX (Ref. 4.1) of the Code for the shielded metal-arc and gas tungsten-arc welding processes are listed in Table 4.1.

Whenever a WPS for the repair or replacement of a containment pressure boundary component is being drafted, the additional requirements and exemptions provided in the original construction code and in Section XI, Subsection IWA-4000 (Ref. 4.2) of the Code should be considered so that all applicable welding variables and test conditions can be identified. Welding requirements applicable to repairs and replacements of containment pressure boundary components are summarized in Sect. 3.5.

4.2.2 Test Coupon (Procedure)

Procedure qualification is established based on results obtained from a test coupon or weldment that has been prepared by a skilled workman using the welding variables identified in the WPS. The welding procedure qualification test is intended to establish the properties of the weldment, not the skills of the workman. Guidance for establishing the size, shape, and dimensions of the test coupon are provided in Section IX (Ref. 4.1) of the Code.

Weldment properties are determined by mechanical testing performed on test specimens taken from the coupon. Testing may involve tension tests, guided-bend tests (side-bend, face-bend, or root-bend), fillet-weld tests, or notch-toughness tests. The types and numbers of test specimens required to qualify a WPS as well as the applicable acceptance criteria are provided in Section IX (Ref. 4.1) of the Code. Qualification is generally established based on pass-fail acceptance criteria. However, if any test specimen fails to meet the applicable acceptance criteria, the entire test coupon is consider as failed and another test coupon must be prepared.

4.2.3 Procedure Qualification Record

The completed PQR must include documentation of all essential and, when required, supplementary essential variables for each welding process used during the welding of the test coupon. Nonessential or other variables may also be recorded if desired, but all variables that are recorded must be the actual variables (including ranges) used during the welding of the test coupon. Variables that are not monitored during welding, may not be recorded. When more than one welding process or filler metal is used to weld a test coupon, the approximate thickness of the weld metal deposited by each welding process and filler metal combination must be recorded.

After the PQR has been written, an authorized employee of the manufacturer or contractor must certify the PQR by signing and dating the form. This certification is intended to be the manufacturer's or contractor's verification that the information in the PQR is a true record of the variables that were used during the welding of the test coupon and that the mechanical test results are in compliance with Section IX requirements. Additional information can be incorporated into a PQR at a later date provided the information is substantiated as having been part of the original qualification condition by laboratory record or similar data. All changes to a PQR require recertification by an authorized employee of the manufacturer or contractor.

4.2.4 Standards for Welding Qualification

The format of the WPS and the PQR have not been standardized. However, sample forms are included in Section IX to serve as guides for WPS and PQR preparation. Although well suited for most applications, these forms do not lend themselves to cover combinations of welding processes or more than one F-Number filler metal in the test coupon.

Guidelines for describing arc welds and for recording arc weld material property and nondestructive examination data in computerized data bases have been published by AWS (Refs. 4.5 and 4.6). These guidelines provide a mechanism for accurately and precisely storing weld data for later searches and comparisons. They also provide a framework for recording data that is included in WPSs and PQRs.

Standard WPSs that present information for producing acceptable welds using the listed conditions and variables have been published by AWS (Refs. 4.7 through 4.16). Data that support these standard WPSs have been derived from two or more PQRs completed under the auspices of the Welding Research Council. Although these WPSs may not be suitable for use in the repair or replacement of containment pressure boundary components, they illustrate the content and format of qualified WPSs for the shielded metal-arc and gas tungsten-arc welding processes.

4.3 Performance Qualification

Each manufacturer or contractor that performs construction in accordance with code requirements is responsible for conducting tests to qualify the performance of the welders and welding operators that it employs. Performance qualification is established by a demonstration of a welder's or welding operator's ability to make sound welds in accordance with a qualified WPS. Performance qualification requirements are provided in Section IX (Ref. 4.1) of the Code.

Candidates for performance qualification must be employed by the manufacturer or contractor that is responsible for qualification testing and be under the full supervision and control of the manufacturer or contractor during the production of the performance test coupon. This requirement is intended to ensure that the manufacturer or contractor has determined that its welders and welding operators are capable of developing acceptable weldments using its qualified WPS.

4.3.1 Welding Variables (Performance)

Essential welding variables for welder and welding operator performance qualification are listed in Section IX (Ref. 4.1) of the Code. Those applicable to specific welding processes and those for automatic and machine welding are provided. Automatic welding involves equipment that performs the welding operation without adjustment of the controls by the welding operator. Machine welding involves equipment that performs the welding operation under the constant observation and control of the welding operator. Tables 4.2 and 4.3 show the essential variables that are applicable to the SMAW, GTAW, automatic, and machine welding processes.

Welder or welding operator requalification is required whenever a change is made in one or more essential variables. When a combination of welding processes is required to make a weldment, each welder or welding operator involved in the production is required to be qualified for each welding process.

4.3.2 Test Coupon (Performance)

Welders and welding operators may be qualified by radiography of a completed test coupon prepared specifically for performance testing, by visual and mechanical examinations of the test coupon, or by radiography of the welder's or welding operator's initial production welding. Plate, pipe, or other product forms may be used to make test coupons for performance qualification. In general, the test coupon design used for procedure qualification is usually suitable for performance qualification.

Two or more welders or welding operators, each using a different welding process, may be qualified in combination in a single test coupon. Welders and welding operators may also be qualified by making tests with each individual welding process in separate test coupons or with a combination of welding processes in a single test coupon. However, failure of any portion of a combination test in a single test coupon constitutes failure of the entire combination.

Welds considered unacceptable by radiographic examination are those in which linear or rounded indications exceed the limits specified in Section IX (Ref. 4.1) of the Code. Examples of unacceptable indications include any type of crack or zone of incomplete fusion or penetration, any elongated slag inclusion that exceeds a prescribed length, or any rounded indication that exceeds 20 percent of the base metal thickness or 3 mm (0.125 in.), which ever is smaller. Test coupons considered unacceptable by visual examination are those in which incomplete joint penetration with incomplete fusion of weld and base metal is detected. Test specimens taken from the test coupon are considered unacceptable when guided-bend tests (side-bend, face-bend, or root-bend) or fillet-weld tests fail to meet pass-fail acceptance criteria. Failure to meet radiographic, visual, or mechanical examination acceptance criteria mean that the welder or welding operator has failed.

4.3.3 Performance Qualification Certification

The welder/welding operator performance qualification (WPQ) is a record of the essential variables, the type of test and test results, and the ranges qualified for each welder or welding operator. A sample WPQ form is included in Section IX (Ref. 4.1) of the Code suggesting an acceptable format for recording this data. The form includes a signature and data blocks for use by a representative from the manufacturing or contracting organization in certifying that the statements in the record are correct and that the test coupons were prepared, welded, and tested in accordance with the requirements provided in Section IX (Ref. 4.1) of the Code.

Each qualified welder and welding operator is assigned an identifying number, letter, or symbol by the manufacturer or contractor. These identifiers are used to distinguish one individual's work from another.

References

4.1 "Qualification Standards for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators," *ASME Boiler and Pressure Vessel Code*, Section IX, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

4.2 "Rules for Inservice Inspection of Nuclear Power Plant Components," *ASME Boiler and Pressure Vessel Code*, Section XI, Division 1, Subsection IWA, General Requirements, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

4.3 "Rules for Construction of Nuclear Power Plant Components," *ASME Boiler and Pressure Vessel Code*, Section III, Division 1, Subsection NE, Class MC Components, American Society of Mechanical Engineers, New York, New York, July 1, 1995.

4.4 "Rules for Construction of Nuclear Power Plant Components," *ASME Boiler and Pressure Vessel Code*, Section III, Division 2, Code for Concrete Reactor Vessels and Containments, Subsection CC, Concrete Containments (Prestressed or Reinforced), American Society of Mechanical Engineers, New York, New York, July 1, 1995.

4.5 "Standard Guide for Describing Arc Welds in Computerized Material Property and Nondestructive Examination Databases," ANSI/AWS A9.1-92, American Welding Society, Miami, Florida, 1992.

4.6 "Standard Guide for Recording Arc Weld Material Property and Nondestructive Examination Data in Computerized Databases," ANSI/AWS A9.2-92, American Welding Society, Miami, Florida, 1992.

4.7 "Standard Welding Procedure Specification (WPS) for Shielded Metal Arc Welding of Carbon Steel, (M-1/P-1, Group 1 or 2), 3/16 through 3/4 inch, in the As-Welded Condition, with Backing," ANSI/AWS B2.1.001-90, American Welding Society, Miami, Florida, 1990.

4.8 "Standard Welding Procedure Specification (WPS) for Gas Tungsten Arc Welding of Carbon Steel, (M-1/P-1, Group 1 or 2), 3/16 through 7/8 inch, in the As-Welded Condition, with Backing," ANSI/AWS B2.1.002-90, American Welding Society, Miami, Florida, 1990.

4.9 "Standard Welding Procedure Specification (WPS) for Shielded Metal Arc Welding of Carbon Steel (M-1/P-1/S-1, Group 1 or 2) 1/8 through 1-1/2 inch Thick, E7018 As-Welded or PWHT Condition," ANSI/AWS B2.1-1-016-94, American Welding Society, Miami, Florida, 1994.

4.10 "Standard Welding Procedure Specification (WPS) for Shielded Metal Arc Welding of Carbon Steel (M-1/P-1/S-1, Group 1 or 2) 1/8 through 1-1/2 inch Thick, E6010 As-Welded or PWHT Condition," ANSI/AWS B2.1-1-017-94, American Welding Society, Miami, Florida, 1994.

4.11 "Standard Welding Procedure Specification (WPS) for Gas Tungsten Arc Welding Followed by Shielded Metal Arc Welding of Carbon Steel (M-1/P-1/S-1, Group 1 or 2) 1/8 through 1-1/2 inch Thick, ER70S-2 and E7018 As-Welded or PWHT Condition," ANSI/AWS B2.1-1-021-94, American Welding Society, Miami, Florida, 1994.

4.12 "Standard Welding Procedure Specification (WPS) for Shielded Metal Arc Welding of Carbon Steel (M-1/P-1/S-1, Group 1 or 2) 1/8 through 1-1/2 inch Thick, E6010 (Vertical Uphill) Followed by E7018 As-Welded or PWHT Condition," ANSI/AWS B2.1-1-022-94, American Welding Society, Miami, Florida, 1994.

4.13 "Standard Welding Procedure Specification (WPS) for Shielded Metal Arc Welding of Austenitic Stainless Steel (M-8/P-8/S-8, Group 1) 1/8 through 1-1/2 inch Thick, As-Welded Condition," ANSI/AWS B2.1-8-023-94, American Welding Society, Miami, Florida, 1994.

4.14 "Standard Welding Procedure Specification (WPS) for Gas Tungsten Arc Welding of Austenitic Stainless Steel (M-8/P-8/S-8, Group 1) 1/8 through 1-1/2 inch Thick, As-Welded Condition," ANSI/AWS B2.1-8-024-94, American Welding Society, Miami, Florida, 1994.

4.15 "Standard Welding Procedure Specification (WPS) for Gas Tungsten Arc Welding followed by Shielded Metal Arc Welding of Austenitic Stainless Steel (M-8/P-8/S-8, Group 1) 1/8 through 1-1/2 inch Thick, As-Welded Condition," ANSI/AWS B2.1-8-025-94, American Welding Society, Miami, Florida, 1994.

4.16 "Standard Welding Procedure Specification (WPS) for Shielded Metal Arc Welding of Carbon Steel (M-1/P-1/S-1, Group 1 or 2) 1/8 through 1-1/2 inch Thick, E6010 (Vertical Downhill) Followed by E7018 As-Welded or PWHT Condition," ANSI/AWS B2.1-1-026-94, American Welding Society, Miami, Florida, 1994.

Table 4.1 Welding procedure specification variables for shielded metal-arc and gas tungsten-arc welding.

Variable category	Variable description	Shielded Metal-Arc Welding (SMAW)	Gas Tungsten-Arc Welding (GTAW)
Joints	Change in the type of groove	N	N
	Deletion of backing in single-welded groove welds	N	NA
	Addition of backing or change in its composition	NA	N
	Change in the specified root spacing	N	N
	Addition or deletion of retainers	N	N
Base Metals	Change in group number	S	S
	Test coupon thickness limits impact	S	S
	Test coupon thickness limits the qualified thickness above 203 mm (8 in.)	E	E
	Change in base metal thickness beyond the range qualified	E	E
	Welding pass thickness over 12.7 mm (0.5 in.)	E	NA
	Change in P-No. qualified	E	E
	Change from one P-No. 5, 9, or 10 designation to another	E	E
Filler Metals	Change in size of the filler metal	NA	N
	Change from one F-Number to another	E	E
	Change from one A-Number to another	E	E
	Change in nominal size (diameter) of electrode	N	NA
	Change in electrode diameter to over 6.35 mm (0.25 in.)	S	NA
	Change in AWS classification	S	S
	Deletion or addition of filler metal	NA	E
	Omission or addition of consumable inserts	NA	N
	Change in filler metal from bare (solid) or metal cored to flux cored or vice versa	NA	E
	Change in deposited weld metal thickness beyond the range qualified	E	E
	Change in AWS classification	N	N
Positions	Addition of other welding positions than those qualified	N	N
	Change from any position to vertical uphill progression	S	S
	Change from upward to downward or from downward to upward in the progression specified for any pass of a vertical weld	N	N
Preheat	Decrease of more than 56°C (100°F) in the preheat temperature qualified	E	E
	Change in the maintenance or reduction of preheat upon completion of welding prior to any required PWHT	N	NA
	Increase of more than 56°C (100°F) in the maximum interpass temperature recorded on the PQR	S	S

E – Essential variable in which a change will affect the mechanical properties of a weldment.
S – Supplementary essential variable in which a change will affect the notch-toughness properties of a weldment.
N – Nonessential variable in which a change will not affect the mechanical properties of a weldment.
NA – Not applicable to the process.

Table 4.1 (Cont'd) Welding procedure specification variables for shielded metal-arc and gas tungsten-arc welding.

Variable category	Variable description	Shielded Metal-Arc Welding (SMAW)	Gas Tungsten-Arc Welding (GTAW)
PWHT	Change in PWHT requirements from those recorded on PQR	E	E
	Change in PWHT temperature and time ranges	S	S
	Thickness limitations apply when the PWHT temperature exceeds the upper transition temperature	E	E
Gas	Addition or deletion of trailing shielding gas or change in its composition	NA	N
	Change from one gas to another or to a mixture	NA	E
	Change in the specified flow rate range	NA	N
	Addition or deletion of gas backing or change in backing gas composition or flow rate range	NA	N
	Deletion of backing gas or change in gas composition for groove welds in designated base metals	NA	E
	Change in specified trailing shielding gas parameters for designated base metals	NA	E
Electrical Characteristics	Increase in heat input or an increase in volume of weld metal deposited per unit length of weld over that qualified	S	S
	Addition or deletion of pulsing current to DC power source	NA	N
	Change in current or polarity	S or N	S or N
	Change in the range of amperage or voltage	N	N
	Change in tungsten electrode	NA	N
Technique	Change from the stringer bead to the weave bead technique or visa versa	N	N
	Change in orifice, cup, or nozzle size	NA	N
	Change in the method of interpass cleaning	N	N
	Change in the method of back gouging	N	N
	Change in width, frequency, or dwell time of oscillation (for machine or automatic welding only)	NA	N
	Change in multipass per side to single pass per side	NA	S or N
	Change from single electrode to multiple electrode, or visa versa	NA	S or N
	Change from closed chamber to out-of-chamber conventional torch welding in P-No. 5X metals, but not visa versa	NA	E
	Change in spacing of multiple electrodes in machine or automatic welding	NA	N
	Change from manual or semiautomatic to machine or automatic welding or vice versa	N	N
	Addition or deletion of peening	N	N

E – Essential variable in which a change will affect the mechanical properties of a weldment.
S – Supplementary essential variable in which a change will affect the notch-toughness properties of a weldment.
N – Nonessential variable in which a change will not affect the mechanical properties of a weldment.
NA – Not applicable to the process.

Table 4.2 Essential variables for welders for the shielded metal-arc and gas tungsten-arc welding processes.

Variable category	Essential variable description	Shielded Metal-Arc Welding (SMAW)	Gas Tungsten-Arc Welding (GTAW)
Joints	Deletion of backing in single-welded groove welds	E	E
Base Metals	Change in the pipe diameter beyond the range qualified	E	E
	Change from one P-Number to any other P-Number or to an unlisted base metal	E	E
Filler Metals	Deletion or addition of filler metal	NA	E
	Change from one F-Number to any other F-Number or to any other filler metal	E	E
	Omission or addition of consumable inserts	NA	E
	Change in deposited weld metal thickness beyond the range qualified	E	E
Positions	Addition of welding positions other than those already qualified	E	E
	Change from upward to downward or from downward to upward in the progression specified for any pass of a vertical weld	E	E
Gas	Omission of inert gas backing	NA	E
Electrical Characteristics	Change from AC to DC, or vice versa; and in DC welding, a change from straight polarity to reverse polarity, or vice versa	NA	E

E – Essential variable for welding operator performance qualification.
NA – Not applicable to the process.

Table 4.3 Essential variables for welding operators for the automatic and machine welding processes.

Essential variable description	Automatic welding	Machine welding
Change from automatic to machine welding	E	NA
Change in the welding process	E	E
Change from direct visual control to remote visual control and vice versa	NA	E
Deletion of an automatic arc voltage control system for GTAW	NA	E
Deletion of automatic joint tracking	NA	E
Addition of welding positions other than those already qualified	NA	E
Deletion of consumable inserts	NA	E
Deletion of backing	NA	E
Change from single pass per side to multiple passes per side but not the reverse	NA	E

E – Essential variable for welding operator performance qualification.
NA – Not applicable to the process.

5. SPECIAL RESTORATION PRACTICES

5.1 Underwater Welding

Underwater welding has been used for many years for special salvage operations or for making temporary structural repairs. Practical difficulties encountered in underwater welding include rapid quenching of the weldment by the surrounding water and susceptibility of the weldment to hydrogen embrittlement. Both tensile strength and ductility have been found to be drastically reduced compared with similar joints welded in air (Ref. 5.1). As its name implies, underwater welding is performed below the water surface, but underwater welding can be performed in either a wet or a dry environment.

Dry underwater welding is performed in a dry habitat and often requires construction of a customized high-pressure chamber around the welding zone. The dry environment allows production of high-quality welds. Shielded metal-arc, gas metal-arc, and gas tungsten-arc welding processes can be used for dry underwater welding applications, but the large amounts of smoke and fumes produced by the shielded metal-arc welding often make it the least desirable option. Because an underwater chamber can be very expensive and time consuming to design, fabricate, and setup, dry underwater welding may not be the most desirable option except in special or unique situations.

Wet underwater welding is performed at ambient pressure with the welder/diver in the water without any mechanical barrier between the water and the welding arc. Wet welding has been demonstrated to produce acceptable welds at depths much greater than those encountered in containment pressure boundary component repairs, but the relatively poor quality of welds made in a wet environment is due primarily to problems of heat transfer, welder visibility, and the presence of hydrogen in the arc atmosphere during the welding operation (Ref. 5.2).

Although both dry and wet underwater welding environments experience increased pressure with depth, the wet environment also increases the cooling rate during welding. Depending on the heat input and the plate thickness, a shielded metal-arc weld produced above water takes between 8 and 16 seconds to cool from 800 to 500°C (1,470 to 930°F) compared to the same weld produced underwater which takes between 1 and 6 seconds to cool the same amount (Ref. 5.2). The structure of steel after the welding procedure is completed depends on the cooling rate and the temperature from which it cools (Ref. 5.3). It can very from soft, ductile pearlitic structure to hard, less-ductile martensitic structure. Rapid cooling of the weld metal produces a quenching effect that influences the weld metal phase transformation characteristics and produces a weld solidification structure with reduced toughness and ductility. Enhanced cooling also produces significant amounts of martensite in the heat affected zone (HAZ) in nearly all low-carbon steels. This effect can be a concern because as the martensite content increases, the HAZ become more susceptible to hydrogen cracking. Additional technical information related to underwater welding is contained in an AWS specification prepared specifically for this condition (Ref. 5.4).

Supplementary rules for dry and wet underwater welding repairs or replacements of P-No. 8 (austenitic stainless steel) and P-No. 4X (low-alloy steel) materials are provided in Code Case N-516 (Ref. 5.5). When applicable, these methods can be used in lieu of the alternative welding methods permitted in Section XI, Subsection IWA-4500 (Ref. 5.6) of the Code provided all other applicable requirements of Section XI are met. Welding processes permitted by Code Case N-516 for underwater repairs and replacements are listed in Table 5.1. Similar code cases for underwater welding of other materials such as carbon steels permitted for construction of containment pressure boundary components have not been approved by ASME.

5.1.1 Underwater Welding Qualification

According to Code Case N-516 (Ref. 5.5), the WPS for dry and wet underwater welding qualification must conform to the requirements of Section IX (Ref. 5.7) of the Code for groove welds. Additional welding variables applicable to underwater welding procedure specification qualification are identified in Table 5.2.

Welders and welding operators for dry and wet underwater welding must be qualified in accordance with requirements provided in Section IX (Ref. 5.7) of the Code and the additional variables listed in this code case. These additional performance qualification variables are listed in Table 5.3.

5.1.2 Filler Metal Qualification

Code Case N-516 (Ref. 5.5) requires that the filler metal be qualified. Filler metal qualification is achieved by preparing an all-weld-metal coupon in accordance with ASME welding rod, electrode, and filler metals specification SFA-5.4 (Ref. 5.8) using the production welding process at an acceptable depth that is approximately the same as the depth of the production weld. Testing requirements and acceptance criteria for the all-weld-metal coupon are provided as part of the code case.

5.1.3 Confirmation Weld

Before underwater production welding can be initiated, Code Case N-516 (Ref. 5.5) requires that a confirmation weld be produced at the welding location to demonstrate that the welding system is functioning properly. This confirmation weld must be made using the qualified welding procedure with each production welding system. Additional conditions for the confirmation weld are listed in Table 5.4. In lieu of a confirmation weld, this code case permits the substitution of procedure qualification at the underwater location.

5.1.4 Examination

When the underwater environment makes it impractical to conduct the required examinations, Code Case N-516 (Ref. 5.5) requires that the following examinations be performed.

1. After the defect has been removed, the cavity must be visually examined remotely at a minimum of 5x and evaluated using surface examination acceptance criteria.

2. The weld must be visually examined remotely at a minimum of 5x and evaluated using surface examination acceptance criteria.

3. The weld can be examined by ultrasonic testing techniques using a procedure qualified for the underwater environment in lieu of any other required volumetric examination.

Acceptance criteria for these examinations must be based on applicable requirements of Section XI (Ref. 5.6) of the Code or the applicable construction code.

5.2 Welding with Concrete Backing

During welding operations, base material immediately adjacent to the welding arc can reach temperatures as high as 1,370°C (2,500°F) for a short period of time (Ref. 5.3). Because metal is a good heat conductor and air is very poor, the thermal gradient near the welding arc depends primarily on the thickness of the base material being welded. For thick sections, where heat disperses rapidly through the base material by conduction, the thermal gradient is generally quite pronounced especially when the base material is not preheated. By comparison, a narrow band of red-hot base material may be visible for a short distance behind the welding arc in relatively thin sections such as liners of reinforced concrete containments. Table 5.5 points out the difference that base material thickness can have on the instantaneous cooling rate for bead-on-plate surface welds backed by air. These values reflect instantaneous cooling rates for base material at a nominal temperature of 760°C (1,400°F). The effects of welding induced high-temperature exposure on the properties and qualities of the weld metal, HAZ, and base material can be significant. Consequently, measures necessary for assuring predictable weldment behavior are reflected in the prescriptive rules and requirements provided in the ASME Code for welding procedure specification and welder/welding operator performance qualification. For example, preheat, interpass temperature limits, and PWHT requirements are often specified to help ensure that high-quality weldments are produced.

Although the ASME Code rules and requirements are considered comprehensive and complete for most routine welding activities, they do not adequately address the impacts that repair welding operations can have on other containment components and materials such as embedment anchors that are attached to the concrete containment liner and concrete that has been cast against the liner. Figures 5.1 and 5.2 illustrate situations in which high temperatures produced by repair or replacement welding of a containment pressure boundary component could affect adjacent concrete and metallic components including embedment anchors and reinforcing bars embedded in the concrete. Ways in which high temperatures from repair welding operations can adversely affect concrete and metallic items embedded in concrete are summarized in Table 5.6.

5.2.1 Concrete Temperature Limits

Recognizing that concrete strength tends to decrease with increasing temperature (Ref. 5.9), building and construction codes for concrete provide temperature limits for the concrete to assure predictable behavior and performance. Table 5.7 identifies the rules and requirements pertaining to high-temperature exposure of concrete and metallic embedments that appear in selected codes (Refs. 5.6 and 5.10 to 5.12). Absent from the table are rules and requirements written specifically for welding of base materials backed by concrete. Building codes and guidance documents prepared by organizations such as the American Concrete Institute (ACI) and The International Union of Testing and Research Laboratories for Materials and Structures (RILEM) do not adequately address this issue because very little quantifiable data about rapid, localized heating of concrete are available (Refs. 5.13 and 5.14).

5.2.2 Welding Qualification Issues

To minimize or eliminate potential high-temperature effects of repair welding operations on concrete and metallic embedments, the issues listed in Table 5.8 need to be considered when plans for welding repairs of containment pressure boundary components backed by concrete are being prepared.

5.3 Welding Repair Alternatives for Inaccessible Areas

Innovative welding solutions are being considered for the repair of degraded carbon and low-alloy steel components because welding provides an effective means for making the types of high-quality repairs that are required by utility owners, jurisdictional authorities, and regulatory agencies. One innovative solution under development involves an outside surface weld overlay repair to remedy inside surface erosion-corrosion damage to carbon steel piping (Ref. 5.15). If adequately developed and thoroughly tested, this solution could be submitted for ASME consideration as a code case. Once approved, use of this technique would eliminate the need for repair of the inside pipe surface by providing sufficient replacement metal on the outside of the pipe to restore structural integrity.

Besides pipe repairs, this innovative solution might also be applicable to repairs of inaccessible areas of metal containments and liners of concrete containments damaged by corrosion. Figure 5.3 shows a situation in which an inaccessible area of a metal containment shell has corroded to the point that its structural capacity is no longer considered adequate and a repair is required. In this case, repair welding is only feasible from one side due to the narrow gap between the metal shell and the biological shield wall. Four possible welding repair techniques for this situation are shown in Figs. 5.4 to 5.7 and described below.

5.3.1 Replacement Plate Welding Repair

Figure 5.4 shows a conventional replacement plate welding repair. In this repair technique, the structural integrity of the containment is restored to its preservice condition by removing the defective area, replacing it with new plate material, performing the necessary repair welding and PWHT, and conducting the required nondestructive evaluations and leakage-rate tests.

5.3.2 Doubler Plate Welding Repair

A doubler plate welding repair is shown in Fig. 5.5. Structural capacity and leaktight integrity are provided in this repair technique by removing the damaged portion of the metal shell, fitting a larger plate over the hole, performing the necessary repair welding and PWHT, and conducting the required nondestructive evaluations and leakage-rate tests.

5.3.3 Stiffener Plate Welding Repair

Installation of stiffener plates as shown in Fig 5.6 is another repair technique that could be used to strengthen the remaining shell without affecting the leaktightness of the containment. Use of stiffener plates eliminates the need for repair of the corroded surface by providing additional structural elements to restore structural integrity. Because this repair technique does not involve repair of the corroded surface, it has no effect on the leaktight integrity of the containment.

5.3.4 Overlay Welding Repair

Surface overlay welding as shown in Fig. 5.7 might be considered the most desirable alternative repair technique. Use of surface overlay welding eliminates the need for repair of the corroded surface by providing sufficient replacement metal to restore structural integrity. This repair technique is also desirable because it has no effect on the leak-tightness of the containment.

5.4 Temporary Non-Code Repairs

Whenever leakage from an ASME Code Class 1, 2, or 3 component pressure boundary (i.e., pipe wall, valve body, pump casing, etc.) is discovered, the component must be declared inoperable (Ref. 5.16). If the flaw is detected while the plant is in operation, the plant may need to be shut down before the flawed component can be repaired or replaced and the plant returned to a safe operating condition. Rules for repairing flawed components are provided in Section XI, Subsection IWA (Ref. 5.6) of the Code. Repairs completed in accordance with these requirements ensure that the structural integrity of the component has been restored.

Repairs not in compliance with rules provided in Section XI (Ref. 5.6) of the Code are considered non-code repairs. Techniques that could be used to make temporary non-code repairs to flawed piping include clamps with rubber gaskets, encapsulation of leaking pipes in cans using liquid sealants, and certain types of weld overlays. However, temporary non-code repairs of ASME Code Class 1, 2, and 3 piping are considered unacceptable unless they are first approved in writing by the NRC. Guidance from the NRC for performing non-code repairs to flawed piping is provided in Generic Letter 90-05 (Ref. 5.17). For Class 1, 2, and 3 piping, a licensee is required to perform code repairs or request the NRC to grant relief for temporary non-code repairs on a case-by-case basis regardless of pipe size. Relief requests are usually made by licensees to avoid unscheduled plant shutdowns.

5.4.1 Class 1 and 2 Piping

To be considered acceptable, temporary non-code repairs of Class 1 and 2 piping must have load-bearing capability similar to that provided by engineered weld overlays or engineered mechanical clamps. Relief requests based on repairs such as encapsulation of leaking pipes in cans using liquid sealants, clamps with rubber gasketing, or non-engineered weld overlays (patches) will not be granted because these repair techniques are considered unacceptable. However, engineered weld overlays or engineered mechanical clamps that are designed to meet the load-bearing requirements of the piping may be acceptable under certain conditions (Ref. 5.17). Use of engineered weld overlays and engineered mechanical clamps in BWR plants are discussed in Generic Letter 88-01 (Ref. 5.18 and 5.19).

5.4.2 Class 3 Piping

Because of the rather frequent instances of small leaks in some Class 3 piping systems, such as service water systems, relief requests for temporary non-code repairs of Class 3 piping will be considered by the NRC. Guidance for such a request consists of assessing the structural integrity of the flawed piping by a flaw evaluation and the overall degradation of the system by an augmented inspection. In addition, the licensee evaluation should consider system interactions such as flooding, spraying water on equipment, and loss of flow. Furthermore, temporary non-code repairs should be evaluated for design loading conditions.

Temporary non-code repairs of Class 3 piping in high-energy systems where the maximum operating temperature exceeds 93°C (200°F) or the maximum operating pressure exceeds 1.9 MPa (275 psi), must have load-bearing capability similar to that provided by engineered weld overlays or engineered mechanical clamps. Licensee requests for high-energy Class 3 piping repairs based on techniques such as encapsulation of leaking pipes in cans using liquid sealants, clamps with rubber gasketing, or non-engineered weld overlays (patches) are not considered acceptable. For temporary non-code repairs of Class 3 piping in moderate-energy systems, that is, other than high-energy systems, the licensee may consider non-welded repairs. To ensure acceptable in service performance, the structural integrity of the temporary non-code repair of Class 3 piping should be assessed periodically.

For Class 3 piping, two specific flaw evaluation approaches should be considered, namely, the "through-wall flaw" and the "wall thinning" approaches. If the flaw is found acceptable by the "through-wall flaw" approach, a temporary non-code repair may be proposed. If the flaw is found acceptable by the "wall thinning" approach, immediate repair is not required but the licensee should comply with the guideline for repair and monitoring. An augmented inspection is a part of the relief acceptance criteria. The extent of the augmented inspection is more stringent for high-energy lines than for moderate-energy lines because of the potential for more severe failure consequences.

A request for relief from requirements of Section XI (Ref. 5.6) of the Code was submitted to the NRC on January 16, 1991 (Ref. 5.20). The request was prepared in accordance with guidance provided in Generic Letter 90-05 (Ref. 5.17) to cover temporary non-code repairs of Class 3 stainless steel piping located inside the containment. During the latter stages of a scheduled refueling outage, nondestructive examinations of service water system supply and return piping for a containment fan cooler and service water containment penetrations produced indications of degradation resulting from microbiologically induced corrosion (MIC). Although the defects were within ASME Code allowable limits, flaw growth rates in the presence of MIC are not predictable making continued use of the service water system during the next operating cycle unjustified. Relief was requested to allow the installation of welded stainless steel sleeves over susceptible welds in the service water piping and over welds at containment penetrations that indicated MIC damage. Figures 5.8 and 5.9 show the proposed repair configurations. According to the request, the sleeves constituted an engineering repair, restored the piping to its full structural and pressure-retaining capability, and complied with Section XI repair requirements with the single exception that existing flaws were not removed.

5.4.3 Containment Pressure Boundary Components

Containment pressure boundary component degradation is usually discovered during a general inspection of accessible interior and exterior surface areas. General inspections are performed in accordance with 10 CFR 50, Appendix J (Ref. 5.21) requirements prior to each containment leakage-rate test (Refs. 5.22 and 5.23). Flaws discovered as a result of these inspections and tests that do not meet acceptance criteria (defects) must be repaired before the plant is allowed to return to service. Consequently, there is no need for submitting a relief request to the NRC for a temporary non-code repair of the containment aimed at keeping the plant in operation until the next scheduled outage.

5.5 Protective Coating Repairs

Organic coating systems, or paints as they are more commonly known, are used in nuclear power plant containments to protect ferrous metal surfaces from corrosion and to facilitate decontamination of metal and concrete surfaces. Corrosion protection is needed for all exposed carbon steel items including surfaces of metal containment shells, concrete containment liners, structural steel elements, uninsulated mechanical equipment, piping system components and related hardware, and electrical-mechanical machinery. Protective coatings also play an important role in achieving and maintaining radiological control by providing surfaces that can be readily decontaminated. Although reasons for using protective coatings are based primarily on economic considerations, factors that could influence their use include material compatibility, heat transfer characteristics, and the consequences of failure during a design basis accident.

5.5.1 Regulatory Overview

Application of protective coatings on structures, equipment, and components in nuclear power plants is not required by the NRC because coatings provide no specific safety-related function to mitigate the consequences of postulated accidents. However, quality assurance requirements provided in 10 CFR 50, Appendix B (Ref. 5.21) are applicable to protective coatings because failure and disbonding during operating and emergency conditions could interfere with engineered safety system required for safe shutdown and cooling of the reactor vessel. Potential consequences of protective coating failure are identified below (Ref. 5.24).

1. Massive delaminations or peeling of coatings during a loss-of-coolant accident could block containment sumps used to recirculate cooling water.

2. Plugging of flow passages by paint chips or debris could block water flow to containment spray nozzles, emergency pumps, or the reactor core.

3. Chemical- or mechanical-induced damage to the reactor coolant system such as intergranular

stress-corrosion cracking and abrasion could be caused by the decomposition of coating materials and their subsequent chemical interaction with reactor safety system components (e.g., hydrogen generation due to radiolytic decomposition).

Acceptance criteria for protective coating systems (including coating repairs) are provided in Sect. 6.1.2 of the NRC Standard Review Plan (Ref. 5.25). According to these criteria, coating systems applied to the insides of containments are acceptable if they meet the regulatory positions of Regulatory Guide 1.54 (Ref. 5.26) and the standards of ANSI N101.2 (Ref. 5.27). Regulatory Guide 1.54 describes an acceptable method for complying with NRC quality assurance requirements with regard to protective coatings applied to ferritic steels, aluminum, stainless steel, zinc-coated (galvanized) steel, concrete, or masonry surfaces of water-cooled nuclear power plants. The requirements and guidelines included in ANSI N101.4 (Ref. 5.28) are generally acceptable, subject to the four exceptions listed in Regulatory Guide 1.54, because they provide an adequate basis for complying with the pertinent quality assurance requirements of 10 CFR 50, Appendix B (Ref. 5.21). In addition, the containment coating system is acceptable if it has been evaluated as to its suitability to withstand a postulated design basis accident and qualified under conditions that take into account the postulated design basis accident.

Since ANSI N101.2, N101.4, and 5.12 (Ref. 5.27 to 5.29) were issued in the early 1970s, responsibility for updating, rewriting, and issuing appropriate ANSI replacement standards has been transferred to ASTM, specifically ASTM Committee D-33, on Protective Coating and Lining Work for Power Generation Facilities (Ref. 5.30). Now, after 25 years of inservice experience and performance data on protective coatings have been developed, a very restrictive set of guides, standard practices, specifications, test methods, and quality assurance requirements for coatings for use in nuclear power plants have been prepared and issued (Refs. 5.21 and 5.25 to 5.47). Requirements for monitoring the effectiveness of maintenance of nuclear power plants are provided in 10 CFR 50.65 (Ref. 5.48).

Technical guidance for NRC inspections of filled organic coatings used in maintenance of safety related-equipment is provided in the *NRC Inspection Manual* (Ref. 5.49). According to this document, filled organic coatings including epoxy, polyester, urethane, and phenolic materials are appropriate for use over eroded or corroded areas provided the ASME Code minimum thickness has not been violated. Coatings are not ASME Code materials and thus cannot be used to perform structural repairs. Areas where the ASME Code minimums are not met must be replaced or restored by weld build-up in the location of the wall loss prior to application of the coating. Inspectors are instructed to ensure that the licensee has considered the following items.

1. Is the selected coating appropriate for the system temperature, immersion service, chemical environment (pure water, sea water, borated water), and intended purpose (corrosion barrier versus erosion resistance)?

2. Was ultrasonic testing performed prior to application of the coating to verify that minimum wall thickness requirements were satisfied?

3. Have the consequences of a coating failure been analyzed?

4. Were coating application procedures in place and followed?

5. Were the coating manufacturer's specified time and temperature for adequate cure followed prior to returning equipment to service?

6. Following coating applications to pumps, examine what performance testing was performed to verify pump acceptance.

5.5.2 Potential Degradation Mechanisms and Failure Criteria

Selection of an appropriate repair coating system for containment surfaces should include consideration of the expected service environment. The five major stressors that can potentially cause coating degradation are temperature, condensation and immersion, radiation, physical damage, and corrosion of base metal (Ref. 5.50). Ways in which coatings can fail include checking, cracking, blistering, flaking, peeling, delamination, and scaling.

Checking is the phenomenon manifested in coating films by slight breaks in the film that do not penetrate through the last applied coating. Where precision is necessary in evaluating a coating film, checking may be described as visible (as seen with the naked eye) or as microscopic (as observed under a magnification up to 10x). Although checking is not easily recognized, a standard test method for evaluating the degree of checking has been established (Ref. 5.51).

Cracking is a break or a split in the coating system extending through the film or to the substrate. Where this phenomenon is difficult to determine, the break should be called a crack only if the underlying surface if visible. The use of a magnification of 10x is recommended in cases where it is difficult to differentiate between cracking and checking. A standard method for evaluating the degree of cracking has been established. This method is based on comparison to pictorial standards (Ref. 5.52).

Blistering is the formation of bubbles in a coating film resulting from some weakness in the coating system. A standard procedure has been established for describing the size and density of blisters so that comparisons of severity can be made (Ref. 5.53).

Flaking is a phenomenon manifested in coating films by the actual detachment of pieces of the film itself either from its substrate or from coating previously applied. Peeling, delamination, and scaling may also be used to describe this phenomenon which is generally preceded by cracking, checking, or blistering. Flaking is the result of loss of adhesion and is usually due to stress-strain factors coming into play. A standard method for evaluating the degree of failure has been established. This method is based on comparison to pictorial standards (Ref. 5.54).

5.5.3 Underwater Coating Repairs

Protective coatings located in immersion areas of nuclear power plants have experienced premature failure while in service. Although the coating degradation and resulting pitting corrosion are localized, cleaning and coating repairs have been performed to halt the corrosion process and prevent additional coating degradation (Ref. 5.55). In BWR plants, coating degradation has occurred in the suppression chambers where demineralized cooling water for the reactors is stored. The suppression chambers, which are part of the containment pressure boundary, are constructed of carbon-steel components that are, in most cases, coated. Materials located below the water line are exposed to aggressive environmental conditions including exposure to ionizing radiation and radiological contamination, high-pressure steam releases, decontamination operations, demineralized water immersion, and abrasive action from sludge (Ref. 5.56). In PWR plants, premature coating failures can occur in immersion areas of condensate storage tanks.

Successful protective coating system performance depends on periodic inspections aimed at early detection of defects and failures, identification of repair alternatives, and timely execution of repairs. Options for coating inspection in immersion areas involve either draining to allow access for inspection personnel or underwater inspection by qualified divers.

Pitting corrosion is localized degradation that can be detected most effectively by draining the affected area and inspecting under dry conditions (Ref. 5.55). Problems associated with draining the suppression chamber in a BWR plant include treatment of radiologically contaminated water, decontamination of all internal surfaces, and installation of rigging or scaffolding to provide the required access. Decontamination is a labor-intensive effort that may subject workers to increased risk of radiation exposure. In addition, mobilization and demobilization of equipment and personnel for decontamination, repair, and inspection can severely damage or destroy the original coating. Other activities related to suppression chamber draining include reactor vessel defueling, drain pump installation and operation, high-pressure water decontamination of all internal components, and packaging and disposal of radioactive waste.

The preferred alternative to draining the suppression chamber in a BWR plant is underwater inspection and repair. Potential advantages include reduced radiation exposure of personnel and elimination of the need for draining (Ref. 5.57). Desludging, coating inspection, and underwater coating repair are the fundamental elements of this alternative (Ref. 5.58). Desludging reduces radiological exposure and increases visibility. Sludge and debris accumulation is due primarily to corrosion products from uncoated piping systems. Removal is accomplished by divers using brushes that loosen the debris and high-volume vacuum systems that draw the debris through large-capacity, high-efficiency filters. Debris that is collected by the filters is treated as radioactive waste. After desludging operations are completed, a qualitative visual inspection of the entire surface area is performed to determine the overall condition of the coating and to identify areas where cracking, blistering, flaking, and corrosion have occurred. For those areas where general corrosion has occurred, sufficient nondestructive thickness measurement should be obtained so that the wall thickness of the degraded component can be precisely established. In areas where localized or pitting corrosion has occurred, pit shape, density, and depth should be established (Ref. 5.59). Results of the nondestructive examinations should then be recorded and used to assess the current condition of the degraded component (Ref. 5.60). The data may also be used as a baseline for trending future performance or for comparison with companion data to establish an instantaneous corrosion rate. Areas where the wall thickness is below the minimum acceptable level must be either repaired or replaced prior to coating.

Damaged coatings in areas without significant metal loss should be repaired using a 100 percent solids underwater-cured epoxy coating. Use of this type of epoxy should be considered because it is formulated to displace water in contact with the surface of the metal and it cures in 24 to 36 hours depending on the temperature. To maximize the quality of the epoxy coating repair, the spot should be cleaned with power grinding tools, the edges of the coating should be feathered, and adjacent areas should be roughened to provide good adhesion for the replacement coating. After cleaning, the epoxy coating should be applied to the bare metal and overlapped onto the existing coating. Although this underwater repair process is suitable for spot coating repairs, it is not recommended for major recoating work (Ref. 5.58). As with any coating system used to protect containment pressure boundary components, the quality assurance requirements provided in 10 CFR 50, Appendix B (Ref. 5.21) are applicable to underwater coating repairs.

5.6 Options for Restoring Damaged Bellows

Stainless steel bellows expansion joints are used in nuclear power plants as flexible seals between process piping and the containment vessel wall. The piping, which may carry steam or other liquids at high pressures and temperatures, moves under the influence of temperature changes and applied forces. As the pipe moves relative to the containment wall, the bellows expands and contracts to accommodate the differential movement while maintaining the leaktight integrity of the containment. When properly installed, the bellows is not part of the process piping. It is intended to serve as a pressure boundary between the inside of the containment vessel and the surrounding atmosphere. In order to serve its intended function, bellows expansion joints cannot withstand significant mechanical abuse. However, despite efforts to protect the bellows, inadvertent damage such as mechanical denting, arc strikes, tool gouges, and scratches have occurred making remedial action necessary.

During the early years of nuclear power plant construction, there were few successful attempts to repair bellows that had been damaged after installation. Manufacturers of stainless steel bellows discouraged attempts at repairs, and the ASME Code prohibited welding repairs on bellows. Eventually, advancements in welding capabilities and development of specially designed copper back-up dies permitted successful repairs to damaged bellows (Ref. 5.61). Finally, after testing programs were conducted to develop data needed to understand the performance of repaired bellows, action was taken by ASME to approve a code case detailing rules under which repairs to bellows could be performed. Code Case N-315 (Ref. 5.62) was approved on February 14, 1984. This code case addresses repair of bellows elements for Section III, Division 1, Class 2, 3, and MC construction (Ref. 5.63).

Options for restoring the leaktightness and structural integrity of bellows that have been damaged while in service are described below (Refs. 5.61 and 5.64). However, restoration activities that produce discontinuities in the welds or base metal, changes in wall thickness resulting from the addition of welded patches or removal of metal by blending (grinding), or unevenness or irregularities in the bellows contour may affect the useful service life of the bellows.

5.6.1 Replacement of Penetration Assembly

Replacement of on entire penetration assembly that contains a damaged bellows is an option that could be taken, but this approach is generally not considered. Removal of walls and equipment to provide access necessary for the replacement would be expensive and time consuming, especially, if a plant shutdown is required to complete the replacement.

5.6.2 Replacement of Damaged Bellows

Removal of damaged bellows with one or more plies and replacement with a new one is a feasible option provided there is sufficient access for a crew of skilled craftsmen and their equipment. In this procedure, a new bellows element is cut in half using longitudinal saw cuts. After removal of the damaged bellows, the new bellows parts are reassembled around the penetration. Reconnection is a two-step process. The first step involves completion of the longitudinal seam welds that follow the contour of the convolutions. After these welds are completed, the circumferential attachment welds are completed joining the ends of the bellows to the pipe and the containment shell. Due to site-specific conditions, it may be necessary for the craftsmen to wear life-support equipment. Depending on the conditions, there may even be special restrictions on access frequency and time available at the work site because of radiation levels. For bellows replacement to be successful, thorough preparation, qualification, execution, and quality control are essential.

5.6.3 Installation of New Enveloping Bellows

When the outer ply of a two-ply bellows is damaged and its removal could damage an otherwise sound inner ply, a larger enveloping bellows can be installed around the damaged outer ply. Installation is similar to that described in Sect. 5.6.2 except thick plate rings that extend outward from the existing bellows support pipe to the new bellows diameter are used to connect the new bellows to the pipe. The monitoring function that was lost when the outer ply of the original bellows was damaged now takes place in the annular space between the enveloping bellows and the inner ply of the original bellows. Although functional, the redesigned penetration assembly may need to be analyzed and evaluated to ensure that affected components can accommodate the change in spring constants resulting from the addition of the enveloping bellows.

5.6.4 In-Place Welding Repairs to Damaged Bellows

In-place welding repairs have been successful in restoring the leaktight integrity of single-ply bellows and the outer ply of two-ply bellows. Holes as large as 25 mm (1 in.) in diameter have been effectively repaired with both insert plug patches and lapped patches. Slots up to 0.8 mm (1/32 in.) wide by 12.7 mm (1/2 in.) long have been sealed by groove welding and others have been sealed with fillet-welded lap patches.

According to requirements provided in Code Case N-315 (Ref. 5.62), welding repairs of bellows elements may be made by an N Certificate Holder (see Sect. 2.6.4), but the size of the repair is limited to 2,580 sq. mm (4 sq. in.). Requirements for N Certificate Holders involved in Code Case N-315 (Ref. 5.62) bellows repair are listed below.

1. Prior to performing the repair, the proposed repair technique must be qualified on a full-scale facsimile bellows by depositing weld metal to simulate the production repair. The facsimile bellows weld repair must be nondestructively examined and pneumatically or hydrostatically tested in the presence of the Authorized Nuclear Inspector (see Sect. 2.6.5). Duplicates of damaged areas can be reproduced using modeling clay, silicone rubber compounds, or metalized replicas (Ref. 5.61).

2. A revision to the Design Report must be prepared listing tests and calculations that ensure the repaired bellows meets the requirements of the Design Specification. The effect of the repair on the design of the bellows must be evaluated by testing a facsimile bellows that has been repaired. The revised Design Report must be certified by the N Certificate Holder and reviewed by the Owner.

3. Following fatigue testing, proof testing must be demonstrated by a hydrostatic test of the facsimile bellows.

4. Following completion of the fatigue and hydrostatic tests, the repaired areas must be examined by the liquid penetrant or magnetic particle method.

5. Welders and welding procedures must be qualified for groove welding using the GTAW process.

6. Prior to making the repair on the actual bellows, the welder must demonstrate on a prototype test assembly, under the conditions (including accessibility and position) that will be seen when making the production repair weld, the capability to make a weld repair acceptable to the Authorized Nuclear Inspector.

7. Repairs must be made by deposition of weld metal or by butt welding repair that does not alter the original design configuration.

8. The root pass and final pass of the weld repair must be examined by the liquid penetrant or magnetic particle method.

9. The completed repair must be subjected to a hydrostatic or pneumatic test.

10. The data report for the component or system must include reference to this Code Case N-315 (Ref. 5.62).

5.6.5 Removal of Severe Dents

When access permits, a small contoured anvil can be pushed into position inside a dented or mashed convolution to force the damaged surface to return essentially to its original shape. External cosmetic work such as blending is usually required while the anvil is in place.

5.6.6 Blending the Surface

When bellows are found damaged with dents or gouges that are not considered severe, the stress intensifying characteristics of the abrupt change in contour can be lessened by surface blending. If some surface metal was removed when the damage occurred, an appraisal of the loss must be made with respect to pressure requirements. Obviously, it is desirable that little or no additional metal be removed at the deepest point during blending.

5.7 Cathodic Protection

Corrosion is an electrochemical process that causes metals to deteriorate due to a reaction with its environment. Electrochemical reactions occur whenever an anode and a cathode are electrically connected while immersed in an electrolyte (Ref. 5.65). Active corrosion cells like this have anodic areas where corrosion occurs and cathodic areas where corrosion does not occur. As long as all four corrosion-cell components are present and the electrical circuit is not interrupted, corrosion will continue. However, if the electrolyte does not contact anodic areas, or if all anodic areas on a piece of metal are converted to cathodic areas, corrosion will be prevented.

Anodes are metallic surfaces where electrical current leaves the metal and enters the electrolyte. Locations where this occurs exhibit corrosion as metal ions form and electrons are released. Cathodes are metallic surfaces where electrical current enters the metal from the electrolyte. Anodes and cathodes can be two separate pieces of metal, as in lead-acid batteries, or different areas on the same piece of metal. Solutions ranging from fresh to salt water or the strongest alkalis to the strongest acids can serve as electrolytes provided they are capable of conducting electricity. Electrical connection between anodes and cathodes can be any metallic path that allows electrons to flow. Connection between anodic and cathodic areas on the same piece of metal is provided by the metal itself.

Corrosion of carbon steel in water occurs when iron losses electrons creating ferrous ions. These ions combine with water and oxygen to produce various compounds such as ferrous hydroxide and ferric oxide (rust) depending on the temperature and other environmental conditions. Corrosion protection for carbon-steel components exposed to air or water is often accomplished by applying a thin coating such as paint or zinc (galvanizing) to the surface. The coating keeps water from contacting the underlying metal thereby interrupting the electrical circuit between anodic and cathodic areas. An effective but less practical method is to keep the relative humidity of the surrounding air lower than a critical level below which water will not form on exposed surfaces. For iron, the critical relative humidity level is about 60 percent (Ref. 5.66).

An alternative corrosion prevention technique that is quite effective under certain conditions is called cathodic protection. Cathodic protection is defined as the reduction or elimination of corrosion by making the metal a cathode. This condition can be achieved either by means of an impressed direct current or attachment to a sacrificial anode (Ref. 5.65). In applying cathodic protection to a metal structure, the objective is to force the entire surface of the structure exposed to the environment to collect current from the environment making the exposed surface a cathode. When this condition is achieved, corrosion is successfully mitigated (Ref. 5.65). The following examples describe three practical applications of cathodic protection.

1. Corrosion of buried or submerged pipelines and tanks is routinely controlled by application of

either an impressed current cathodic protection system or sacrificial anodes.

2. Galvanized steel water pipes are protected from corrosion by the zinc coating that serves as a sacrificial anode.

3. Glass-lined, carbon-steel tanks of domestic water heaters are protected from corrosion by magnesium rods that are immersed in water inside the tanks to serve as sacrificial anodes.

Cathodic protection can be used to maintain structures in their present service condition without allowing additional corrosion damage to occur (Ref. 5.67). It can also be used to enhance the effectiveness of other corrosion mitigation techniques. Although cathodic protection may not necessarily be the only acceptable method for controlling corrosion at a specific location, it is the only technique capable of totally reversing those chemical and electrical phenomena causing corrosion. To determine whether or not cathodic protection is applicable, the situation should be carefully evaluated to ensure that all four corrosion-cell components identified earlier can be factored into a workable design that will provide the required service life. Long-term effective corrosion control is now possible with minimum routine monitoring and periodic system evaluation using automated data acquisition and control. However, cathodic protection should only be considered when there is an aging-management commitment to monitor and maintain the system. Advantages and disadvantages of cathodic protection systems are summarized in Table 5.9.

Although potentially useful in corrosion mitigation, cathodic protection should not be considered under the following conditions.

1. For atmospherically exposed metallic components that extend from the concrete such as steel anchors and embedments, metal containment shells, and liners of reinforced concrete structures. These conditions are not suitable because an electrolyte such as concrete, soil, or water must exist between the steel and the anode.

2. When a cathodic protection anode cannot be installed in an electrically continuous electrolyte with the steel. If the steel to be protected and the anode are separated by air or completely shielded by dielectric materials such as plastics or epoxy coatings, protection current cannot flow. In addition, if another metal, whether electrically continuous or discontinuous, partially shields the steel being protected, cathodic protection may not be applicable.

3. If there is insufficient or no electrical continuity within the majority of the affected steel. Electrical continuity of reinforcing bars, steel embedments, and other metallic components can be measured and verified. When electrically discontinuous steel components are identified, electrical continuity between these components can be established by means of wire attachments or welding to another electrically continuous component. However, if the majority of reinforcing bars and steel embedments in a structure are not electrically continuous, this technique may not be practical.

4. When the cathodic protection system cannot be designed to avoid hydrogen generation that could result in hydrogen embrittlement of posttensioning steel tendon or high-strength bolting materials.

5.7.1 Sacrificial Anode Cathodic Protection Systems

Sacrificial anode cathodic protection systems rely on a metal that is naturally anodic to the structure being protected in the environment of interest. Three metals — magnesium, zinc, and aluminum — are commonly used as sacrificial anodes (Ref. 5.66). Magnesium is used routinely in buried soil applications, zinc is used in both fresh and marine water environments, and aluminum is used most often in offshore structures where lighter weight is important. These particular metals are well suited for use as sacrificial anodes because they exhibit well defined corrosion processes and are naturally anodic to carbon steels in most environments.

Basic components of a sacrificial anode cathodic protection system are identified in Table 5.10. Because these components generally require no routine maintenance during their useful service life, sacrificial anode cathodic protection systems are considered passive. Fig. 5.10 shows how sacrificial anodes are connected to a buried pipeline to create a cathodic protection system capable of protecting the outside surface of the pipe from corrosion.

The voltage difference between sacrificial anodes and cathodes is limited to about one volt or less depending on the anode material and the specific environment (Ref. 5.66). This limitation reduces the current distribution pattern along the cathode and makes sacrificial anode cathodic protection systems less suited for use in freshwater applications and low-conductivity environments such as concrete.

Initial efforts to stop corrosion of the drywell at the Oyster Creek nuclear power plant included installation of a sacrificial anode cathodic protection system (Ref. 5.68). This system relied on anodes that were inserted into the sandbed through small-diameter existing holes through the concrete biological shield wall. This scheme was only effective for a short period of time because, as the sand around the anodes dried out, the electrical circuit between the cathode (drywell shell) and the anodes was broken thereby rendering the system ineffective. Additional information about the Oyster Creek drywell corrosion problem is provided in Sect. 6.1.

5.7.2 Impressed Current Cathodic Protection Systems

Impressed current cathodic protection systems rely on an external electrical power source to provide the required direct current (DC). Batteries, engine generator sets, thermoelectric generators, fuel cells, and solar cells may be used to power this type of cathodic protection system, but rectifiers attached to alternating current (AC) utility power lines are frequently used. These systems, with their necessary array of electrical components, are more complex than sacrificial anode cathodic protection systems making them potentially less reliable.

Basic components of an impressed current cathodic protection system are identified in Table 5.11. To function properly, the positive terminal of the power source must be connected to the anodes and the negative terminal must be connected to the structure (cathode). Reversal of these connections will cause accelerated corrosion of the structure. Application of an impressed current cathodic protection system for a buried pipeline is shown in Fig. 5.11.

Major differences in the application of impressed current cathodic protection to either atmospherically exposed or buried or submerged structures are related to the type and the position of the anodes. For atmospherically exposed portions of chloride-ion contaminated reinforced concrete intake structures, the anodes must be distributed over the surface of the structure which is relatively close to the metal being protected. Anodes for underground or submerged structures are remotely placed in soil or water away from the structure and electrically connected to the structure being protected. Uniform protection current then flows for some distance through the electrolyte from the anodes to the structure. To ensure a long service life, anodes for impressed current cathodic protection systems are usually made from nonconsumable materials that are naturally cathodic to steel. High-silicon cast iron or graphite anodes are often used to protect buried or submerged structures while conductive polymeric materials and precious metals (platinized titanium or tantalum) are used to mitigate corrosion of steel embedded in concrete (Ref. 5.66).

5.7.3 Stray Electrical Current

Unlike natural corrosion that is influenced by environmental factors such as oxygen concentration or pH, stray-current corrosion is induced by errant electrical currents from an external source. Stray electrical current is defined as current that follows a path other than the intended circuit (Ref. 5.66). For example, current that leaves its intended path because of insufficient electrical connections within the intended circuit or poor insulation around the intended conductive material and finds its way through an electrolyte to an alternate low-resistance metal conductor such as a buried pipeline is considered stray current. Accelerated corrosion occurs at locations along the surface of the alternate conductor where the stray current reenters the electrolyte. Fortunately, most electrical currents flow along an intended circuit and are therefore not classified as stray currents.

Stray electrical currents can originate from both AC and DC sources. Damage caused by stray AC is less common than that caused by DC because periodic reversal of current flow is not as detrimental as flow in only one direction. When stray AC causes corrosion, it usually decreases in severity as the frequency increases (Ref. 5.66). Stray current can be either dynamic or static in nature. Static or steady-state stray currents exhibit little or no time-dependent variation whereas dynamic stray currents that vary in amplitude and may change locations as a function of time as they pass to and from the electrolyte. Potential sources of stray electrical currents at nuclear power plants are identified in Table 5.12 (Ref. 5.67).

It is often difficult to detect static stray current due to its non-changing nature. Time-dependent variations associated with dynamic stray currents are usually much easier to detect because of amplitude or frequency changes. Techniques most commonly used to detect stray electrical currents include half-cell potential measurements and cooperative testing. Reference electrodes such as copper-copper sulfate and silver-silver chloride are routinely used to make half-cell potential measurements. Each half cell consists of a pure metal in contact with a solution of known concentration of its own ions. When two half cells are coupled together to form a reference electrode, they create characteristic and reproducible electrical potentials that can be measured with a volt meter. Cooperative testing requires involvement with another party to determine the source of the stray current. Application of these techniques varies depending on whether the stray current is static or dynamic. In areas where dynamic stray current is suspected, electrical potential measurements acquired at prescribed time intervals can provide indications that the stray current fluctuates with time or is related to a periodic event. These indications can help identify the source(s) of the stray current. Data that exhibit constant response, such as no change in electrical potential with time, can be used to eliminate dynamic stray current from consideration.

When static stray current is suspected, time-dependent electrical potential measurements do not provide sufficient information to identify the source and other techniques must be used. One such technique involves acquiring half-cell potential measurements as a function of distance. High potential values may indicate locations where stray current is being picked up from the electrolyte. Areas where low potential values are measured may indicate locations where the stray current is reentering the electrolyte and accelerated corrosion is occurring. Another means available for determining static stray current is to identify the probable sources of DC and then ask the operators of the other sources to sequentially participate in cooperative testing. During cooperative testing, or interference testing as it is sometimes called, the other operators in turn cycle the current from their source "on" and "off". The owner of the structure experiencing the stray current then records half-cell potential measurements while the current sources are interrupted. After the source of stray current has been confirmed, potential solutions to the problem can be identified. In some applications, it may not be practical or advisable to interrupt the suspected current source. In these instances, it may be possible for the other party to simply vary the current so that intended fluctuations can be detected. If the cause of stray current corrosion cannot be modified or eliminated, it may be possible to use impressed current cathodic protection as a means to mitigate effects of stray currents.

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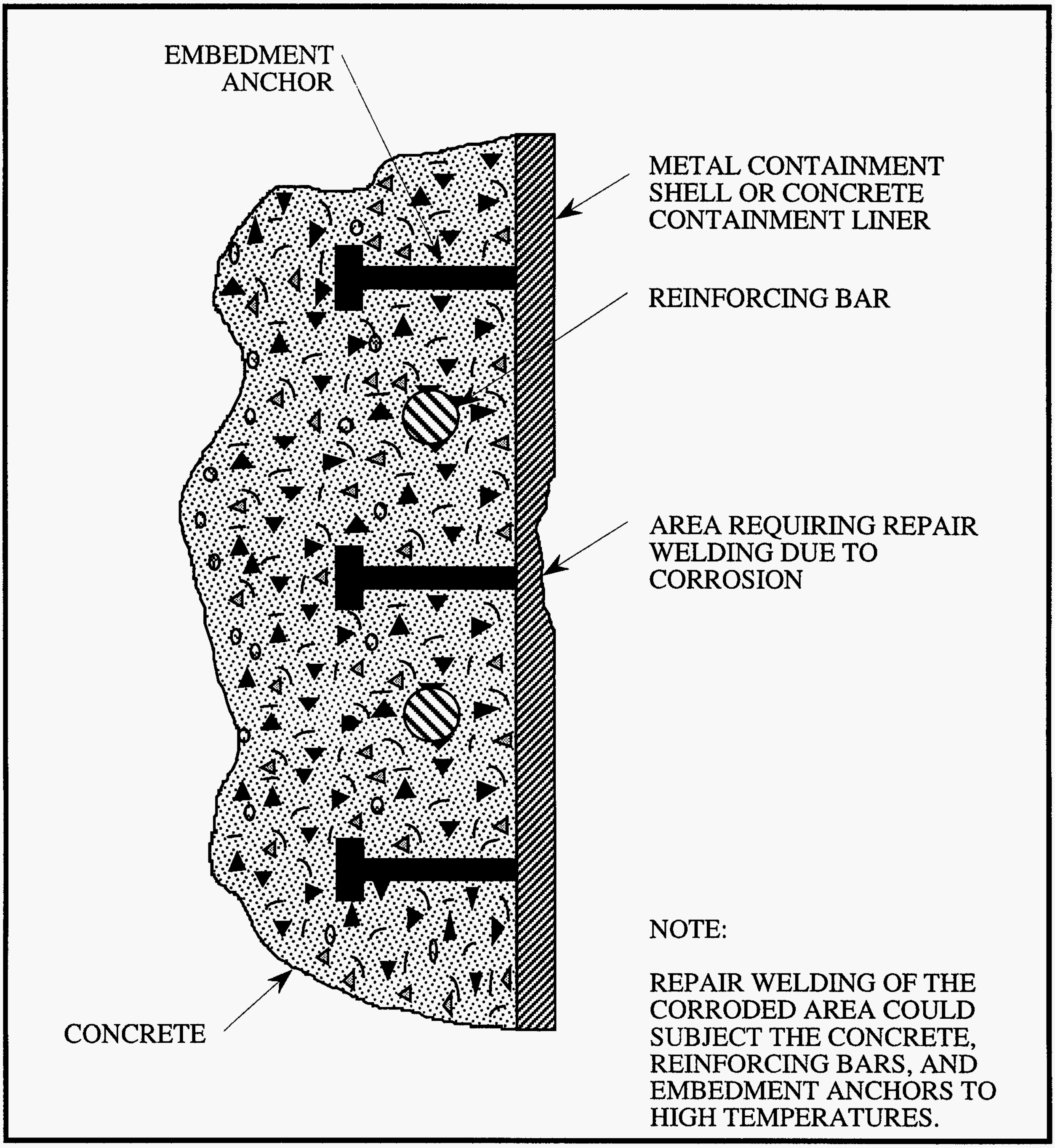

Fig. 5.1. Metal containment shell or concrete containment liner requiring welding repair due to corrosion.

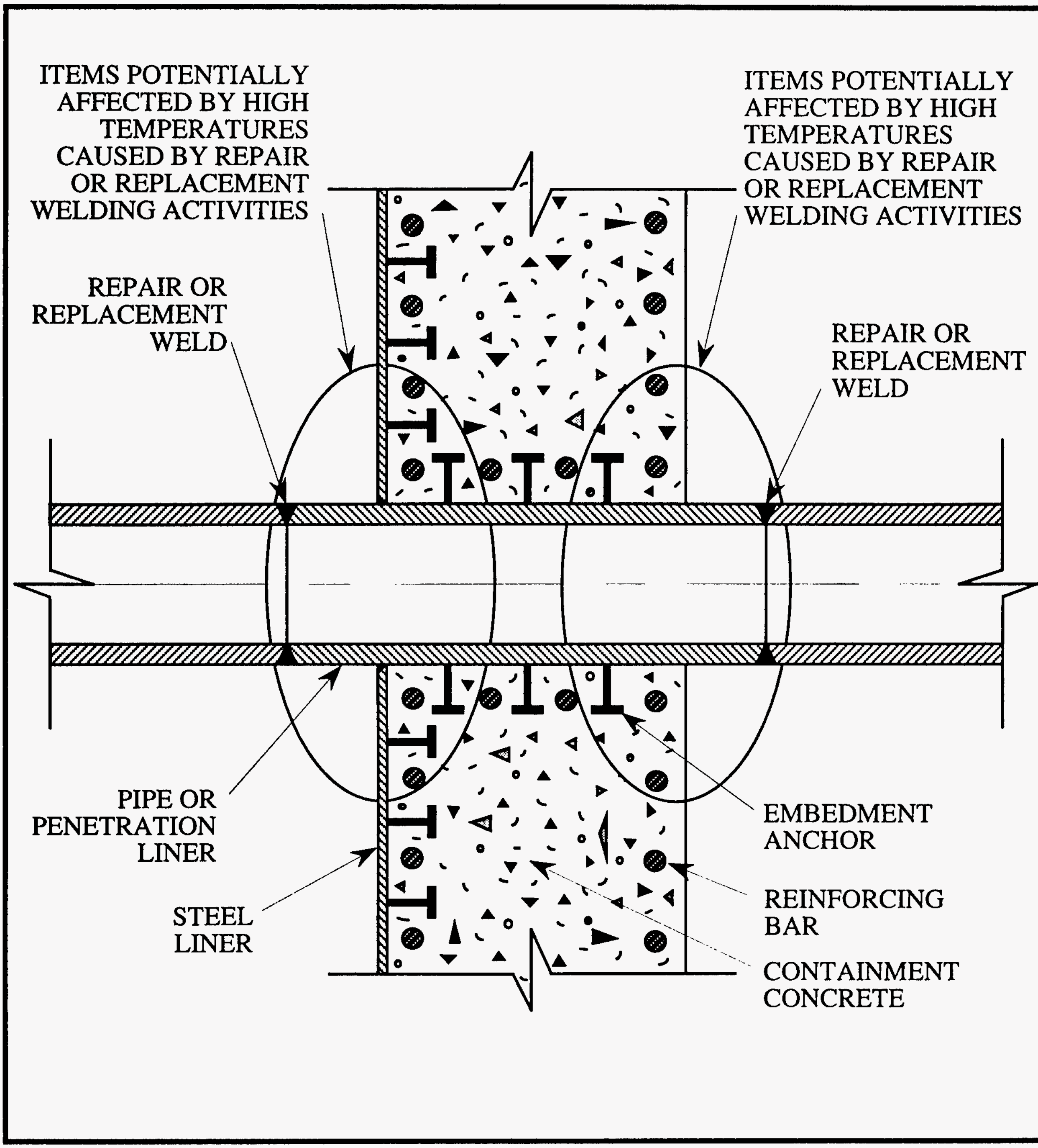

Fig. 5.2. Items potentially affected by high-temperatures produced by repair or replacement welding.

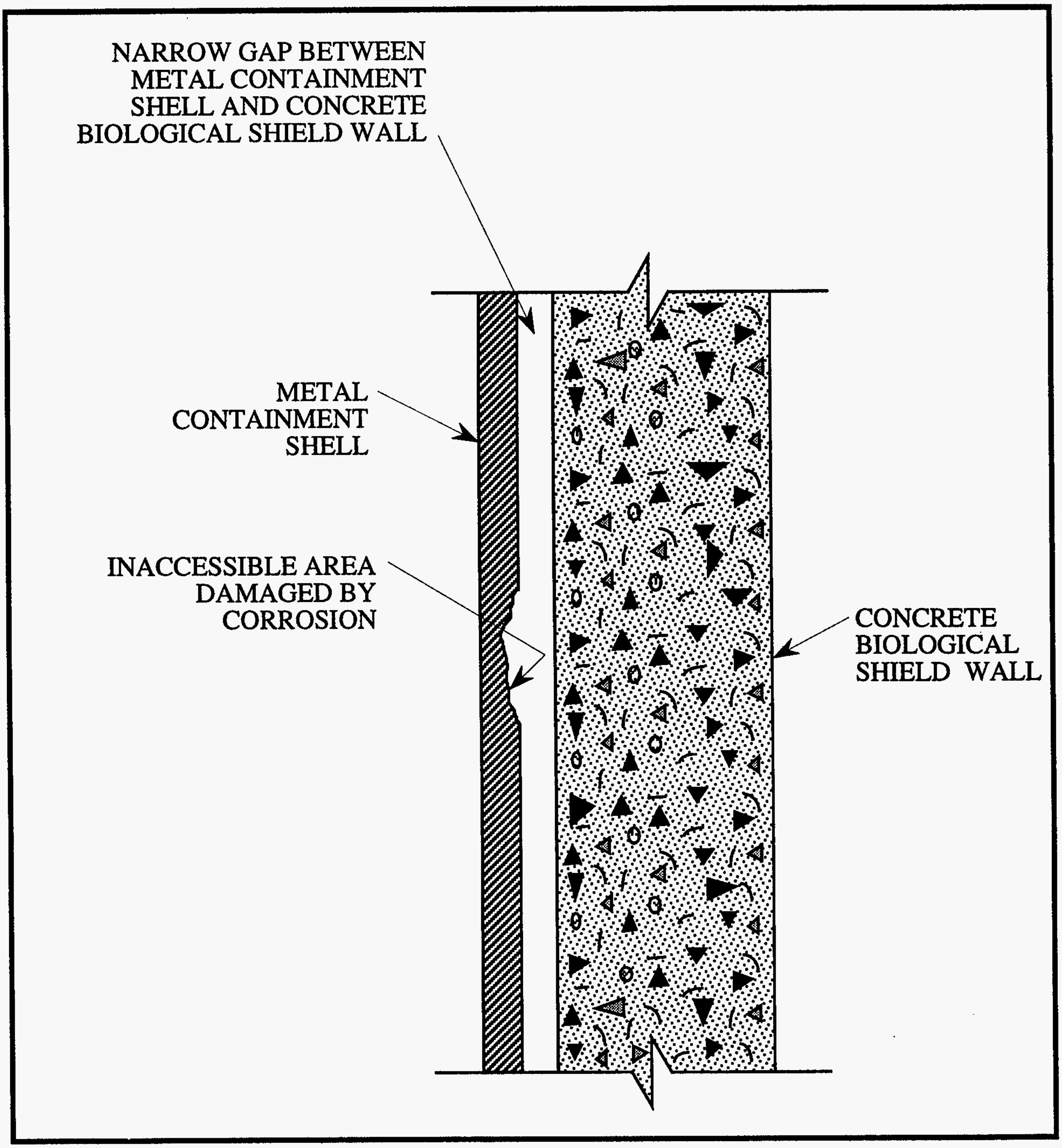

Fig. 5.3. Inaccessible area of a metal containment shell corroded to that point that its structural capacity is no longer considered adequate and a repair is required.

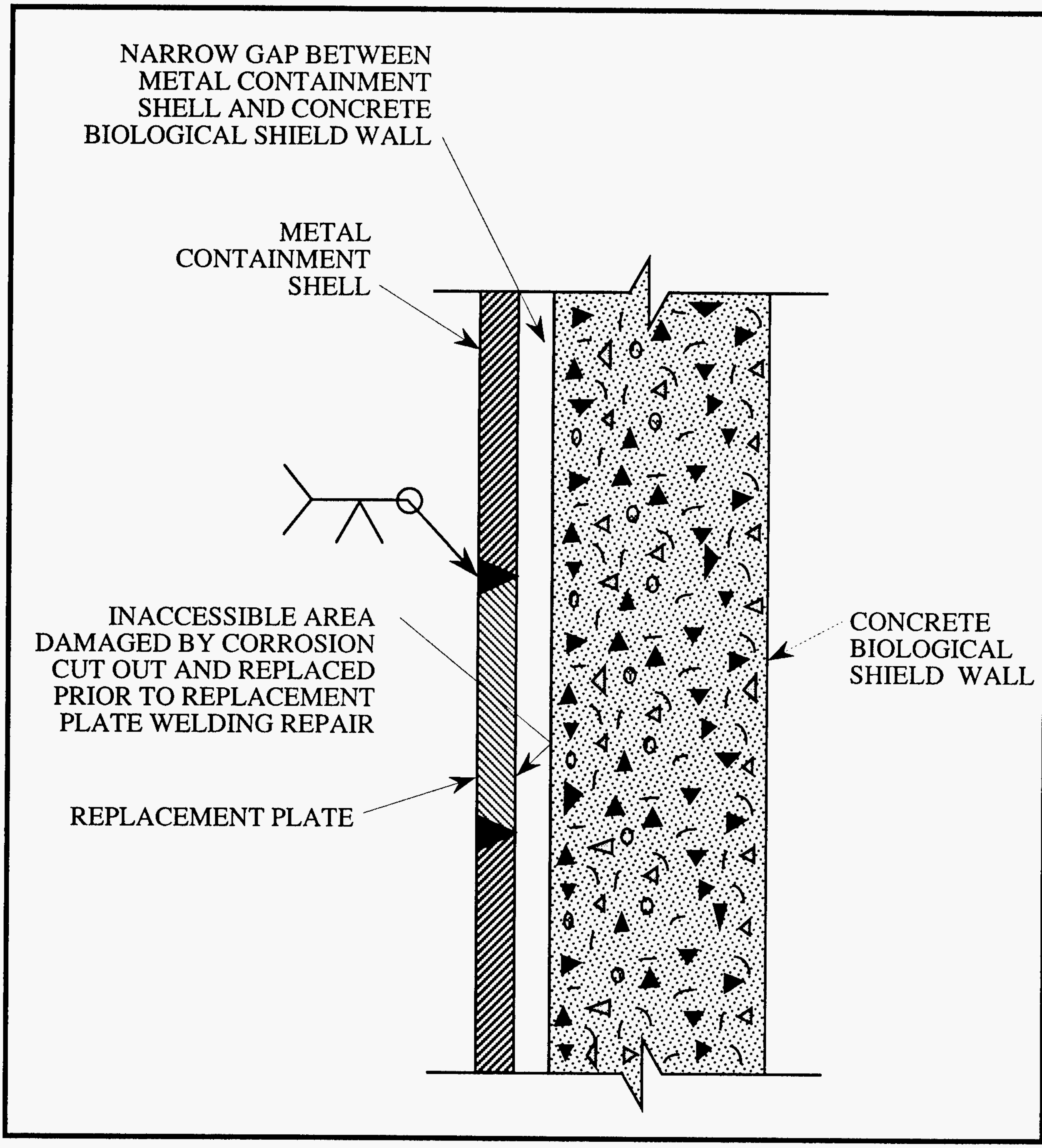

Fig. 5.4. Replacement plate repair welding technique.

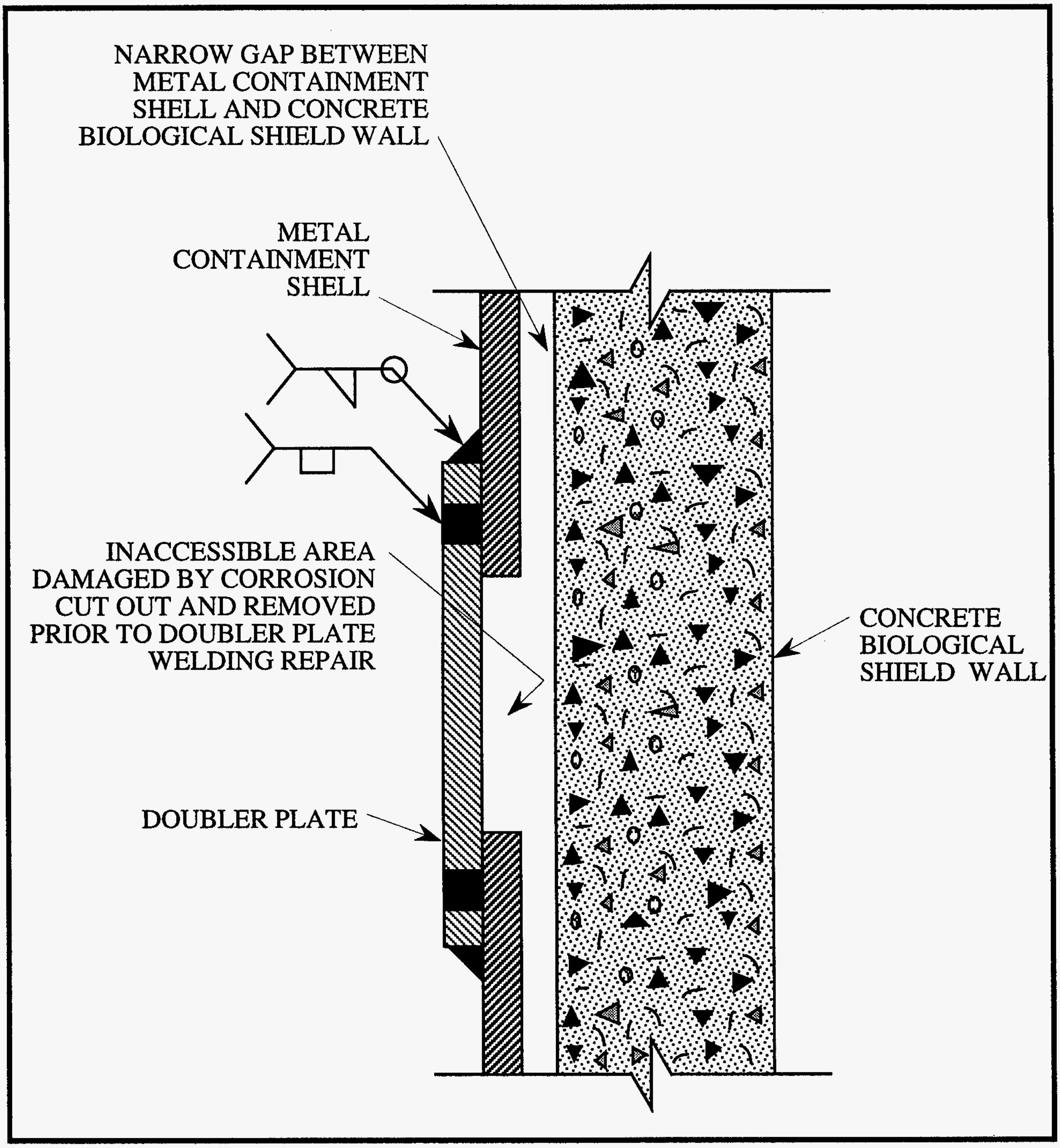

Fig. 5.5. Doubler plate repair welding technique.

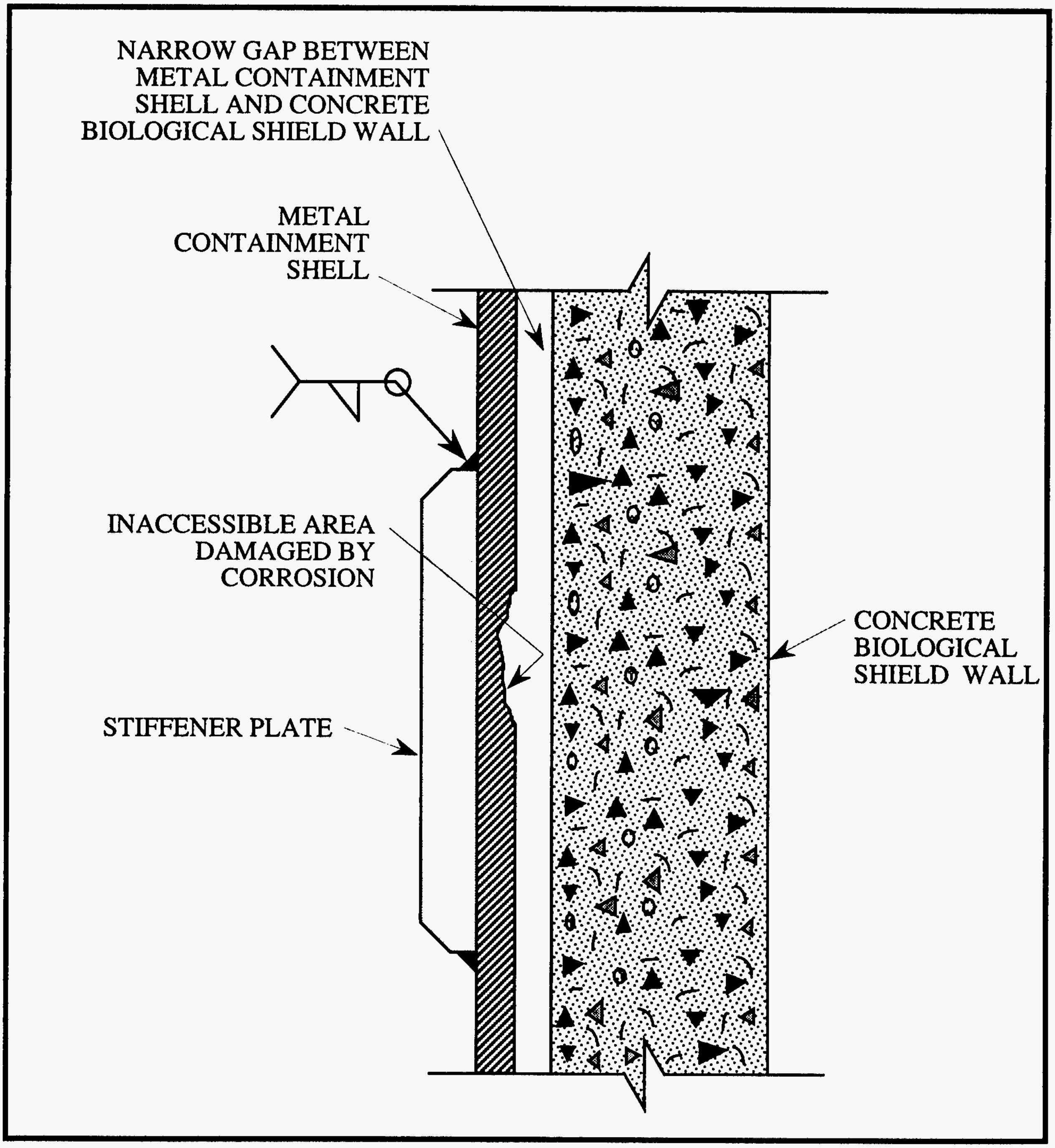

Fig. 5.6. Stiffener plate repair welding technique.

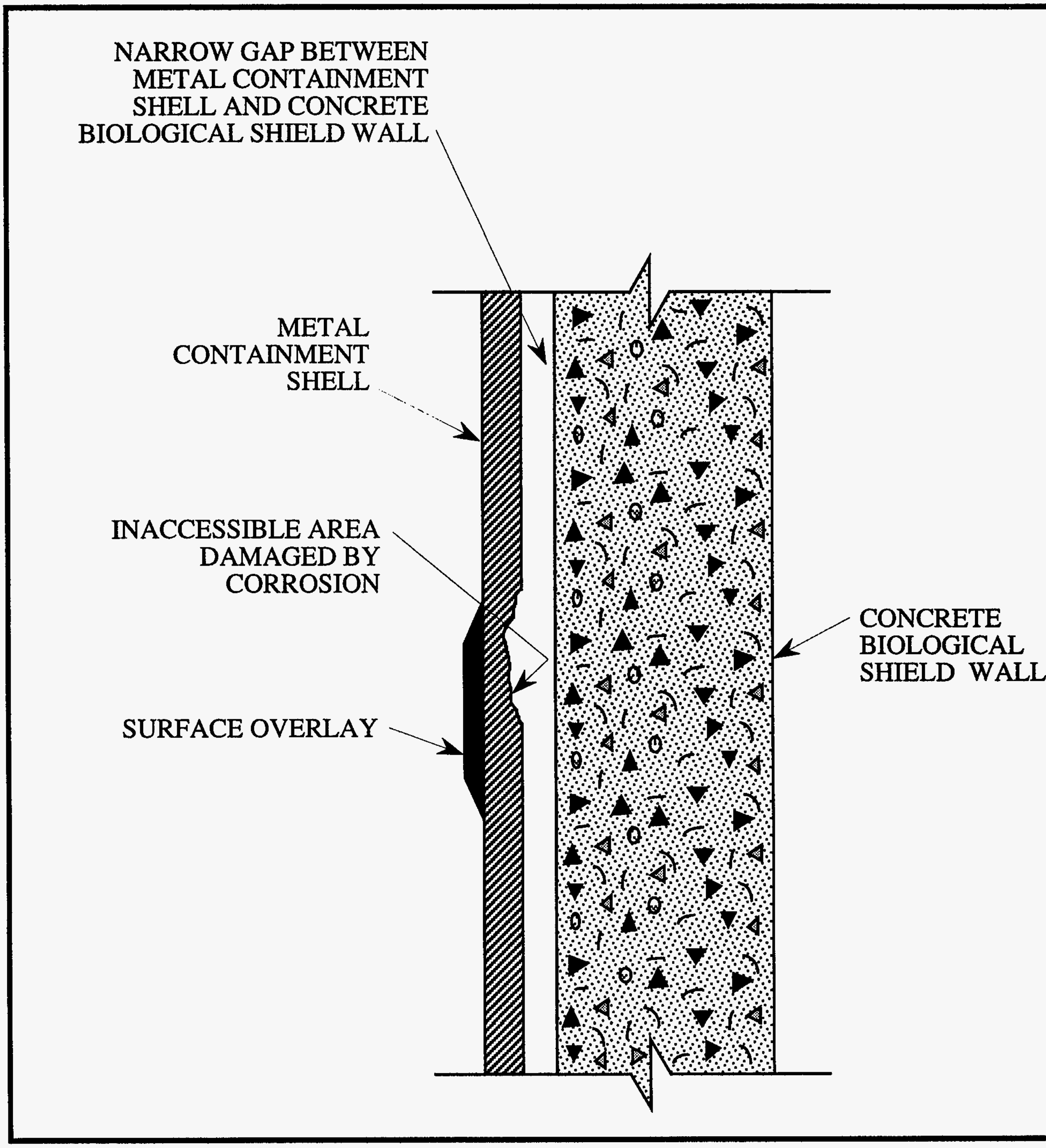

Fig. 5.7. Surface overlay repair welding technique.

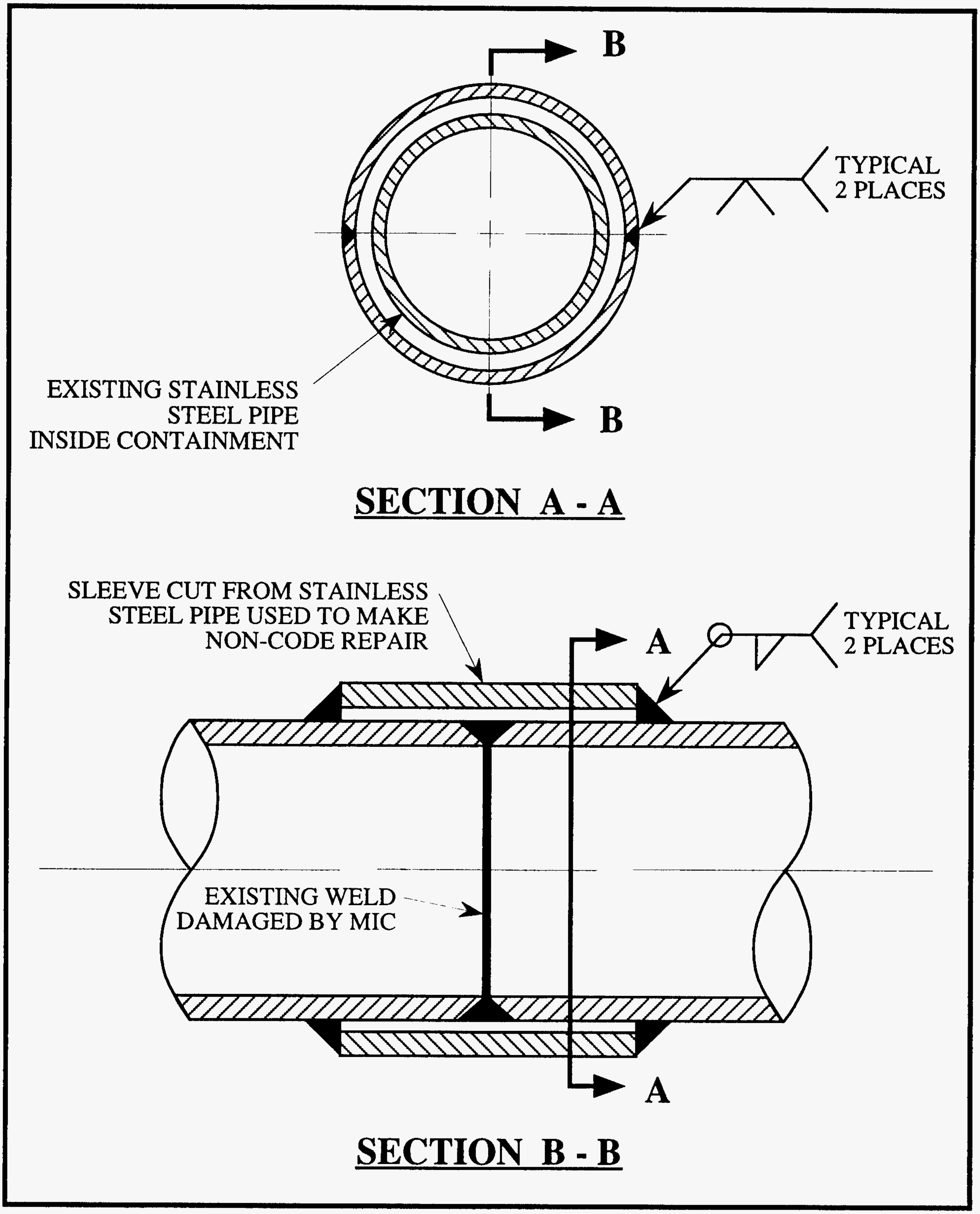

Fig. 5.8. Proposed non-code repair for welds in ASME Class 3 stainless steel piping damaged by microbiologically induced corrosion (MIC).

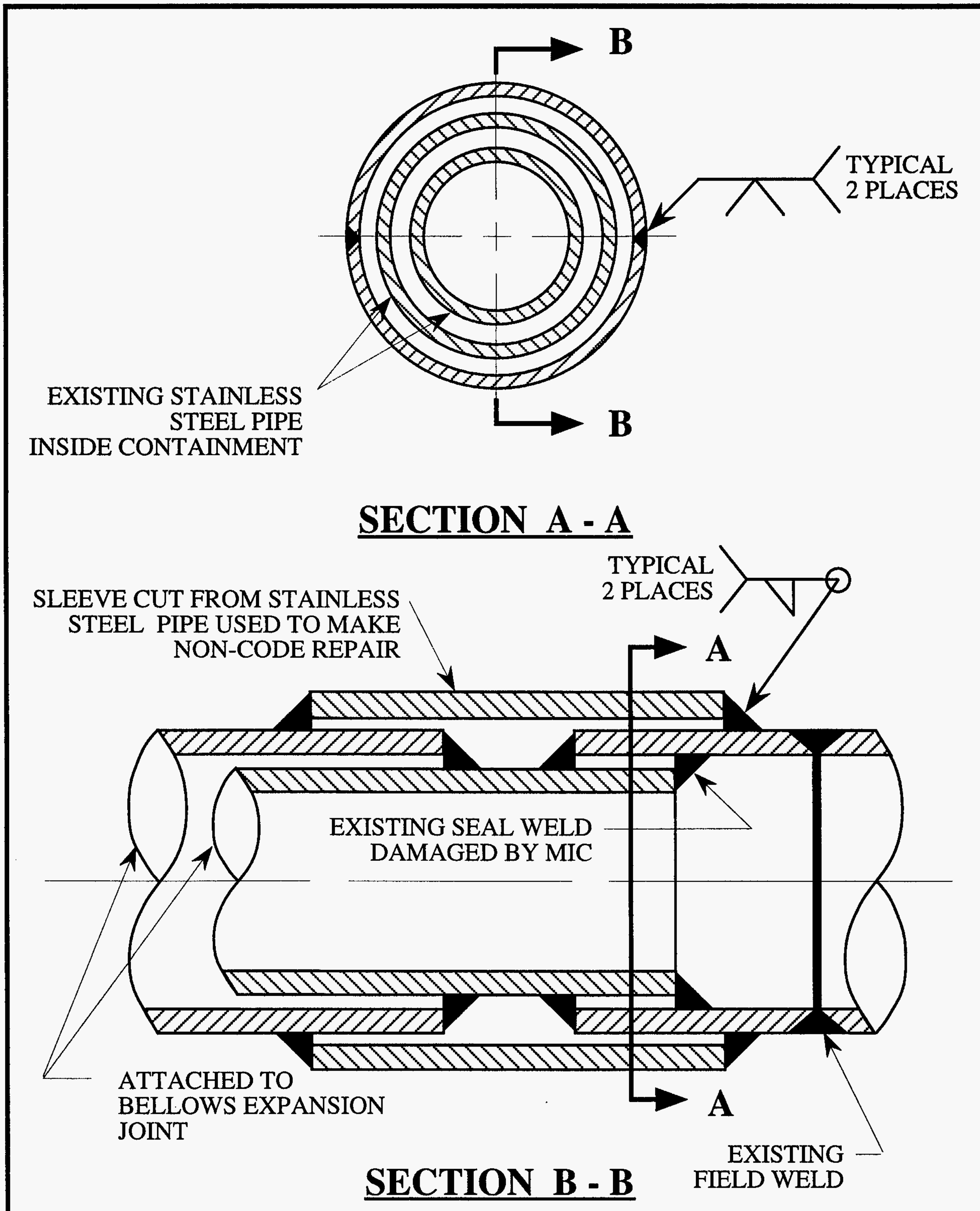

Fig. 5.9. Proposed non-code repair for welds at containment penetrations in ASME Class 3 stainless steel piping damaged by microbiologically induced corrosion (MIC).

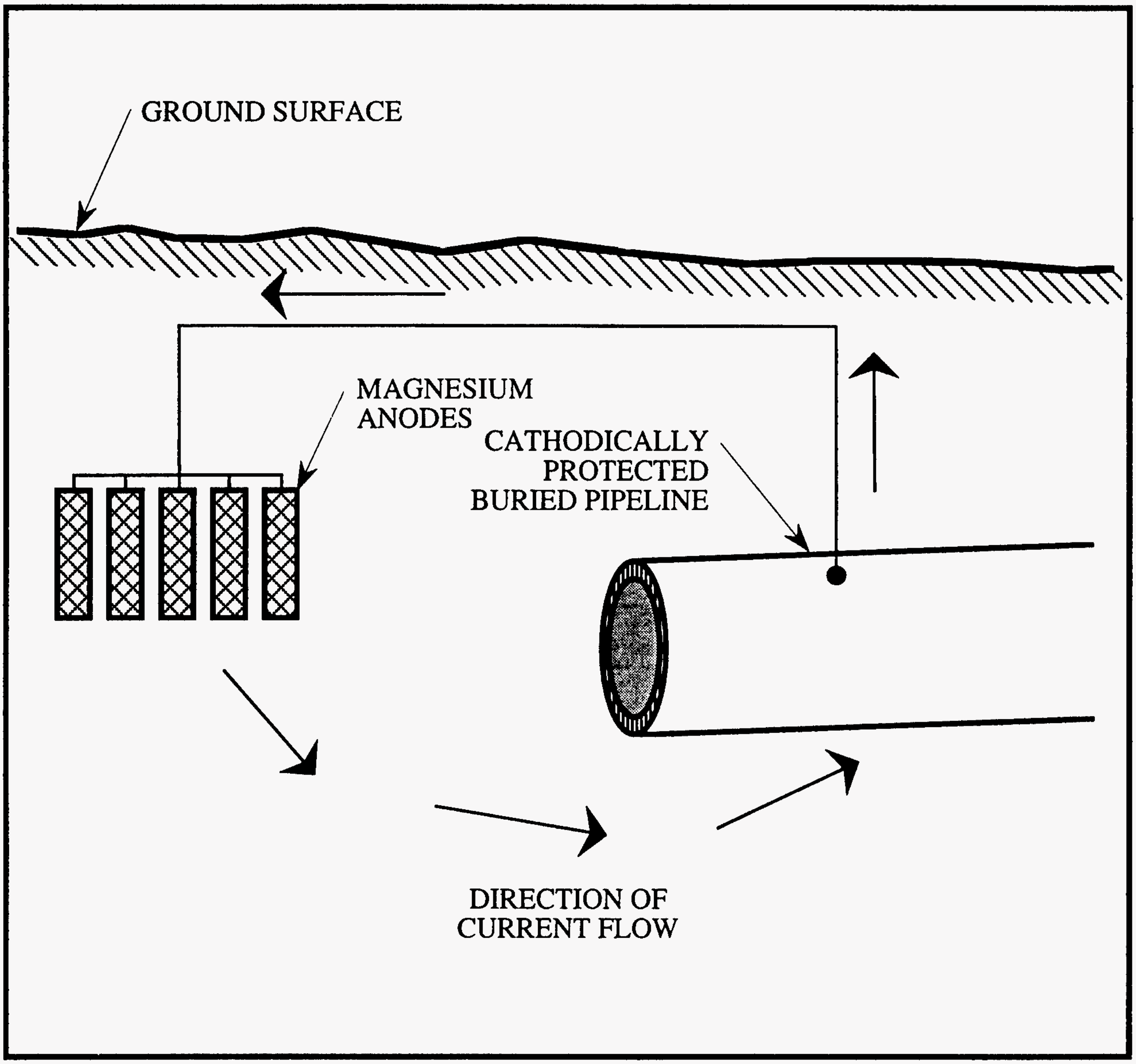

Fig. 5.10. Sacrificial anode cathodic protection system used to protect a buried pipeline.

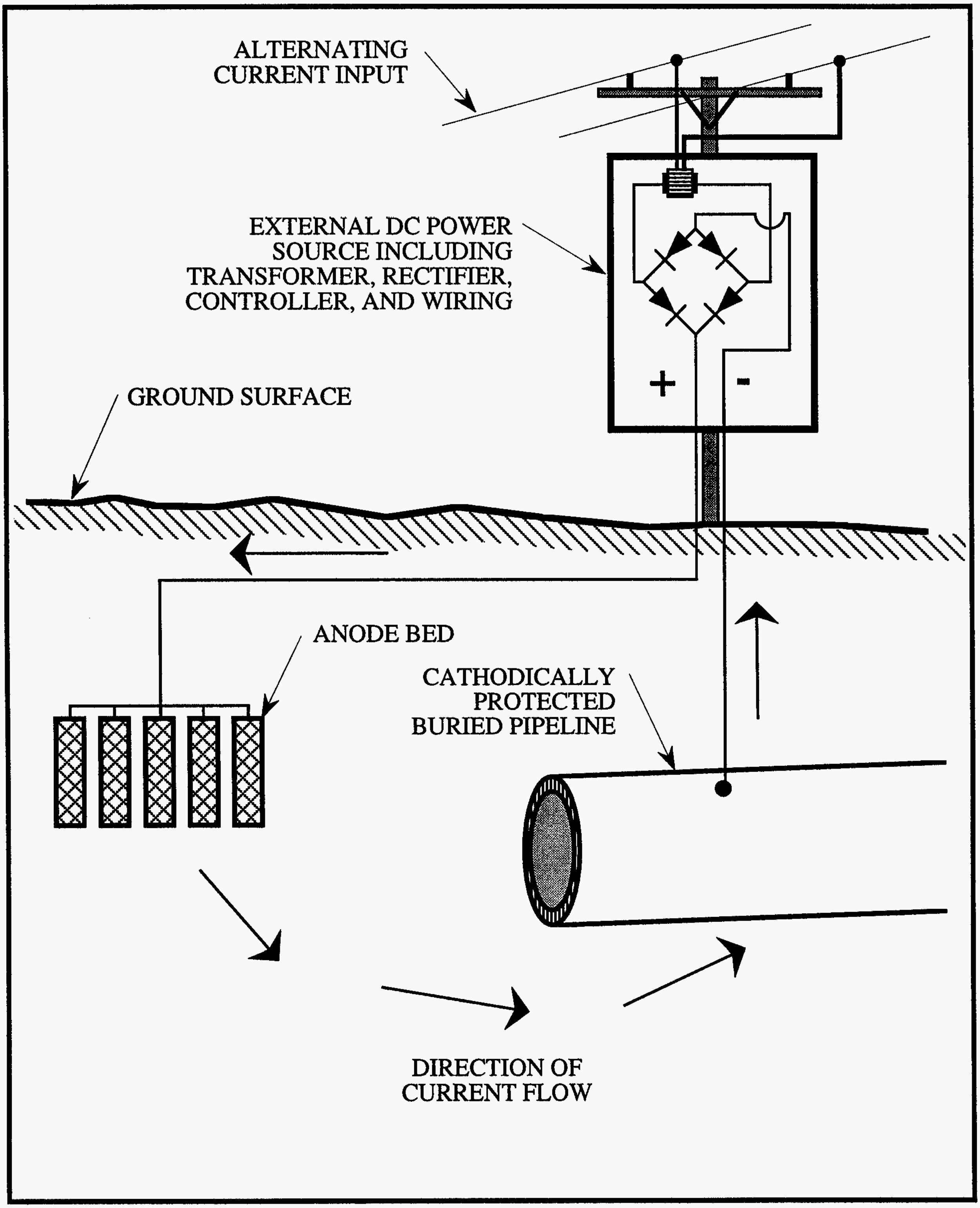

Fig. 5.11. Impressed current cathodic protection system used to protect a buried pipeline.

Table 5.1 Welding processes permitted by Code Case N-516 for underwater repairs and replacements of P-No. 8 and P-No. 4X materials.

Welding process[1]	Dry welding	Wet welding
Shielded Metal-Arc Welding (SMAW)	Yes	Yes
Plasma-Arc Welding (PAW)	Yes	No
Gas Tungsten-Arc Welding (GTAW)	Yes	No
Gas Metal-Arc Welding (GMAW)	Yes	Yes [2]

(1) Combinations of applicable processes are also permitted
(2) Flux Cored Arc Welding (FCAW)-type only

Table 5.2 Additional variables for underwater welding procedure specification qualification.

Variable description	Dry welding	Wet welding
Change in the method for underwater transport and storage of filler material	E	E
Addition or deletion of waterproof or supplementary coatings for the filler metal or a change in the type of any waterproof or supplementary coatings	E	E
Change in depth beyond that qualified	E	E
Change in electrode diameter beyond the range used in qualification	NA	E
Change in the nominal background gas composition (background gas is gas that displaces water and is not necessarily intended to shield the arc)	E	NA
Use of a larger diameter electrode than that used in qualification (SMAW and FCAW)	E	NA
Change in the ASME weld metal specification AWS filler metal classification, or, if not conforming to an AWS filler metal classification, a change in the manufacturer's trade name for the electrode filler metal	NA	E
Addition of welding positions other than those qualified	NA	E
Change from upward to downward, or vice versa, in the progression specified for any pass of a vertical weld	NA	E
Change from the stringer bead technique to the weave bead technique, or vice versa, in the vertical position	NA	E
Change from AC to DC, or vice versa, and a change in polarity in DC welding	NA	E
Change from wet backside to dry backside for backing thickness less than 6.35 mm (0.25 in.)	NA	E
Increase in time of electrode exposure to the underwater environment (SMAW and FCAW)	N	NA
Increase in time of electrode exposure to water	NA	N
Change in the method of protecting, removing moisture from, or otherwise conditioning bare filler metal and bare electrodes in the underwater environment	N	NA
Decrease in included angle, a decrease in root opening, or an increase in root face	NA	N

E – Essential variable in which a change will affect the mechanical properties of a weldment.
N – Nonessential variable in which a change will not affect the mechanical properties of a weldment.
NA – Not applicable to the process.

Table 5.3 Additional variables for underwater welder and welding operator performance qualification.

Variable description	Dry welding	Wet welding
Change in welding mode	E	NA
Change in the SFA specification AWS filler metal classification	E	E
Addition or deletion of supplementary coatings for the filler metal or a change in the type of any supplementary coatings	E	E
Change in depth beyond that qualified	E	E
Use of a larger diameter electrode than that used during performance qualification (SMAW and FCAW)	E	E
Change in salt or borated water to fresh water	NA	E
Addition of welding positions other than those qualified	NA	E
Change in polarity or type of power source	NA	E
Change from the stringer bead technique to the weave bead technique	NA	E
Change in welder's view from beneath to above the water surface	NA	E
Decrease in included angle, a decrease in root opening, or an increase in root face	NA	E

E – Essential variable for welder or welding operator performance qualification.
NA – Not applicable to the process.

Table 5.4 Additional conditions applicable to an underwater confirmation weld.

- The confirmation weld for material less than 6.35-mm (0.25-in.) thick must simulate the production weld joint pressure differential and wet or dry backside conditions
- The confirmation weld must be made in one of the positions to be used in production.
- The confirmation weld must be at least 152-mm (6-in.) long and simulate the production weld length.

Table 5.5 Instantaneous cooling rates for bead-on-plate surface welds at a nominal base material temperature of 760°C (1,400°F).

Base material thickness, mm (in.)	Instantaneous cooling rate, °C/sec. (°F/sec.)
6.44 (0.25)	23 (41)
12.7 (0.50)	60 (108)
25.4 (1.00)	100 (180)

Table 5.6 Ways in which welding induced high-temperature exposure can adversely affect concrete and concrete embedments.

Material or component	Adverse affect	Potential significance
Portland Cement Concrete (Ref. 5.9)	Explosive spalling	Rapid and localized heating of concrete can produce explosive spalling due to forces resulting from thermal expansion of the heated materials or very high steam pressures in the concrete pores that cause tensile stresses that are larger than the tensile strength of the concrete. Explosive spalling can occur when the temperature of the concrete reaches about 315°C (600°F).
	Volume change leading to shrinkage, expansion, or cracking	Absorbed water and chemically combined water are gradually lost from the hydrates in portland cement paste up to about 850°C (1,560°F). Dehydration of the calcium hydroxide in the cement paste begins about 400°C (750°F) and is essentially complete at 600°C (1,100°F). Some conventional aggregates undergo crystal transformation when exposed to high temperatures over about 370°C (700°F).
	Strength and stiffness reduction	On heating, strength and stiffness of concrete decrease due to loss of bonds (dehydration effects) and microcracking resulting from differences in thermal expansion between the aggregates and the cement paste matrix. The decrease in compressive strength becomes very significant at temperatures above 450°C (840°F).
Metallic Items Embedded in Concrete	Concrete cracking or spalling	Heating of metallic embedments such as anchor studs attached to concrete containment liners can produce concrete cracking or spalling as the embedments expand and lengthen relative to the surrounding concrete.
	Loss of bond with concrete	Cracking and spalling of concrete caused by high-temperature exposure can significantly degrade the bond between embedments and the surrounding concrete.

Table 5.7 Rules and requirements pertaining to high-temperature exposure of concrete and metallic embedments.

Source	Issue	Rule or requirement
ASME Code Section III, Division 2, Subsection CB-3430, 1995 Edition (Ref. 5.11)	Temperature limits for concrete reactor vessels	Temperature limits are provided for construction, normal, abnormal and severe environmental, extreme environmental, and failure loading conditions. The maximum allowable effective liner temperature is limited to 149°C (300°F) at the liner-concrete interface and 204°C (400°F) between cooling tubes.
ASME Code Section III, Division 2, Subsection CC-3440, 1995 Edition (Ref. 5.11)	Temperature limits for concrete containments	The temperature of concrete is limited under normal conditions to 66°C (150°F) except for local areas, such as around penetrations, where the maximum temperature is limited to 93°C (200°F). During an accident or any other short-term period, the maximum concrete temperature is limited to 177°C (350°F). Higher temperatures are permitted provided strength tests are performed and there is evidence that the increased temperatures do not cause deterioration of the concrete with or without load.
ASME Code Section III, Division 1, Subsection CB-4300 and Division 2, Subsection CC-4300, 1995 Edition (Ref. 5.11)	Preheating prior to bending or straightening of reinforcing bars	The temperature of the bar at the concrete surface is limited to 260°C (500°F). Any method of applying preheat that does not harm the bar material or the concrete may be used.
ASME Code Section XI, Division 1, Subsection IWA-4540, 1995 Edition (Ref. 5.6)	Alternative repair welding method involving butter bead—temper bead repairs of metal containments and liners of concrete containments (See Sect. 3.5.4)	Requirements are provided for repair welding when factors such as water backing make preheat and PWHT impractical. A production test is required as part of the qualification process prior to any repair welding. No temperature limits are provided.
AWS Structural Welding Code—Reinforcing Steel ANSI/AWS D1.4-92 Subsection 4.3 (Ref. 5.10)	Control of distortion, shrinkage, and heat	When welding is performed on bars or other structural components embedded in concrete, allowance shall be made for thermal expansion of the steel to prevent spalling or cracking of the concrete or significant destruction of the bond between concrete and the steel reinforcing bar. No temperature limits for concrete or steel are provided.
Code Requirements for Nuclear Safety Related Concrete Structures ACI 349-90 (Ref. 5.12)	Welding of attachments to large concrete embedments	Welding of attachments to large concrete embedments is permitted provided the welding is performed in accordance with good practice to avoid excessive expansion of the embedment which could result in spalling or cracking of the concrete or excessive stress in the embedment.

Table 5.8 Issues that need to be considered in a Repair/Replacement Plan for welding repairs of containment pressure boundary components backed by concrete.

Issue	Consideration
Concrete removal prior to repair welding	Whenever repair welding of a containment pressure boundary component backed by concrete is being planned, consideration should be given to removing the concrete prior to repair welding. This approach will ensure that a high-quality weld is produced and that the concrete is not exposed to high temperatures.
Maximum allowable concrete temperature	If removal of concrete prior to repair welding is not feasible, a maximum allowable temperature limit for the affected concrete should be specified. Based on limited quantifiable test data about the effects of rapid, localized heating on concrete and no established guidance from applicable codes and standards, a maximum allowable concrete temperature of 260°C (500°F) is suggested. Short-term exposure of concrete to this temperature is not expected to cause significant concrete strength reduction, and explosive spalling of the concrete should not be a serious concern. However, ensuring that the specified temperature limit is not exceeded during the welding repair may be difficult or impossible due to the inaccessibility of the exposed concrete surface and problems associated with making precise concrete surface temperature measurements.
Embedment temperature limits	When heat generated by repair welding will affect items such as steel anchor studs and structural or nonstructural attachments that are embedded in the concrete, a maximum allowable temperature limit for the embedment at the embedment-concrete interface should be specified. Using requirements presented in the AWS Structural Welding Code for Reinforcing Steel (Ref. 5.10), a maximum allowable embedment temperature of 260°C (500°F) at the embedment-concrete interface is suggested. Short-term exposure of metallic embedments to this temperature is not expected to produce thermal expansion that would cause significant spalling or cracking of the concrete or significant destruction of the bond between concrete and the embedment.

Table 5.9 Advantages and disadvantages of cathodic protection systems.

Advantages
• Cathodic protection can be nondestructively evaluated using sensors or monitors placed on or near the affected structure. These devices can be used to assess the extent of corrosion and to collect data for evaluating the time-dependent degradation of the structure. • Sacrificial anode cathodic protection systems are relatively simple passive systems that function as long as an anode and a cathode are electrically connected while immersed in an electrolyte. • Cathodic protection systems for nuclear power plant containment pressure boundary components can usually be installed for less than the cost of replacement. However, cathodic protection may not be suitable for all situations. • Cathodic protection can be used to mitigate effects of stray currents. • Properly installed and activated cathodic protection systems can halt corrosion of steel embedded in chloride-ion contaminated reinforced concrete structures. Even underpowered impressed current cathodic protection systems can extend the remaining useful life of these structures.
Disadvantages
• For cathodic protection to be effective, electrical continuity between all metallic components to be protected must be provided. Reinforcing bars in concrete structures are typically interconnected by wire ties, steel supports, and other metallic connections. When suitable electrical connections between reinforcing bars and other major steel components do not exist, wiring can be installed and welding can be performed to ensure continuity. • Undesirable hydrogen can be generated at the cathode of an electrochemical cell when the potential of the cathode reaches the hydrogen evolution potential. The value of this potential depends on the chemical reactions associated with the cell. • Due to potential hydrogen generation, application of impressed current cathodic protection to high-strength and highly stressed steel used in certain bolting applications and in posttensioned concrete containment construction may result in hydrogen embrittlement of the affected metals. • All impressed current cathodic protection systems have the potential to cause stray current corrosion of other metals. Stray current leakage from impressed current cathodic protection systems is generally associated with underground and submerged environments where the distance between the anodes and the protected structure is relatively long. On the other hand, stray current leakage to other structures caused by impressed current cathodic protection of atmospherically exposed structures is less likely because the anodes are very close to the structure being protected. • Impressed current cathodic protection systems are considered active systems because they require an external source of DC power. These power sources often require periodic maintenance and therefore may not always be reliable.

Table 5.10 Basic components of a sacrificial anode cathodic protection system.

- Current distribution hardware and related wiring (anode)
- Protected metal structure such as a metal containment shell, liner of reinforced concrete structure, concrete reinforcing bars, metallic components immersed in water, etc. (cathode)
- Concrete, soil, or water capable of conducting electricity (electrolyte)
- Evaluation devices, reference electrodes, wiring, etc. (electrical connection)

Table 5.11 Basic components of an impressed current cathodic protection system.

- Current distribution hardware and related wiring (anode)
- Protected metal structure such as a metal containment shell, liner of reinforced concrete structure, concrete reinforcing bars, metallic components immersed in water, etc. (cathode)
- Concrete, soil, or water capable of conducting electricity (electrolyte)
- Evaluation and control devices, reference electrodes, controller, rectifier, wiring, etc. (external DC power source and electrical connection)

Table 5.12 Potential sources of stray electrical current at nuclear power plants.

Potential Source	Type of Stray Current
Electrical railway and mass transit systems	Dynamic
High voltage direct current (HVDC) systems	Dynamic/Static
Impressed current cathodic protection systems	Static
DC welding operations	Dynamic
Electrical grounding systems	Dynamic/Static
Battery power supplies and battery recharging stations	Dynamic
DC motors such as elevators, cranes, remote controlled valves, etc.	Dynamic
Industrial machinery	Dynamic
Electroplating operations	Dynamic
Telephone systems with very old technology	Dynamic
Electronic and instrumentation and control equipment	Dynamic
Railroad train switch signals	Dynamic
Geophysical effects such as lightning strikes, sun spots, related electromagnetic interferences, and telluric currents	Dynamic

6. CASE HISTORIES OF CONTAINMENT RESTORATION

6.1 Drywell Corrosion at Oyster Creek

GPU Nuclear Corporation's Oyster Creek nuclear power plant is located near Forked River, New Jersey. This plant includes a BWR nuclear steam supply system with a Mark I pressure suppression containment. The containment pressure boundary consists of a steel drywell that surrounds the reactor pressure vessel and much of the primary coolant piping and a torus that is connected to the bottom of the drywell by ten vent pipes. In the unlikely event of an accident, the drywell and torus are designed to safely contain the heat, steam, and radioactive materials preventing their release into the surrounding environment. The containment is a code stamped pressure vessel that was constructed in the 1960s in accordance with requirements provided in Section VIII (Ref. 6.1) of the Code.

The drywell is essentially a free-standing pressure vessel that is surrounded by a concrete biological shield wall. Support for the drywell, reactor pressure vessel, and other steam supply system components is provided by a concrete pedestal that extends upward from the bottom of the drywell shell. The bottom of the drywell shell rests on concrete that is part of the basemat foundation for the plant. There is a nominal 2.54 to 7.62 mm (1 to 3 in.) air gap between the drywell shell and the concrete biological shield wall. This gap, which is filled with compressible insulation, allows the drywell to expand and contract in response to thermal and pressure loads during normal plant operations. A sandbed approximately 1.52 m (60 in.) tall by 0.38 m (15 in.) deep is provided at the base of the air gap where the outside of the drywell shell intersects with the concrete biological shield wall. This feature was required in the original design to provide transitional radial support for the drywell thereby reducing local stresses in the drywell shell.

In the early 1980s, water was discovered leaking out the top of the sandbed through an annulus around the torus vent line. Inspection of this area during a refueling outage revealed that water from the reactor cavity was leaking down and around the outside of the drywell, through the insulation in the air gap, and into the sandbed (Ref. 6.2). During subsequent investigations, it was discovered that the five 102-mm (4-in.) diameter drains that had been installed in the sandbed during the original construction of the plant to remove water from the sandbed were clogged allowing water to saturate the sand and corrode the outside surface of the exposed carbon steel drywell shell. After compacted sand was removed from the drain lines during the twelfth refueling outage in 1988, hundreds of liters (several hundred gallons) of water drained from the sandbed.

Because corrosion of the outside surface of the drywell shell was suspected, extensive ultrasonic testing (UT) was performed from inside the containment to determine the extend and severity of the degradation. These measurements revealed that thinning was most severe in the sandbed region where the original plate thickness was 29.3 mm (1.154 in.) and that shell thickness in some local areas were as low as 20.3 mm (0.80 in.). These findings were particularly alarming because the minimum acceptable drywell shell thickness in the sandbed region was 18.8 mm (0.74 in.). Verification of the UT measurements was achieved by removing 51-mm (2-in.) diameter cores from the drywell shell and physically measuring their thickness. Holes produced by the core drilling operation were replaced with machined plugs that were seal welded to the drywell shell from inside the containment. Figure 6.1 shows the repair technique used to replace the drywell shell material removed during the coring operation. Welding was performed in accordance with the rules and requirements of the original construction code and approved by an Authorized Nuclear Inspector. Once completed, inspected, tested, and accepted, the leaktight integrity of the Oyster Creek containment was restored to its original condition.

Initial efforts to stop the corrosion process involved fixing leaks in the drywell-to-refueling-cavity seal and installing a cathodic protection system. Table 6.1 identifies potential water sources that were investigated at Oyster Creek and describes remedial actions that were taken to eliminate water from the sandbed. In 1988, anodes were inserted into the sandbed through small-diameter holes through the concrete biological shield wall. This scheme for arresting the corrosion process by controlling the flow of current between anodic and cathodic surfaces was only effective for a short period of time. As the sand around the anodes dried out, the electrical circuit between the cathode (drywell shell) and the anodes was broken thereby rendering the system ineffective. The ineffectiveness of the cathodic protection system was verified by UT measurements. Analysis of time-dependent UT data revealed that the rate of corrosion before and after installation of the cathodic protection system was the same.

After attempts to stop the corrosion process by application of cathodic protection failed, aggressive efforts were undertaken to remove the sand and apply a protective coating of epoxy paint to accessible areas of the drywell shell in the sandbed region. Access to the sandbed was provided by drilling 508-mm (20-in.) diameter holes through the concrete biological shield wall about 305 mm (12 in.) away from the ten vent lines. These holes, which were completed in November 1992, were large enough to allow workers to crawl from the torus region into the sandbed. About one week into the fourteenth refueling outage that started on November 28, 1992, workers entered the sandbed and began vacuuming out the sand and cleaning the drywell shell surface in preparation for painting. The workers discovered that the corrosion was relatively uniform and that it could be easily removed with scrapers and hand-held equipment. By the end of January 1993, the drywell shell was cleaned and painted with a two-part, self-curing epoxy coating allowing the plant to return to service at the end of the refueling outage in early February. Application of the protective coating on the outside of the drywell shell was not required by the NRC because coatings provide no specific safety-related function to mitigate the consequences of postulated accidents. Quality assurance requirements provided in 10 CFR 50, Appendix B (Ref. 6.3) were also not applicable in this situation because failure and disbonding during operating and emergency conditions would not interfere with engineered safety system required for safe shutdown and cooling of the reactor vessel.

As the sand was being removed, workers discovered other problems.

- The floor of the sandbed was rough and irregular (large voids were found in some parts of the sandbed floor).
- Segments of reinforcing bars were not embedded in concrete.
- The drain pipes were protruding about 76 to 102 mm (3 to 4 in.) above the rough concrete floor surface.

According to the original design documents, a smooth concrete floor with troughs leading to the five drains was to be constructed to serve as the floor for the sandbed. Because this work was never performed, some standing water always remained at the bottom of the sandbed to sustain the corrosion process even when the drains were functioning properly. In order to solve this problem, a new sandbed floor was installed using an epoxy-based system to fill in the voids, cover the exposed reinforcing bars, and pour a new floor up to the level of the top of the five drain pipes.

Even though the original design called for sand to be installed in the sandbed to provide transitional radial support for the drywell shell, sand was not reinstalled after the floor was repaired and the walls were painted. This consensus decision between GPU Nuclear, General Electric, and NRC personnel was based on results of detailed analytical studies performed to resolve this issue. Results of the entire Oyster Creek investigation also provided the basis for reducing the containment peak pressure from 427 kPa (62 psi) to 303 kPa (44 psi) and for establishing a new minimum drywell shell thickness in the sandbed region of 13.7 mm (0.541 in.).

GPU Nuclear continues to monitor the long-term performance of the drywell shell as part of its overall aging management strategy. Monitoring activities include:

- periodic visual examinations of the epoxy paint,
- UT measurements of the drywell shell above the sandbed, and
- inspections for leakage from the reactor cavity.

So far, no additional thinning of the drywell shell has been detected, the epoxy paint appears to be in excellent condition, and efforts to eliminate water from the sandbed region have been effective.

In the event that remedial actions are required in the future, GPU Nuclear has prepared contingency plans for repairing the drywell shell to restore its structural integrity. The four repair welding techniques that are addressed in the plan include:

1. replacement plate repair welding,
2. doubler plate repair welding,
3. stiffener plate repair welding, and
4. surface overlay repair welding.

Additional information about these techniques is provided in Sect. 5.3 and in Figs. 5.4 to 5.7.

6.2 Torus Corrosion at Nine Mile Point, Unit 1

Niagara Mohawk Power Corporation's Nine Mile Point, Unit 1 nuclear power plant is located near Lycoming, New York, on the southeastern shore of Lake Ontario. This plant includes a BWR nuclear steam supply system that produces 1,850 MWt and a Mark I pressure suppression containment. The containment pressure boundary consists of a steel drywell that surrounds the reactor pressure vessel and much of the primary coolant piping and a torus that is located below the drywell. A series of 10 vent pipes connect the drywell to the torus. In the unlikely event of an accident, the drywell and torus are designed to safely contain the heat, steam, and radioactive materials preventing their release into the surrounding environment. The torus is a carbon steel pressure vessel that was fabricated in 1965 by Chicago Bridge and Iron, Co. (Ref. 6.4).

The torus is a free-standing pressure vessel consisting of 20 pipe-shaped segments or bays that are mitered and welded together. The diameter of the pipe-shaped segments is 8.23 m (27 ft), and the total length of the torus is 112 m (368 ft). Structural support is provided by a series of steel columns that are welded to the torus shell and rest on a concrete floor slab. Four columns are provided in every other bay; two on the outer side and two on the inner side of the torus. The bottom surface of the torus is about 450 mm (18 in.) above the concrete floor. A concrete biological shield wall surrounds the torus creating an enclosure called the torus room. Carbon steel plates that conformed to ASTM A 201*, Grade B requirements were used to fabricate the torus shell (Ref. 6.5). The nominal thickness of these plates was 11.7 mm (0.46 in.) which included a 1.6 mm (1/16 in.) corrosion allowance. Most areas on the outside surface of the torus are accessible for visual inspection, but the surface is coated to prevent corrosion. The inside of the torus is partially filled with water, and all surfaces above and below the water line are not coated. Consequently, thinning of the torus shell due to corrosion has slowly occurred.

Niagara Mohawk has monitored the thickness of the torus shell since 1975 because of its degradation potential and significance to containment integrity. Periodic UT was performed to quantify the amount of wall thinning that had occurred and to estimate the rate of corrosion. Based on visual inspections performed inside the torus, nondestructive examination results, and laboratory analyses of water samples, Niagara Mohawk concluded that the observed wall thinning was being caused by general corrosion and that local attack (pitting, crevice, and biological corrosion) was not occurring. In about 1980, the torus was reanalyzed to address new load combinations and ASME Code allowable stresses. These analyses were based on the minimum nominal wall thickness of 11.7 mm (0.46 in.) and took full credit for the 1.6 mm (1/16 in.) corrosion allowance provided in the original design calculations. After NRC inspections in March 1988 revealing that the torus wall was very near its minimum allowable thickness, additional calculations were performed establishing a worst case minimum wall thickness of 11.4 mm (0.447 in.). These calculations reflected a reduction in condensation oscillation loads and indicated that the most critical location is at the bottom of the torus shell.

Following this engineering evaluation, a new corrosion monitoring program was initiated in August 1989 to measure the thickness of all 40 mid-bay plates on the bottom surface of the torus. Part of the program included suspending metal samples in the torus water so that the thickness of these samples could also be periodically measured. The samples were fabricated from carbon steel that conformed to ASTM A 516, Gr. 70 requirements (Ref. 6.6). Prior to installation, the samples were preconditioned in the same way that laboratory corrosion test specimens are preconditioned prior to exposure testing (Ref. 6.7). This particular steel was used because steel conforming to ASTM A 201, Gr. B requirements is no longer manufactured, and its chemistry was similar to that use in construction of the torus shell. Since the monitoring program began, UT measurements have been performed at six-month intervals. Every effort is made by Niagara Mohawk to use the same personnel and equipment to examine the same locations during each inspection. Results of these UT measurements are used to update the thick-

*Material specification ASTM A 201 was discontinued in 1966 and replaced by ASTM A 515.

ness of the plates and to estimate remaining service life of the torus. At the current rate of corrosion, Niagara Mohawk estimates that the torus shell will be at its minimum acceptable thickness about 2007, very near the end of its 40-year operating license. Additional background information about the corrosion at Nine Mile Point, Unit 1 and analyses performed by Brookhaven National Laboratory to address this type of Mark I torus problem are presented in a reported issued by the NRC (Ref. 6.8).

Over the years, a number of options to mitigate the effects of corrosion were explored by Niagara Mohawk. These options included:

1. using a corrosion inhibitor in the torus water,
2. inerting the torus with nitrogen during outages,
3. coating the inside surface of the torus,
4. installing a cathodic protection system, and
5. modifying the torus to improve its structural capacity.

So far, Niagara Mohawk has taken no actions to implement any of these options. A brief discussion of these options and reasons for rejecting or further considering each option are provided below.

6.2.1 Corrosion Inhibitors

Addition of chemicals to the torus water was rejected for the following reasons. Chemicals to scavenge oxygen, such as hydrazine, would require removal prior to startup; could produce undesirable gases, such as ammonia; could cause pH problems; and could be a safety risk (i.e., carcinogenic). In addition, the possible gains in terms of reducing corrosion were estimated to be minimal.

6.2.2 Inerting the Torus

Maintaining a nitrogen purge on the torus during outages was rejected because of safety concerns. Nitrogen could escape or leak from the torus into the drywell resulting in pockets of low oxygen concentrations. Atmospheric conditions like this could create a potential suffocation hazard for workers.

6.2.3 Coatings

Despite the potential benefits of an effective coating system, application of either an organic or a metal spray protective coating on the inside surface of the torus was rejected. Reasons for rejection include outage critical path impacts, the relatively short service life of a coating in this service environment, the need for extensive long-term maintenance, and ALARA considerations. Application of either coating system would require removing the water, sludge, and debris from the torus and thoroughly cleaning all exposed surfaces in preparation for the coating. According to Niagara Mohawk, of the two coating systems considered, application of a metal spray, such as zinc, zinc-aluminum, or aluminum, would provide at least one distinct advantage over an organic coating. The metal spray coating could be classified as non-safety related. Unlike organic paints and epoxies that fail by producing loose flakes or sheets that could potentially clog the emergency core cooling system (ECCS), consequences of metal spray coating failure would likely not affect plant safety. A catastrophic metal spray failure would result in sheets of metal falling from the surface and sinking to the bottom of the torus without affecting the performance of the ECCS. Compared to organic coatings, metal spray coatings take somewhat longer to apply. However, the time difference is not considered significant.

6.2.4 Cathodic Protection

Installation of sacrificial anodes and an impressed current cathodic protection system were considered to stop the corrosion process. In the sacrificial anode concept, either zinc anodes would be placed in the water and electrically connected to the torus shell, or zinc screens would be welded to the torus shell surface. After installation, the zinc would create a passive protection system requiring no periodic maintenance. However, use of sacrificial anodes was not considered feasible due to low conductivity of the water. An alternative approach based on an impressed current cathodic protection system for this application would be more complex than the sacrificial anodes system just described. This active system would require installation of an electrical conductor 360 degrees around the torus with direct current applied between the cable and the torus shell. Direct current would be supplied by a rectifier powered by an alternating current source. For the system to function properly and provide the required corrosion protection, the conductor would need to be installed under water and supported by structures attached to the torus shell.

Due to concerns about loads imposed on the conductor and its support structure during a loss of coolant accident, and the impracticality of installing a suitable system, installation of an impressed current cathodic protection system was also not considered feasible.

6.2.5 Structural Modifications

Based on information provided by Niagara Mohawk, the most viable option involved structural modifications to the torus shell to enhance its ability to resist applied loads. In this concept, eight stiffener rings would be fillet welded to the outside surface of the torus shell on each of the 20 bays. The stiffener rings would be fabricated from 457-mm (18-in.) wide by 12.7-mm (0.5-in.) thick carbon steel plates rolled through the thickness to conform to the outside surface of the torus shell. All eight stiffener rings for each bay would be spaced longitudinally at 305-mm (12-in.) intervals. The four center stiffener rings would extend 210 degrees around the shell and be centered about the bottom of the torus. Figure 6.2 shows a conceptual view of how these four stiffener rings would be installed on each of the 20 bays. Two adjacent stiffener rings would extend 15 degrees above the horizontal centerline on the outer part of the torus and terminate at the inner column wing plates. The final two stiffener rings would be coped between the outer column wing plates and the miter joint between bays on the inner part of the torus. To accommodate obstructions such as penetrations and reinforcing pads, the stiffener rings would be coped around or bridged to adjacent rings to provide an acceptable load path. The configuration of the stiffener rings to accommodate these obstructions would be developed to allow sufficient access for inspection of the stiffener plate to torus shell fillet welds.

According to preliminary plans prepared by Niagara Mohawk, each ring would be prefabricated in sections that would be approximately 4-m (13-ft) long. This dimension was selected to facilitate movement into the torus room. Once inside, the ring sections would be assembled on the floor, welded together, and then turned and lifted into position. Inherent flexibility of the thin stiffener rings would allow spreading to fit a curvature greater than 180 degrees. In order to minimize the impact on plant operations, Niagara Mohawk would prefer for these stiffener rings to be installed while the plant is in operation. Under these conditions, the torus would contain water making it necessary to weld some parts of each stiffener rings with water backing. The feasibility of performing such welding has not been fully investigated and may not be permitted based on rules provided in applicable sections of the ASME Code. The structural modifications would be performed in phases with work starting first on selected bays. Presuming installation during operations is feasible, initial considerations suggest that the work could proceed on one or more bays at a time without affecting operations or jeopardizing the integrity of the remaining bays. However, analyses of an asymmetric torus configuration has not been completed. If Niagara Mohawk chooses to perform these structural modifications, installation of the stiffener rings would reestablish an adequate corrosion allowance for the projected remaining plant life plus a 20-year extension.

6.3 Liner Plate Corrosion in Concrete Containments

Liners of reinforced and posttensioned concrete containments are typically constructed using relatively thin [about 6.4-mm (0.25-in.) thick] carbon steel plates that are welded together to create a leak-tight barrier against the uncontrolled release of radioactivity to the surrounding environment. Although liner plates are not designed to carry loads, corrosion could have a detrimental effect on containment reliability and availability under design basis accidents and beyond design basis events. Any liner plate thinning can create geometrical transitions that influence strain concentration. This influence could change the failure threshold under challenging environmental or accident conditions and may reduce the design margin of safety. Corrosion that results in thinning, pitting, or cracking is of particular concern when the entire thickness of the liner plate is affected. Holes, pits, and cracks that penetrate completely through the liner plate disrupt the pressure boundary and may create pathways to the surrounding environment. Instances of liner plate corrosion have been reported at nuclear power plants in the United States and France.

6.3.1 U.S. Experience

Potential locations for containment liner plate corrosion in nuclear power plants in the United States include:

- the junction of the containment cylinder and intermediate floors and basemat concrete for PWR and BWR Mark III containments,

- the junction of the drywell and the base or intermediate concrete floors for BWR Mark I and II containments,
- surfaces adjacent to crane rail girders and supports attached to the liner plate,
- water-soaked areas where carbon steel liner plate is used in BWR Mark I and II containments, and
- surfaces behind insulation and ice condenser baskets.

Inspections of containment liners have shown various degrees of corrosion at six nuclear power plants (Ref. 6.9). The types of corrosion that were detected are described below.

- Corrosion of the drywell liner was detected at Brunswick, Units 1 and 2 at various locations near the junction of the concrete floor and the drywell liner.
- Peeled coatings and spots of liner corrosion were identified at Trojan and Beaver Valley, Unit 1.
- Minor corrosion of the containment liner at Salem, Unit 2 was detected prior to an integrated leakage-rate test.
- Discoloration of the vertical portion of the containment liner was observed at an insulation joint at Robinson, Unit 2.

From a safety viewpoint, the only corrosion that was considered significant occurred inside the two Mark I concrete containments at the Brunswick nuclear power plant located approximately 3 km (2 mi.) north of Southport, North Carolina (Refs. 6.10 to 6.15). General and pitting corrosion affecting as much as 50 percent of the nominal 8-mm (5/16-in.) thick liner was detected at several locations along a narrow band around the inside circumference of both drywells. The corrosion was caused by an accumulation of water at the junction of the drywell liner and the concrete floor surface (Elev. 4'-6") at the bottom of the containment. Degradation of sealing materials applied around the inside circumference of the containments at this junction allowed the water to enter and accumulate in this region. Procedures used by the licensee to quantify the extent and depth of the corrosion damage involved:

1. removing concrete adjacent to the liner to provide access for inspection (Unit 1 only),
2. cleaning (sandblasting and wire brushing) the liner plates,
3. selecting designated inspection zones,
4. measuring the base metal plate thickness using ultrasonic testing methods, and
5. determining the depth of pitting and general corrosion using dental molding compound.

Metal loss and pitting depth measurements revealed that there were locations of the liners that were below the minimum acceptable thickness of 5 mm (0.20 in.). Five such sections were identified in Unit 2, but the damage in Unit 1 was more severe. Corrosion was observed around virtually the entire circumference of the Unit 1 drywell. The damage even extended below the level of the concrete floor surface making removal of concrete adjacent to the liner necessary. Although corrosion of the drywell liner for Unit 1 was more severe than the corrosion for Unit 2, the leaktight integrity of both Brunswick containments was never jeopardized because the thinning and pitting did not penetrate completely through the liner plates.

In order to restore damaged liner plates to the required minimum thickness and thereby allow the units to be returned to service, the licensee performed a series of construction activities. Details of these activities are described below. Figure 6.3 shows a cross section of the drywell liner repair for the Unit 1 containment.

1. Areas with significant metal loss or pitting were repaired by overlay welding in which weld metal was deposited on the damaged liner plates to supplement the existing thickness. During welding, efforts were taken to limit the interpass temperature of the liner plates to 79°C (175°F).
2. Following welding, each area was examined using the liquid penetrant test method. Results of this test were used to determine the acceptability of the welding repairs.
3. All damaged and repaired areas were recoated.

4. Mortar was placed in Unit 1 to return the concrete floor to its original elevation and configuration.

5. Intersections of the concrete floors and drywell liners were sealed with an elastomeric sealant.

6.3.2 French Experience

Electricite de France discovered liner plate corrosion near the bottom of several of its 34 900-MW PWR posttensioned concrete containments (Ref. 6.16). Corrosion of the 6-mm (0.24-in.) thick carbon steel liner plates occurred in two separate areas. Both areas were inside the containments and involved liner plates located between the basemat and the 1-m (39-in.) thick concrete floor slab.

Liner plate corrosion was first detected at a plant that had been in service for about 10-15 years. Corrosion occurred in the conical-shaped portion of the liner in an inaccessible area located beneath the concrete floor slab. The corrosion started near the joint sealant at the intersection of the concrete floor and the steel liner and extended downward about 200 mm (8 in.). At some locations the corrosion produced holes through the liner plates that were up to 10 mm (0.40 in.) in diameter. The cause for the corrosion was attributed to a breakdown in the joint sealant in conjunction with the presence of high humidity during construction and operation. Examination of construction details in this area also revealed that water containing corrosive substances was stagnating in some of the pressurization channels that were welded to the outer surface of the liner. These channels were installed during construction and used to inspect the welds that joined the liner plate sections. After the concrete was placed and construction completed, access to the space between the channels and the liner plates was restricted making inspection impossible.

Thinning of liner plates was also observed in some plants at the bottom of the joint in the concrete floor slab. The corrosion reduced the thickness of the liner plates to 3 mm (0.12 in.) in some locations. This damage was attributed to decomposition of the joint sealant and the presence of acidic water (pH = 5) at the liner-concrete interface.

In order to halt the corrosion process and stop further damage, the French developed a repair technique. Steps taken to repair pits and holes through the liner plates involved removing portions of the concrete floor slab at selected locations, sandblasting the corroded liner plates, inspecting the damaged areas, welding cover plates over the pits and holes, coating (painting) the repaired areas, and replacing the concrete to restore the floor to its original configuration. In addition, the pressurization channels were filled with cement grout, the cavity between the liner and the floor slab was filled with a corrosion inhibitor (wax), and a new joint sealant was installed. The new joint sealant consisted of a composite elastomeric material that was shielded by a series of metallic sheets attached by bolts. This method of attachment was selected so that the sheets could be periodically removed to provide access for inspection of the elastomeric material.

Even though corrosion produced pits and holes through the liner plates at some plants, air that escaped from the containments through these holes during periodic integrated leakage-rate tests did not adversely affect the test results. The measured leakage from the containment was less than the allowable leakage limit.

6.4 Metal Containment Corrosion in Germany

There are 20 operating nuclear power plants in Germany. The majority of these plants are of the PWR type with spherical-steel containments that range in diameter from 44 to 56 m (144 to 184 ft). Older containments have a 30-mm (1.18-in.) thick metal shell with a 1-mm (0.039-in.) corrosion allowance. Newer designs use a 38-mm (1.50-in.) thick metal shell with a 2-mm (0.079-in.) corrosion allowance. Except for the lower portion of the metal containment shell embedded in concrete, all areas of the shell are coated. A reinforced concrete shield building about 1.5 to 1.8 m (38 to 46 in.) in thickness surrounds each metal containment primarily to provide protect from aircraft impact. The metal containment shell and the shield building are isolated from each other except for a common foundation.

Instances of metal containment corrosion have occurred at the Obrigheim (KWO) and Neckar I (GKN-1) nuclear power plants (Ref. 6.17). Both of these plants are PWRs that started commercial operation in March 1969 and December 1976, respectively. Corrosion was detected during an inspection of the KWO plant on the inside surface of the containment in the transition area where the metal shell becomes embedded in the concrete floor slab. Thermal insulation was installed at this location during construction to protect the metal shell from high-temperature exposure during a loss-of-coolant accident. Corrosion of the metal shell occurred when high humidity levels inside the containment penetrated this thermal insulation and reached the inside surface of the metal shell. The average depth of corrosion adjacent to the moist insulation was about 1 mm (0.039 in.) with local areas to 6 mm (0.24 in.). In addition to corrosion of the metal shell, galvanized sheet metal covers installed over the insulation were also heavily corroded.

During the inspection of the KWO plant, a portion of the concrete adjacent to the outside surface of the metal shell was removed to a depth of about 100 mm (4 in.) to provide access for visual examination of this suspect area. This examination revealed no corrosion.

Using information obtained from the condition assessments, an evaluation of the degradation was performed indicating that the corrosion was limited, it was not significant enough to present a safety problem, and the metal shell did not need to be restored to its original thickness. Based on these conclusions, a repair program designed to halt the corrosion process and thereby stop further degradation was developed and implemented. Inside the containment, corroded areas of the metal shell were cleaned and reconditioned, a coating was applied to affected areas, and a new seal design (silicone plus metal covers) was installed at the interface between the metal shell and the concrete floor slab. The thermal insulation was not reinstalled because the evaluation revealed that it was not needed. Outside the containment, areas of concern were coated and the thermal insulation was reinstalled at the interface between the metal shell and concrete.

Inspection of the GKN-1 containment revealed corrosion on the inside surface of the metal shell in a transition region similar to that in the KWO plant. Based on this finding, the same repair procedure used at the KWO plant was implemented. Damage observed at the GKN-1 plant provided the basis for recommending that all plants having a transition region of similar design be inspected to determine if the thermal insulation is moist and the metal shell has corroded.

A similar investigation at BWR plants was also performed. Suspect areas such as the transition region where the metal shell penetrates the concrete and locations where platforms are in close proximity to the metal shell were inspected, but no corrosion was detected.

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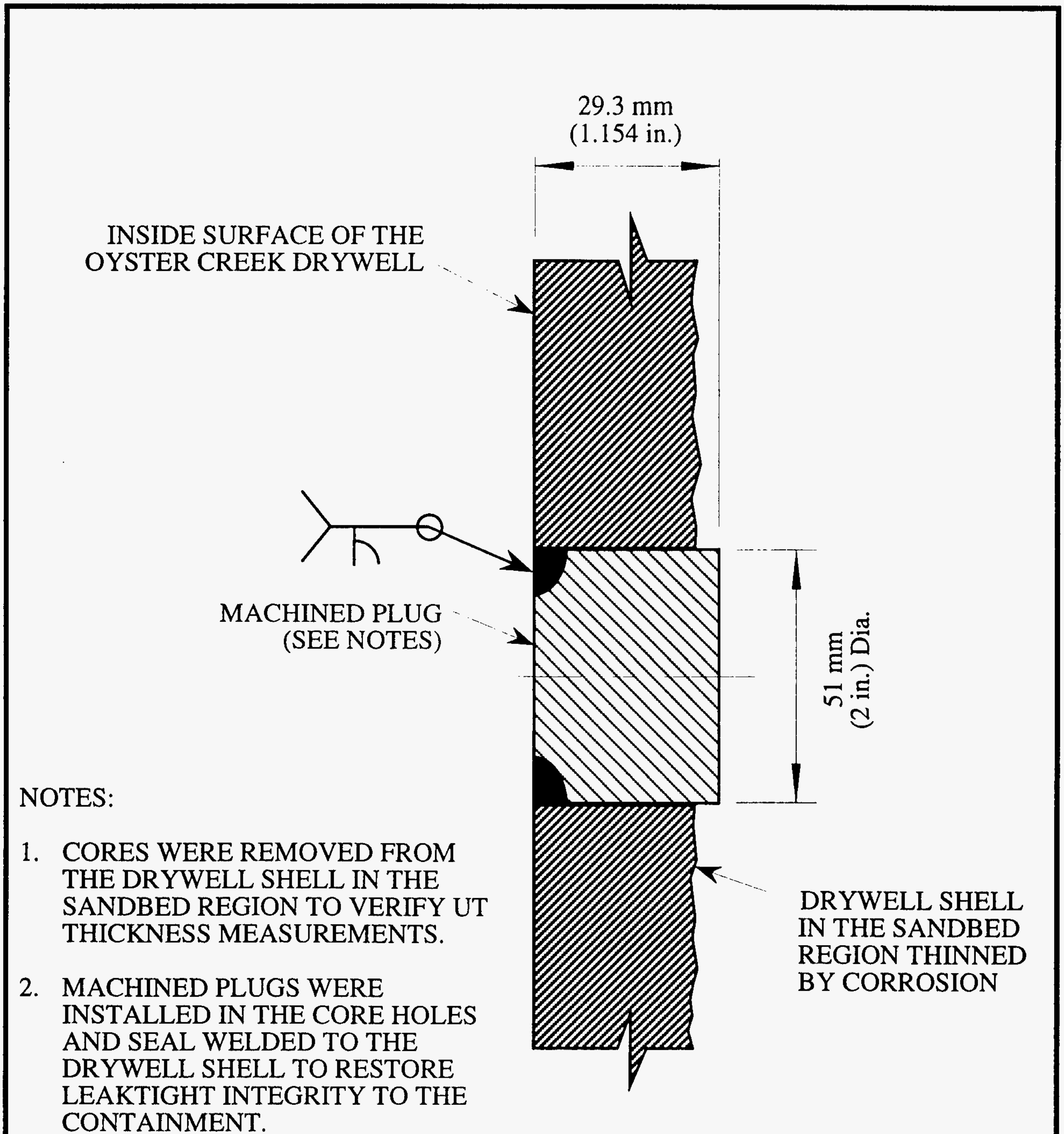


Fig. 6.1. **Repair technique used to replace drywell shell material removed by coring and restore leaktight integrity to the Oyster Creek containment.**

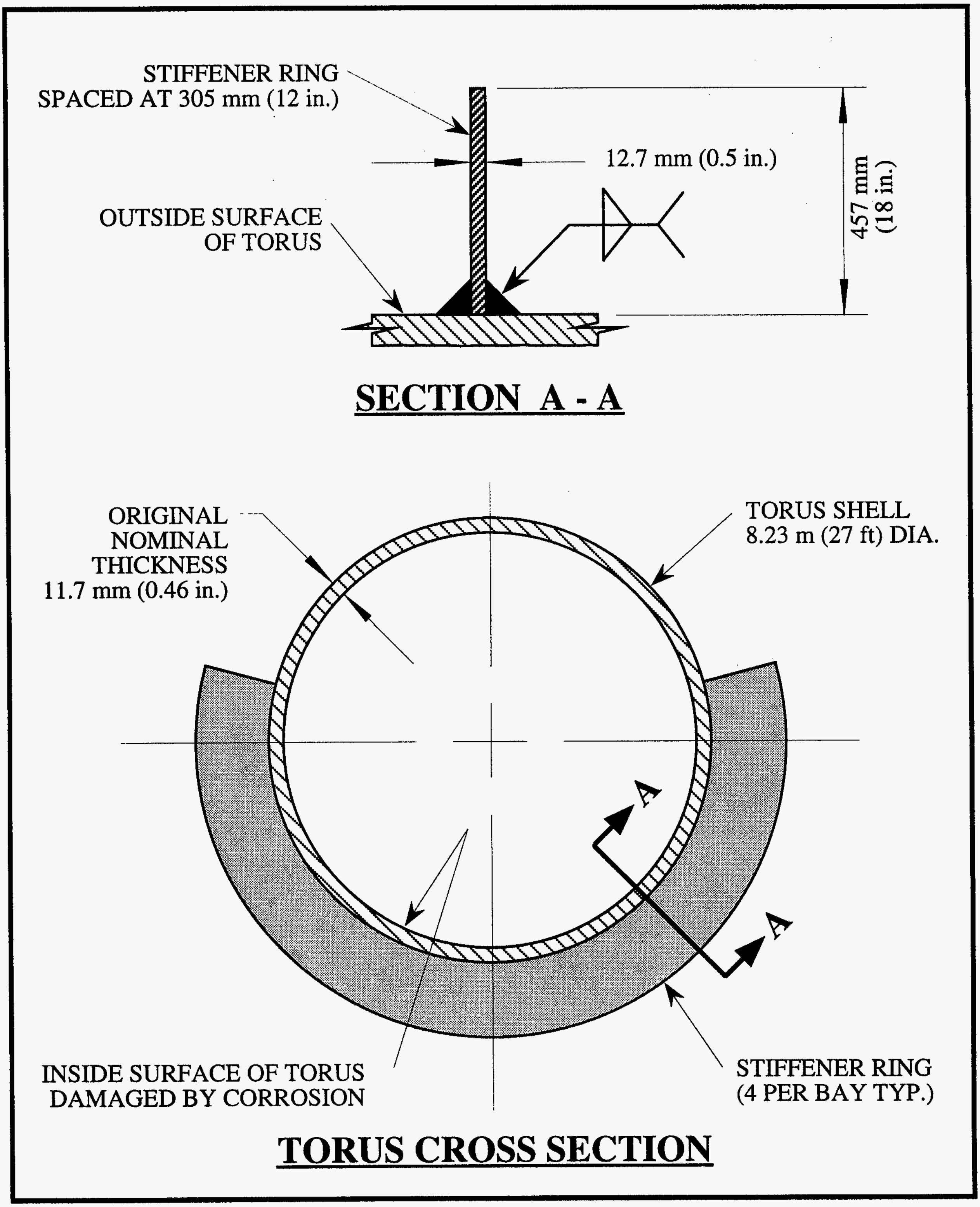
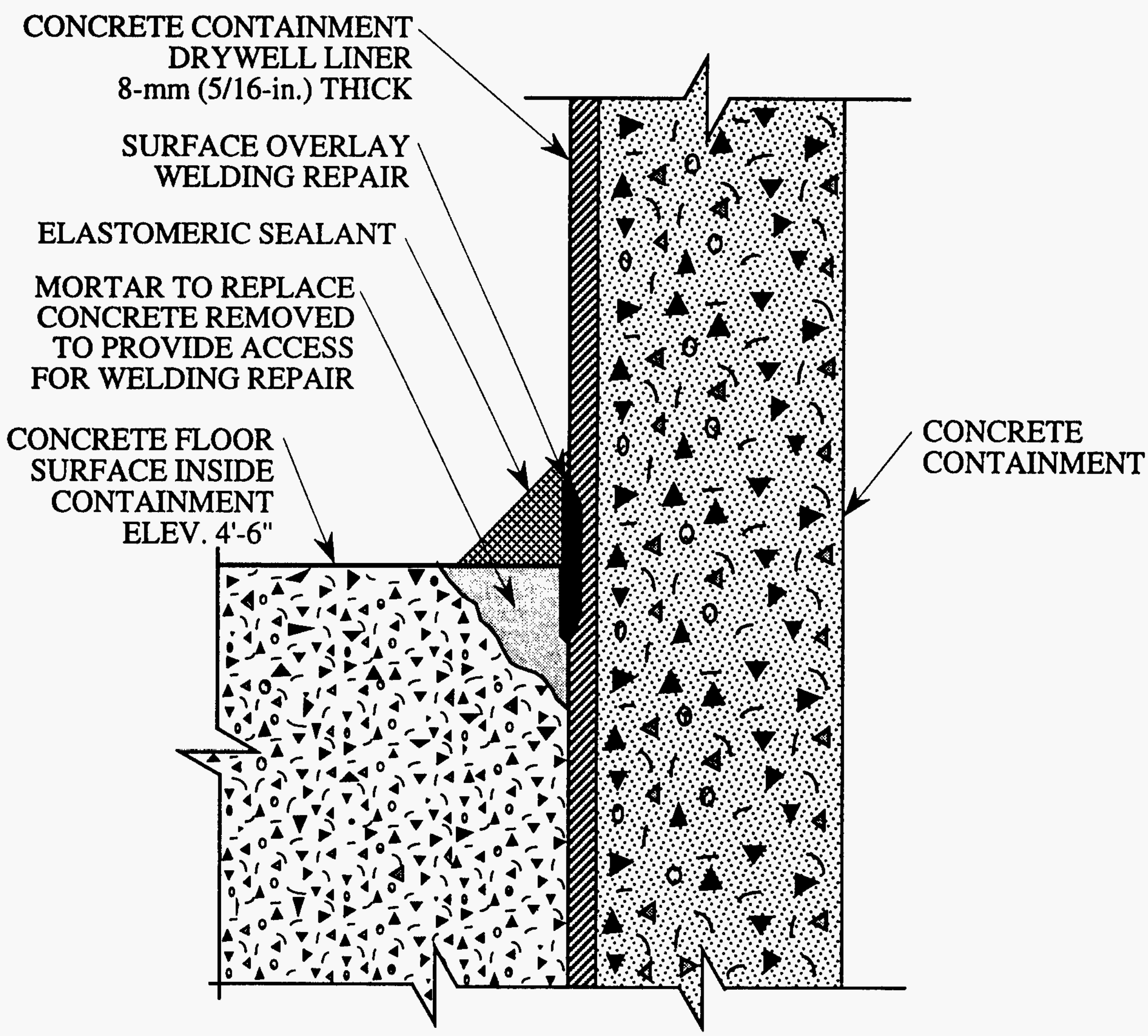


Fig. 6.2. **Conceptual view showing how four of the eight stiffener rings would be installed on the outside surface of each bay of the Nine Mile Point, Unit 1 torus.**



NOTES:

1. CONCRETE AT THE FLOOR-LINER INTERSECTION WAS REMOVED TO PROVIDE ACCESS FOR INSPECTION AND WELDING REPAIR ACTIVITIES.

2. OVERLAY WELDING WAS PERFORMED TO RESTORE PORTIONS OF THE LINER DAMAGED BY CORROSION.

3. AFTER WELDING, AFFECTED AREAS WERE COATED, MORTAR WAS PLACED TO RESTORE THE FLOOR SURFACE, AND AN ELASTOMERIC SEALANT WAS APPLIED AT THE FLOOR-LINER INTERSECTION.

Fig. 6.3. Cross-sectional view of the drywell liner repair performed inside the Brunswick, Unit 1 concrete containment.

Table 6.1 Potential water sources and remedial actions taken to eliminate water from the sandbed at the Oyster Creek nuclear power plant.

Potential water source	Detection method	Remedial action
Spent Fuel Pool	Vacuum Box Testing	Repaired by underwater welding.
Reactor Cavity Seal Bellows	Pressure Testing	No leaks detected.
Reactor Cavity Seal Drain Line	Pressure Testing	Gasket repaired.
Reactor Cavity Seal Under Drain	Video Surveillance	Modified concrete trough contour.
Reactor Cavity Liner	Visual Inspection, Dye Penetrant Testing, and Vacuum Box Testing	Extensive leaks identified. Temporary coated during refueling outage, stainless steel tape and elastomeric coating applied.
Skimmer System Piping	Helium Leakage Testing	System was isolated.
Equipment Storage Pool	Visual Inspection, Dye Penetrant Testing, and Vacuum Box Testing	Repaired by welding.
Sandbed Drains	Examination of Drain Lines	Drains were unclogged allowing water to drain from the sandbed.

7. SUMMARY AND CONCLUSIONS

7.1 Summary

Whenever damage or deterioration that could affect the structural integrity or leaktightness of a metal or concrete containment is detected, the condition must be corrected or evaluated before the containment can be returned to service. Continued service is permitted after one or more of the following actions have been taken.

1. Unacceptable flaws, discontinuities, or areas of degradation have been removed to the extent necessary to meet the acceptance standards.

2. A repair involving welding has been completed such that existing design requirements are met.

3. Replacement of the component or portion of the component containing the unacceptable flaws or areas of degradation has been accomplished.

4. An engineering evaluation has been performed revealing that the flaws, discontinuities, or areas of degradation have no effect on structural integrity or leaktightness.

The first three actions are intended to ensure that metal and concrete containment pressure boundary components remain free from defects that do not meet acceptance criteria during their entire service life. Corrective actions that are taken must be performed in accordance with the repair and replacement procedures, nondestructive examination requirements, and testing methods specified in applicable codes including those editions and addenda of the ASME Code that have been adopted by the NRC. It is the Owner's responsibility to develop a program that defines the managerial and administrative control of the proposed activities. The program must include the applicable construction code edition, addenda, and code cases used for the item being repaired or replaced and a specification for the repair or replacement. In addition, each repair or replacement must be performed in accordance with the Owner's Design Specification. A very important part of the program is development of a plan that identifies essential requirements for completing the repair or replacement and acceptance criteria. After the program, plans, and required evaluations of acceptability have been prepared, they must be submitted for review to enforcement and regulatory authorities having jurisdiction at the plant site, including the NRC. Once approved, the repair or replacement activities can be initiated.

Containment pressure boundary components that have been reduced below the minimum design thickness either by degradation or defect removal may be repaired by welding and returned to service. Prescriptive rules for welding repairs of similar materials, cladding, and dissimilar materials are well established. These rules define base and welding materials acceptable for use in making welding repairs using either the shielded metal-arc or the gas tungsten-arc welding process. Basic criteria for the qualification of welders and welding procedures have also been adopted and codified. Rules for developing welding procedures that are acceptable for underwater repair welding applications and temporary non-code welding repairs of certain classes of piping have even been established for use in special situations. Although rules for welding repairs are intended for use in areas where accessibility is not a problem, innovative welding repair alternatives are being developed for use in repairing inaccessible areas. Four welding repair alternatives include:

- replacement plate welding repairs,
- doubler plate welding repairs,
- stiffener plate welding repairs, and
- overlay welding repairs.

As an alternative to defect removal or repair, items or portions of containment pressure boundary components that contain flaws, discontinuities, or areas of degradation may be replaced with items that meet the acceptance standards. Items used as replacements must be constructed, installed, and documented in accordance with requirements developed by the Owner and approved by the appropriate enforcement and regulatory authorities, including the NRC.

The fourth action is a less prescriptive condition for continued service that has recently been adopted by the NRC. Continued service under these terms means that containment pressure boundary components with defects may be returned to service provided the unacceptable flaw or discontinuity is removed or reduced to an acceptable size and the resultant section thickness created by the removal process is equal to or greater than the minimum design thickness. If the affected component has been reduced below the minimum design thickness, the component must either be repaired, replaced, or evaluated before being returned to service. Defects may be removed or reduced to an acceptable size using a variety of mechanical removal processes including grinding.

Engineering evaluations are performed on a case-by-case basis by qualified engineers and authorized personnel who determine the adequacy of damaged or degraded components for their intended use. Acceptance criteria are generally established so that components with flaws, discontinuities, or areas of degradation that adversely affects structural integrity, leaktightness integrity, or remaining service life of the containment are not considered acceptable for continued service. In general, containments that contain pressure boundary components with flaws, discontinuities, or areas of degradation that are found by engineering evaluation to have no effect on structural integrity or leaktightness may be returned to service without removing the defect or repairing or replacing the defective component. Damaged components are considered acceptable for continued service if either the thickness of the base material is reduced by no more than 10 percent of the nominal thickness or it can be demonstrated by analysis that the reduced thickness satisfies the requirements of the design specification.

7.2 Conclusions

Welding provides an effective means for making the types of high-quality repairs that are required by utility owners, jurisdictional authorities, and regulatory agencies. Rules for routine welding are available in codes and standards for repair situations where the area to be repaired is readily accessible by a skilled workman equipped with the necessary tools. Although intended for routine welding activities, these rules contain numerous exceptions and limitations that must be considered by the Owner as plans for the repair or replacement are being developed. Major topics addressed by these rules along with some of the more significant exceptions and limitations for repair and replacement of degraded containment pressure boundary components are identified and described in Sect. 7.2.1 Special restoration practices for containment pressure boundary component repair or replacement situations not specifically covered by rules provided in the ASME Code are presented in Sect. 7.2.2.

7.2.1 Routine Welding Repair and Replacement Topics

The following topics present important rules, exceptions, and limitations for routine welding activities. These topics will likely be addressed in plans for performing a containment pressure boundary component repair or replacement that are submitted by an Owner to the NRC for consideration.

- Ferrous material specifications permitted for repairs and construction of replacements for metal containments and liners of concrete containments are provided in Section II, Part A (Ref. 7.1) of the Code.

- Welding material specifications permitted for repairs and construction of replacements for metal containments and liners of concrete containments are provided in Section II, Part C (Ref. 7.2) of the Code.

- According to the repair and replacement requirements provided in Section XI, Subsection IWA-4000 (Ref. 7.3) of the Code, welding repairs to similar materials, dissimilar materials, or austenitic stainless steel and nickel-base cladding may only be performed using either the shielded metal-arc welding (SMAW) or the gas tungsten-arc welding (GTAW) process. The following exceptions and limitations for these categories of repair welding may apply.

    1. Repairs to similar metals involving P-Nos. 1, 3, 12A, 12B, and 12C* base materials and associated welds may be made without the specified postweld heat treatment based on requirements provided in Section XI, Subsection IWA-4510 (Ref. 7.3) of the Code. These requirements only apply to repairs that have a maximum finished surface area of 64,500 sq. mm (100 sq. in.) and a depth of repair that is no greater than one-half the base material thickness.

*P-Nos. 12A, 12B, and 12C are material classifications originally identified in Section III and later reclassified and included in Section IX.

2. Repairs to welds that join dissimilar metals involving P-Nos. 8 or P-No. 43 material to P-No. 1, 3, 12A, 12B, and 12C base material can be made without the specified postweld heat treatment based on requirements provided in Section XI, Subsection IWA-4530 (Ref. 7.3) of the Code. These requirements are only applicable to repairs made along the fusion line of a nonferritic weld to ferritic base material where 3.18 mm (0.125 in.) or less of nonferritic weld deposit exists above the original fusion line after defect removal. If the defect penetrates into the ferritic base material, repair of the base material may be performed provided the depth of the repair in the base material does not exceed 9.53 mm (3/8 in.). Repairs to a completed joint must not exceed one-half the joint thickness, and the surface of the completed repair may not exceed 64,500 sq. mm (100 sq. in.).

3. Repairs to austenitic stainless steel and nickel-base cladding on P-Nos. 1, 3, 12A, 12B, and 12C base materials when the ferritic material is within 3.18 mm (0.125 in.) of being exposed can be made without postweld heat treatment based on requirements provided in Section XI, Subsection IWA-4520 (Ref. 7.3) of the Code. When the repair involves two different P-Number or Group Number materials, the welding qualification test assembly must duplicate the combination. Dimensions of the test assembly base material must be at least 305 mm by 305 mm by 51 mm (12 in. by 12 in. by 2 in.) with a clad surface area of at least 203 mm by 203 mm (8 in. by 8 in.) in the region from which the bend test specimens will be taken. The guided bend test acceptance standards in Section IX for cladding must also be applicable to the heat affected zone of the base material.

- Butter bead—temper bead welding is intended for use in the repair of metal and concrete containment pressure boundary components where preheat and postweld heat treatment are impractical. Requirements for this technique are provided in Section XI, Subsection IWA-4540 (Ref. 7.3) of the Code. Butter bead—temper bead welding involves application of a butter layer of surfacing weld metal followed by the application of temper beads or a temper bead layer. This welding sequence eliminates the need for postweld heat treatment. To help ensure the quality of repairs made using butter bead—temper bead welding, the welding procedure and welders must be qualified in accordance with requirements provided in Section IX (Ref. 7.4) of the Code as well as applicable requirements provided in Section III, Division 1, Subsection NE-4000 (Ref. 7.5), Section III, Division 2, Subsection CC-4000 (Ref. 7.6), and Section XI, Subsection IWA-4540 (Ref. 7.3). Welder qualification involves a performance qualification test and a production test prior to any repair welding. In the performance qualification test, the welder prepares a groove weld test specimen that is then examined radiographically in accordance with Section IX requirements. The production test involves the preparation of a production test assembly that may consist of one or more production tests. Any physical obstructions associated with the actual repair must be simulated in the production test.

- Requirements for welding procedure and welding performance qualifications using the SMAW and GTAW processes are provided in Section IX (Ref. 7.4) of the Code. Exceptions and modifications to these requirements as well as repair welding requirements are provided in the construction codes and in Section XI, Subsection IWA-4000 (Ref. 7.3) of the Code.

- Before containment pressure boundary components can be repair welded, a welding procedure specification must be developed and qualified. Its purpose is to determine whether the proposed weldment is capable of providing the required properties for the intended application.

- After a suitable welding procedure specification has been qualified, tests to qualify the performance of the welders and welding operators that actually perform the required welding must be conducted. Performance qualification is established by a demonstration of a welder's or welding operator's ability to make sound welds in accordance with a qualified welding procedure specification. Performance qualification requirements are provided in Section IX (Ref. 7.7) of the Code.

7.2.2 Special Welding Repair and Replacement Topics

The following topics present special rules and technical issues that pertain to containment pressure boundary component repair and replacement situations not specifically covered by rules provided in the ASME Code.

- Supplementary rules for dry and wet underwater welding repairs or replacements of P-No. 8 (austenitic stainless steel) and P-No. 4X (low-alloy steel) materials are provided in Code Case N-516 (Ref. 7.8). When applicable, these methods can be used in lieu of the alternative welding methods permitted in Section XI, Subsection IWA-4500 (Ref. 7.3) of the Code provided all other applicable requirements of Section XI are met. Similar code cases for underwater welding of other materials such as carbon steels permitted for construction of containment pressure boundary components have not been approved by ASME.

- When welding is performed on a metal containment shell or a concrete containment liner backed by concrete, the rate of heat dissipation can affect the quality of the deposited weld metal. Consequently, measures necessary for assuring predictable weldment behavior should be factored into the development of a suitable welding procedure specification and welder/welding operator performance qualification. Although the ASME Code rules and requirements are considered comprehensive and complete for most routine welding activities, they do not adequately address the impacts that repair welding operations and the resulting high temperatures can have on adjacent concrete and metallic components including embedment anchors and reinforcing bars embedded in the concrete.

- Innovative welding solutions are being considered for the repair of degraded carbon and low-alloy steel components located in inaccessible areas. One innovative solution under development involves an outside surface weld overlay repair to remedy inside surface erosion-corrosion damage to carbon steel piping (Ref. 7.9). If adequately developed and thoroughly tested, this solution could be submitted for ASME consideration as a code case. Once approved, use of this technique would eliminate the need for repair of the inside pipe surface by providing sufficient replacement metal on the outside of the pipe to restore structural integrity.

- Welding repair alternatives are being considered for the restoration of structural integrity to degraded metal containments and liners of concrete containments located in inaccessible areas. Before such alternatives can be implemented, they must first be adequately developed and thoroughly tested and then submitted for ASME consideration as a code case.

- Repairs not in compliance with rules provided in Section XI (Ref. 7.3) of the Code are considered non-code repairs. Techniques that could be used to make temporary non-code repairs to flawed piping include clamps with rubber gaskets, encapsulation of leaking pipes in cans using liquid sealants, and certain types of weld overlays. Temporary non-code repairs of ASME Code Class 1, 2, and 3 piping are considered unacceptable unless they are first approved in writing by the NRC. Guidance from the NRC for performing non-code repairs to flawed piping is provided in Generic Letter 90-05 (Ref. 7.10). For Class 1, 2, and 3 piping, a licensee is required to perform code repairs or request the NRC to grant relief for temporary non-code repairs on a case-by-case basis regardless of pipe size. Relief requests are usually made by licensees to avoid unscheduled plant shutdowns.

- Containment pressure boundary component degradation is usually discovered during a general inspection of accessible interior and exterior surface areas based on results of a visual examination. General inspections are performed prior to each integrated containment leakage-rate test. Flaws discovered as a result of these inspections and tests that do not meet acceptance criteria (defects) must be repaired before the plant is allowed to return to service. Consequently, there is no need for submitting a relief request to the NRC for a temporary non-code repair of the containment aimed at keeping the plant in operation until the next scheduled outage.

- Application of protective coatings on structures, equipment, and components in nuclear power plants is not required by the NRC because coatings provide no specific safety-related function to mitigate the consequences of postulated accidents. However, quality assurance requirements provided in 10 CFR 50, Appendix B (Ref. 7.11) are applicable to protective coatings because failure and disbonding during operating and emergency conditions could interfere with engineered safety systems required for safe shutdown and cooling of the reactor vessel. Although reasons for using protective coatings are based primarily on economic considerations, factors that could influence their use include material compatibility, heat transfer characteristics, and the consequences of failure during a design basis accident.

- Options for restoring the leaktightness and structural integrity of bellows that have been damaged while in service include replacement of the penetration assembly that contains the damaged bellows, replacement of the damaged bellows, installation of a new enveloping bellows, in-place welding repairs to damaged bellows, removal of severe dents, and blending the surface. Restoration activities that produce discontinuities in the welds or base metal, changes in wall thickness resulting from the addition of welded patches or removal of metal by blending (grinding), or unevenness or irregularities in the bellows contour may affect the useful service life of the bellows.

Under certain conditions, cathodic protection can be quite effective in preventing corrosion. Corrosion prevention can be achieved either by means of an impressed direct current or attachment to a sacrificial anode. In applying cathodic protection to a metal structure, the objective is to force the entire surface of the structure exposed to the environment to collect current from the environment making the exposed surface a cathode. When this condition is achieved, corrosion is successfully mitigated.

7.3 Recommendations

Effects of high-temperature exposure on concrete resulting from welding repairs to steel liner plates backed by concrete are not well quantified. As discussions in Sect. 5.2 reveal, very little test data about rapid, localized heating of concrete are available. Questions about concrete behavior under these short-term, but severe, service conditions can be effectively answered by performing a carefully controlled experimental investigation in which a representative portion of a containment cross section is constructed, repair welded, and methodically disassembled for examination and testing. Results of this investigation would provide valuable information about the following uncertainties.

- temperature distribution patterns in the vicinity of a liner plate welding repair
- depth and extent of concrete affected by welding repair activities
- extent of concrete cracking and spalling, if any
- changes in mechanical properties of the affected liner plate, reinforcing bars, anchor studs, and embedment anchors
- magnitude of concrete surface irregularities, if any, adjacent to the liner plate repair area

As a minimum, the experimental investigation should involve the construction of at least two types of test sections. To be representative, each test section should include concrete, reinforcing bars, and liner plate that is attached to the concrete either by anchor studs or embedment anchors. Configurations of two candidate test sections are shown in Figs. 7.1 and 7.2.

During liner plate fabrication, simulated corrosion damage could be produced by machining 50 percent of the metal from the liner surface at selected locations to create thinned areas. Overall dimensions of the thinned areas could also be varied so that the effects of damage size and location are examined as test variables. Although grinding could be used to produce the thinned areas, machining provides a more precise means for controlling the location and dimensions of the simulated corrosion damage. At least five thinned areas requiring repair welding could be machined in each liner plate as shown in Fig. 7.3. Prior to concrete placement, thermocouples should be installed at selected locations for use in monitoring concrete and steel temperatures before, during, and after welding.

Two types of welding repairs involving either an overly welding repair technique or a doubler plate welding repair technique should be performed to provide the basis for meaningful comparison. Knowledge gained from this comparison would be useful in selecting the more desirable welding repair technique and in understanding which technique produces the least damage to the concrete, reinforcing bars, and liner anchorage system. Cross-sectional views of both welding repair techniques are shown in

Fig. 7.4. The four recommended test section configurations for the experimental investigation are identified in Table 7.1.

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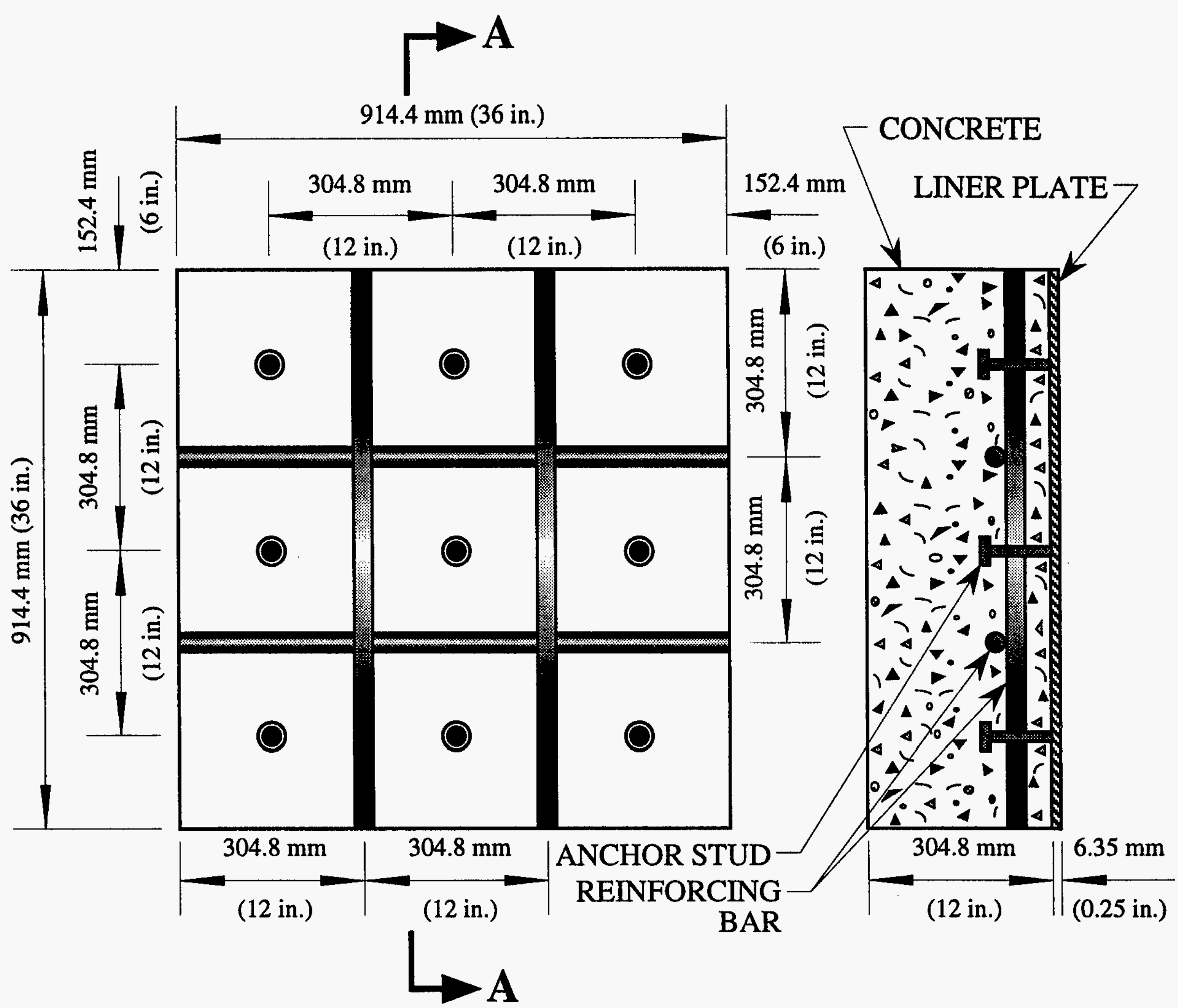


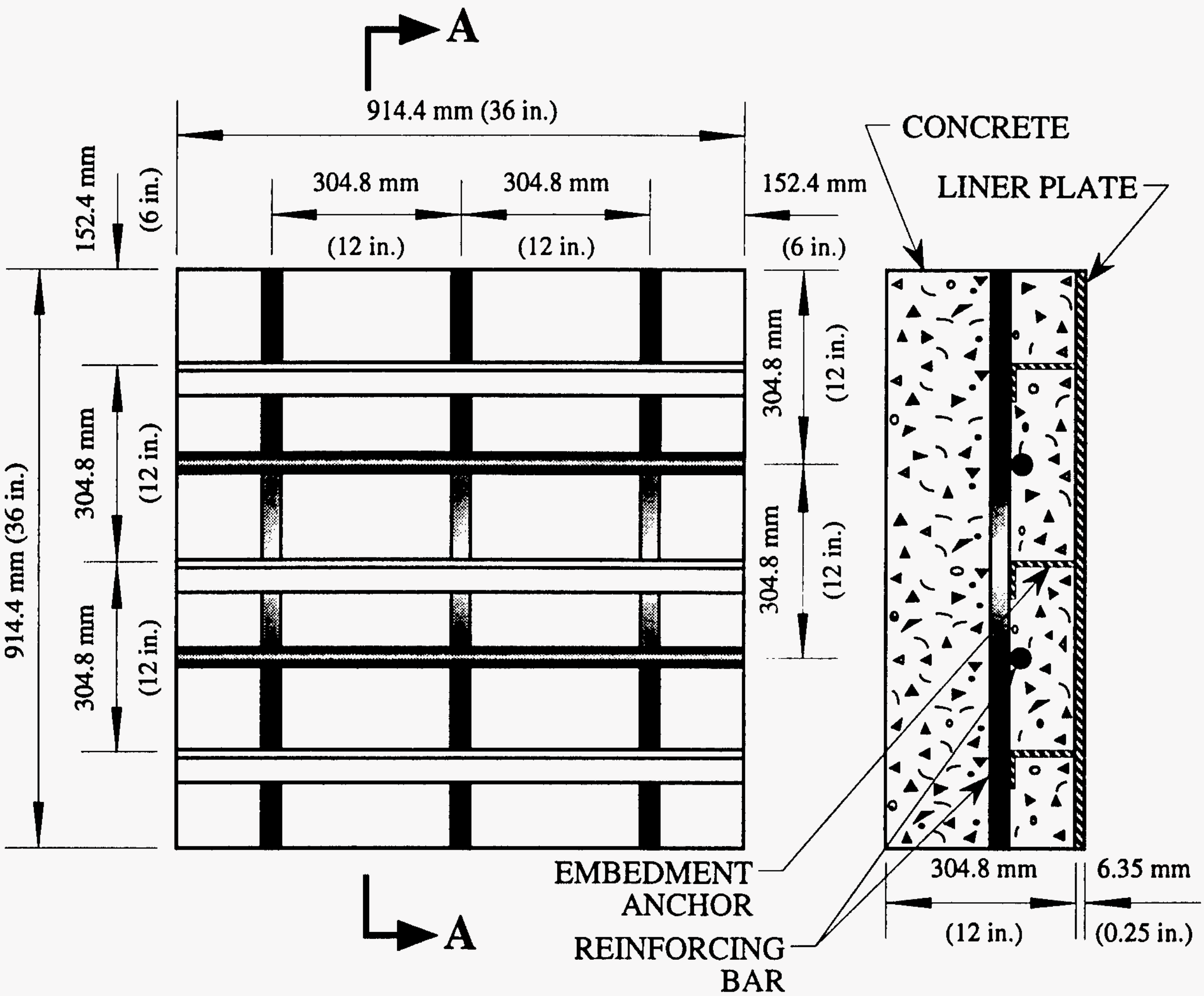
PLAN VIEW
ANCHOR STUD
TEST SECTION

SECTION A - A
(Not to Scale)

NOTE:

THE LINER PLATE AND CONCRETE ARE NOT INCLUDED IN THE PLAN VIEW TO SHOW THE ANCHOR STUD AND REINFORCING BAR ARRANGEMENT.

Fig. 7.1. Recommended anchor stud test section configuration.



PLAN VIEW
EMBEDMENT ANCHOR
TEST SECTION

SECTION A - A
(Not to Scale)

NOTE:

THE LINER PLATE AND CONCRETE ARE NOT INCLUDED IN THE PLAN VIEW TO SHOW THE EMBEDMENT ANCHOR AND REINFORCING BAR ARRANGEMENT.

Fig. 7.2. Recommended embedment anchor test section configuration.

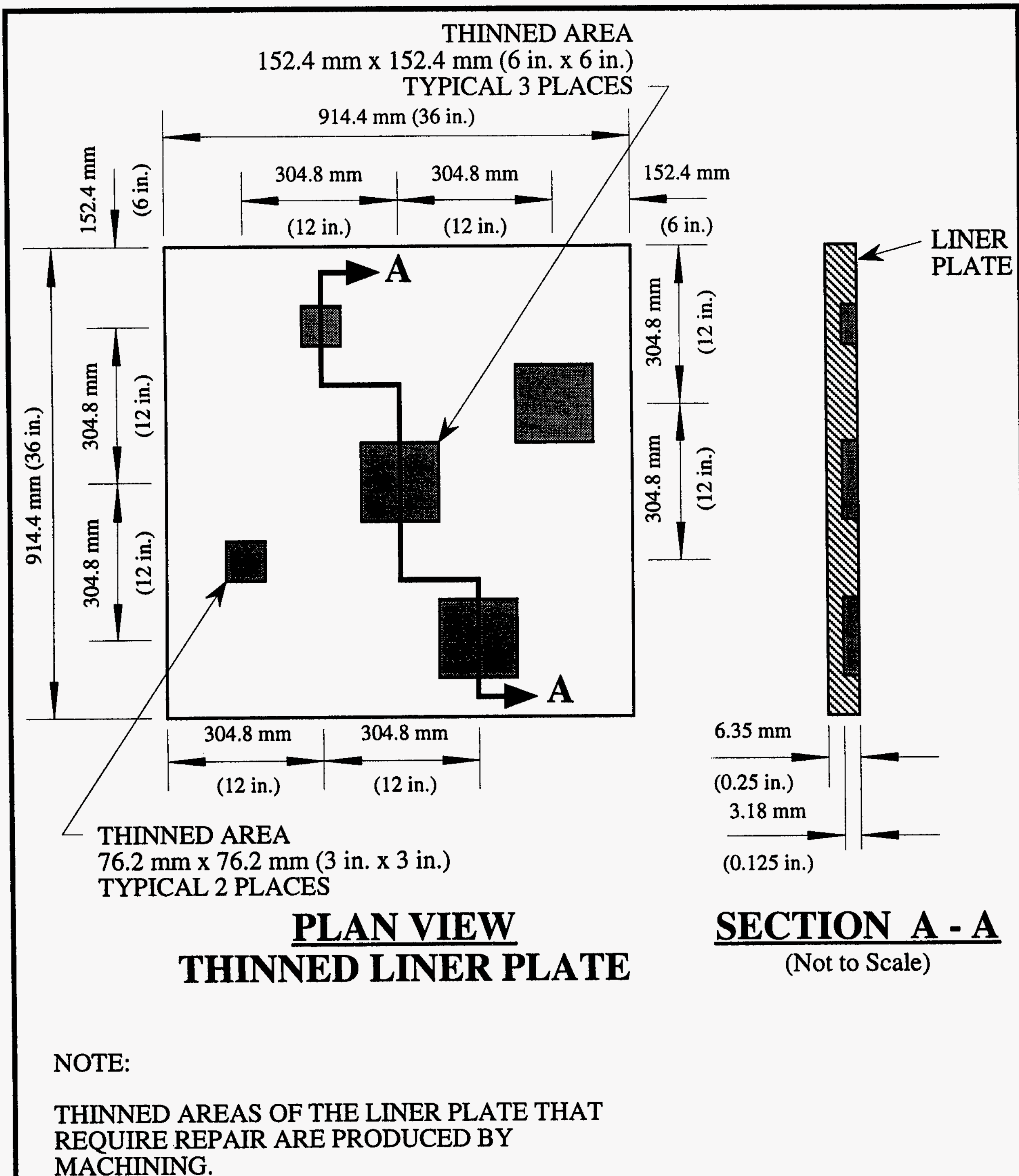
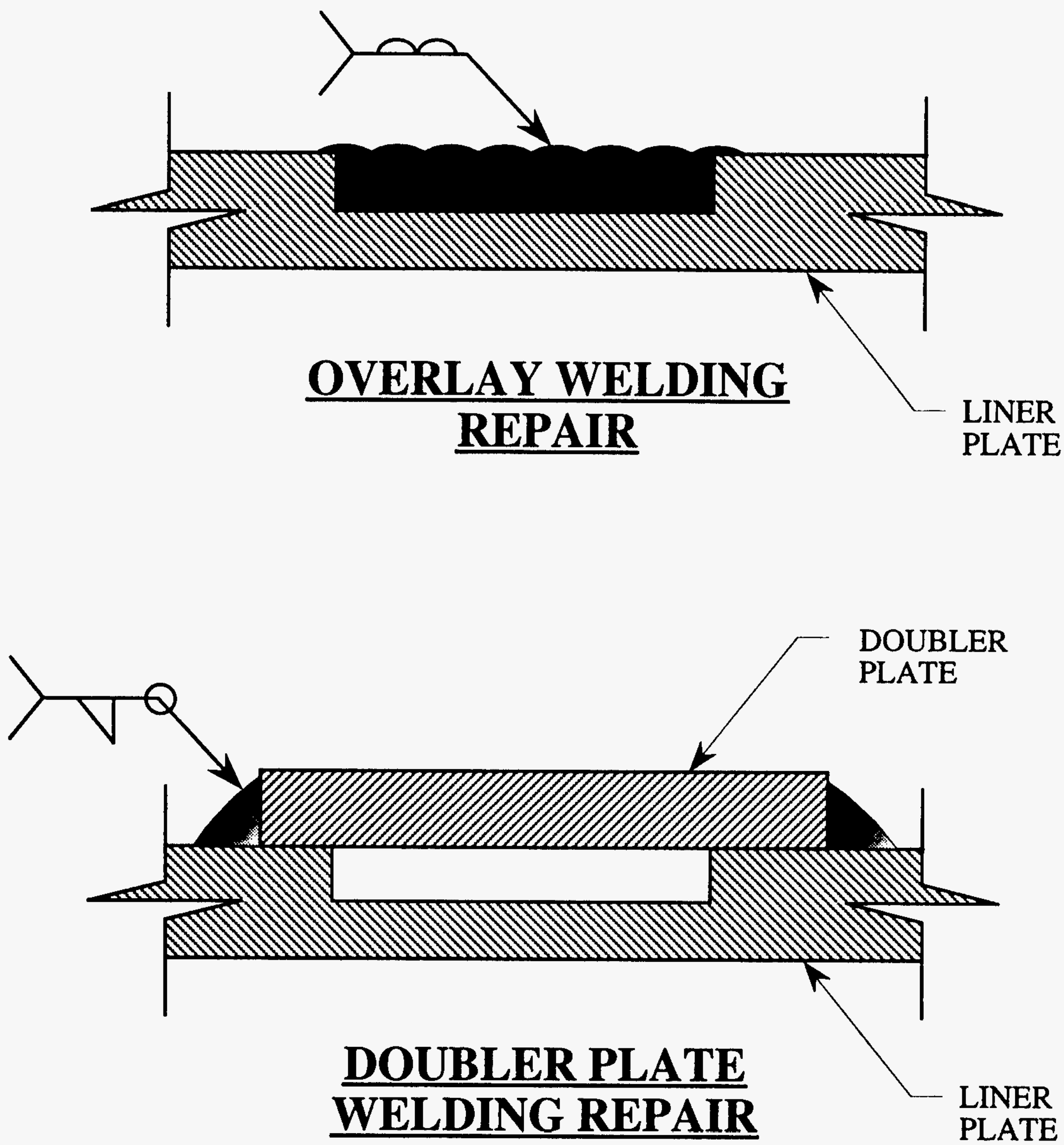


Fig. 7.3. Recommended liner plate configuration.



NOTE:

THINNED AREAS OF THE LINER PLATE THAT REQUIRE REPAIR ARE PRODUCED BY MACHINING.

Fig. 7.4. Recommended liner plate repair welding techniques.

Table 7.1 Recommended test section configurations for the liner plate welding repair experimental investigation.

Test section designation	Test section type	Repair welding technique
1	Anchor Stud	Overlay
2	Anchor Stud	Doubler Plate
3	Embedment Anchor	Overlay
4	Embedment Anchor	Doubler Plate

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10. SUPPLEMENTARY NOTES

W.E. Norris, NRC Project Manager

11. ABSTRACT *(200 words or less)*

The Nuclear Regulatory Commission has initiated a program at the Oak Ridge National Laboratory to provide assistance in their assessment of the effects of potential degradation on the structural integrity and leaktightness of metal containment vessels and steel liners of concrete containments in nuclear power plants. One of the program objectives is to identify repair practices for restoring metallic containment pressure boundary components that have been damaged or degraded in service. This report presents issues associated with inservice condition assessments and continued service evaluations and identifies the rules and requirements for the repair and replacement of nonconforming containment pressure boundary components by welding or metal removal. Discussion topics include base and welding materials, welding procedure and performance qualifications, inspection techniques, testing methods, acceptance criteria, and documentation requirements necessary for making repairs and replacements so that the plant can bereturnedd to a safe operating condition.

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