

BACKGROUND TO PROCEDURES IN SECTION XI OF THE ASME CODE FOR EVALUATION OF FLAWS IN NUCLEAR PIPING

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Summary

Section XI of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code provides requirements for maintaining pressure boundary integrity of components, piping, and equipment during the life of a nuclear power plant. Evaluation procedures and acceptance criteria for the evaluation of flaws in nuclear piping in Section XI of the ASME Code were first published in 1983. Committees under Section XI update Acceptance Standards and evaluation procedures on an ongoing basis in response to industry needs. This article provides an overview of the procedures and acceptance criteria for pipe flaw evaluation in Section XI. Both planar and nonplanar flaws are addressed by Section XI. The evaluation procedures and acceptance criteria cover failure by plastic collapse as characterized by limit load analysis, fracture due to ductile tearing prior to attainment of limit load as characterized by elastic-plastic fracture mechanics (EPFM) analysis, and brittle fracture as characterized by linear elastic fracture mechanics (LEFM) analysis. A major revision to the evaluation procedures and acceptance criteria was published in the 2002 Addenda to Section XI. Evaluation procedures and acceptance criteria in the 2001 Edition, as well as the revisions in the 2002 Addenda, are described in this article. Code Cases that address evaluation of wall thinning in piping systems, as well as temporary acceptance of flaws

in moderate energy piping systems are also described.

1. Introduction

Section XI of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code provides requirements for maintaining pressure boundary integrity of components, piping, and equipment during the life of a nuclear power plant. Pressure boundary integrity includes prevention of leakage from the reactor coolant system, as well as structural integrity in terms of prevention of rupture or burst of the pressure boundary. Section XI provides specific rules for evaluating flaw indications that may be detected during the service life of a nuclear component. Flaw evaluation procedures for austenitic piping were developed in direct response to an industry need to address pipe cracking events occurring in the mid-to-late 1970's. Specifically, the initial pipe cracking events that led to the development of flaw evaluation procedures for austenitic piping were the increasing incidents of stress corrosion cracking in Boiling Water Reactor (BWR) Class 1 piping. Flaw evaluation procedures for austenitic piping were introduced into Section XI with the Winter 1983 Addendum. Flaw evaluation procedures for ferritic piping were subsequently introduced into Section XI with the Winter 1989 Addendum. Committees under Section XI update Acceptance Standards and evaluation procedures on an ongoing basis in response to industry needs.

Both planar and nonplanar flaws are addressed by Section XI. The evaluation procedures and acceptance criteria cover failure by plastic collapse as characterized by limit load analysis, fracture due to ductile tearing prior to attainment of limit load as characterized by elastic-plastic fracture mechanics (EPFM) analysis, and brittle fracture as characterized by linear elastic fracture mechanics (LEFM) analysis. The flaw evaluation procedures include subcritical crack growth due to fatigue and stress corrosion cracking. The evaluation procedures are based on synthesis of, and validation against, experimental results.

The purpose of this article is to provide an overview of the procedures and acceptance criteria in Section XI for evaluation of in-service flaws in nuclear piping. The general approach in Section XI for pipe flaw evaluation is first described. A major revision to the evaluation procedures and acceptance criteria was published in the 2002 Addenda to Section XI. Evaluation procedures and acceptance criteria in the 2001 Edition, as well as the revisions in the 2002 Addenda, are described. The recent focus of activities in Section XI has been to address Primary Water Stress Corrosion Cracking (PWSCC) in Alloy 600 components and Alloy 82, 182 and 132 dissimilar metal welds in piping in Pressurized Water Reactor (PWR) coolant environments. A number of revisions and ongoing activities related to PWSCC in piping are described in this article. Evaluation procedures and acceptance criteria that are an alternative to those in the main body of Section XI are provided in Code Cases. Code Cases that address evaluation of wall thinning in piping systems, as well as temporary acceptance of flaws in moderate energy piping systems, are described. Finally, planned future developments in Section XI for pipe flaw evaluation are described. Changes to the pipe flaw evaluation procedures in Section XI are supported by technical basis documents, and a number of these documents are listed in the references for this article.

In the 2007 Edition to Section XI, the phrase “safety factor” was replaced with the phrase “structural factor” to maintain consistency with the same revision made to other Sections of the ASME Code. The phrase “structural factor” is used in this article, and should be considered synonymous with “safety factor” in Editions and Addenda prior to the 2007 Edition.

2. Overview of ASME Section XI for Pipe Flaw Evaluation

2.1. Flaw Evaluation Process

The steps that are generally followed in an in-service flaw evaluation are as follows. Additional details are provided later in this article.

- (a) The piping item is examined. The scope and extent of the examination, including the inspection method to be used (i.e., volumetric, surface, or visual) are defined in IWB-2500, IWC-2500 and IWD-2500 of Section XI for Class 1, 2 and 3 piping items, respectively. When an inspection signal exceeds the detection threshold limit from calibration, the flaw indication is reportable.
- (b) When no reportable flaw indications are found, the piping item is acceptable with no need for further evaluation.
- (c) When a reportable flaw indication is found, the flaw geometry is determined from the in-service inspection results in accordance with IWA-3300 of Section XI. Flaw dimensions must be determined by the size of a rectangle or square that fully contains the area of the flaw. The length, ℓ , of the rectangle or one side of the square is parallel to the inside pressure retaining surface of the component. The depth of the rectangle or one side of the square is normal to the inside pressure retaining surface of the component, and is denoted as a for a surface flaw and $2a$ for a subsurface flaw. Characterization of dimensions of surface planar flaws is illustrated in Figure 1, and of subsurface planar flaws in Figure 2.
- (d) Multiple flaws in close proximity are combined in accordance with the requirements of IWA-3330 of Section XI.
- (e) The flaw dimensions are compared with the allowable flaw dimensions in the Section XI Acceptance Standards.
- (f) When the flaw size is less than the allowable flaw size in the Acceptance Standards, the flaw is acceptable with no need for further evaluation.
- (g) When the flaw size exceeds the allowable flaw size in the Acceptance Standards, one of the following actions must be followed:
 - (i) The flaw may be evaluated using analytical procedures that are provided in Section XI, and are described in this article. The flaw must then be re-inspected prior to the end of the evaluation period.
 - (ii) The piping item may be repaired or replaced.

Procedures and acceptance criteria that are an alternative to those in the main body of Section XI are provided in Code Cases. Code Cases generally reflect improvements to technology or a response to an immediate industry need. The contents of Code Cases are generally incorporated into the main body of the Code at a later date.

FIG. IWA-3310-1 SURFACE PLANAR FLAWS ORIENTED IN PLANE NORMAL TO PRESSURE RETAINING SURFACE
 Illustrative Flaw Configurations and Determination of Dimensions a and ℓ
 ($\frac{1}{2}$ in. = 13 mm)

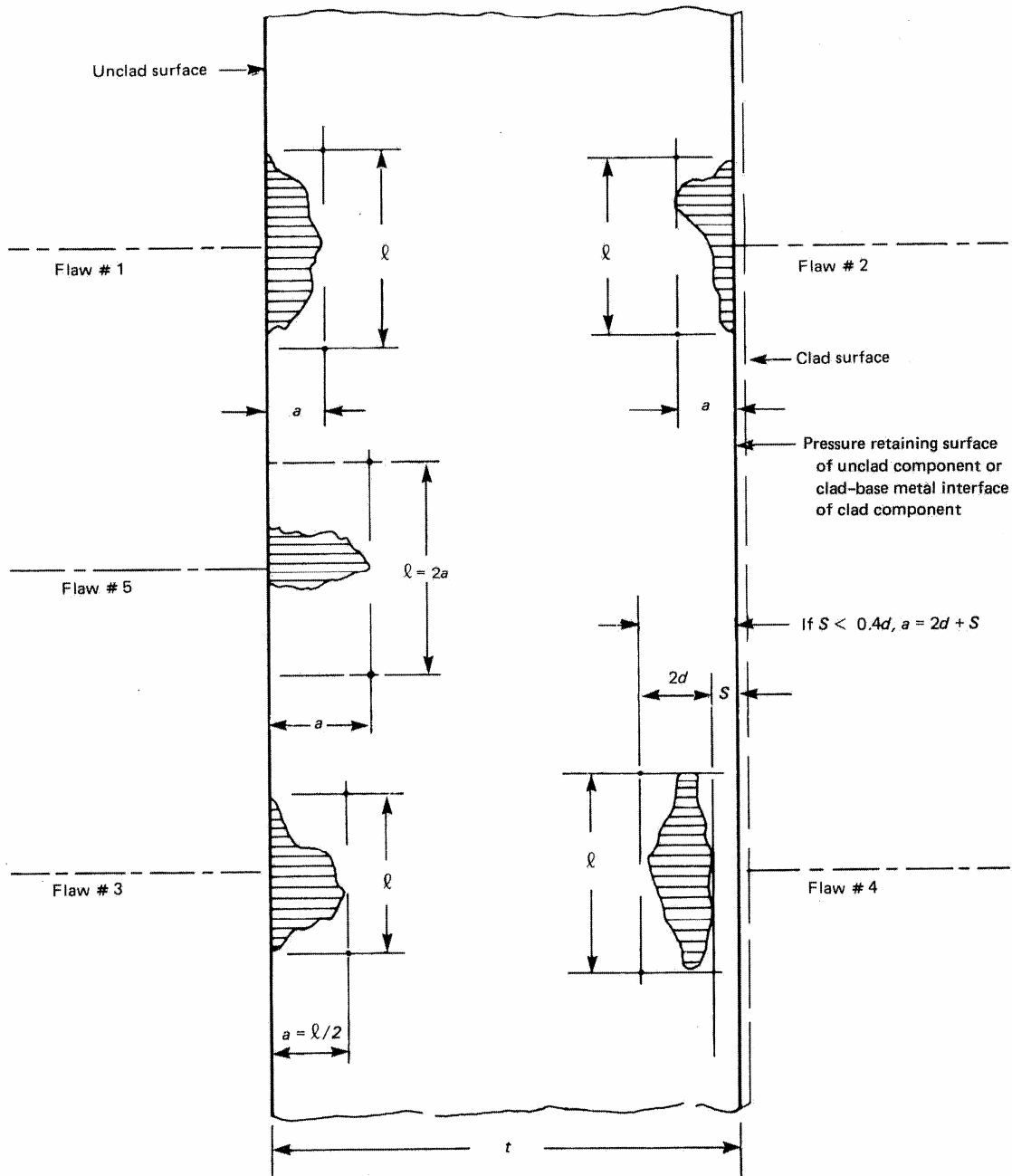


Figure 1. Illustration of Characterization of Dimensions of Surface Planar Flaws in Section XI of ASME Code (Figure IWA-3310-1 of ASME Section XI)
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FIG. IWA-3320-1 SUBSURFACE PLANAR FLAWS ORIENTED IN PLANE NORMAL TO PRESSURE RETAINING SURFACE
 Illustrative Flaw Configurations and Determination of Dimensions $2a$ and ℓ Where S Is $\geq 0.4a$
 (1 in. = 25 mm)

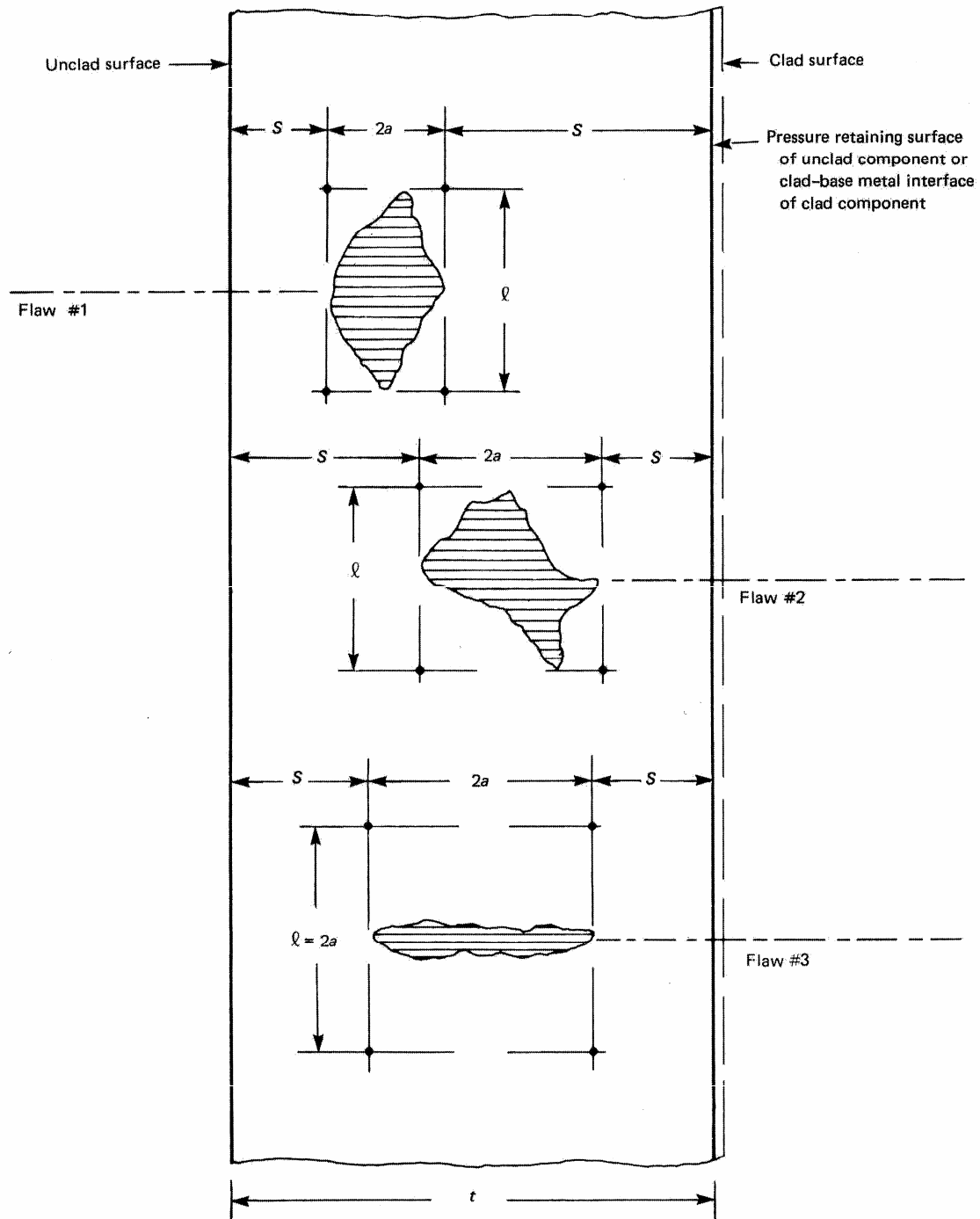


Figure 2. Illustration of Characterization of Dimensions of Subsurface Planar Flaws in Section XI of ASME Code (Figure IWA-3320-1 of ASME Section XI)
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2.2. Approach for Analytical Evaluation of a Flaw in a Piping Item

The analytical evaluation procedures and acceptance criteria are currently applicable to nominal pipe sizes DN 100 (NPS 4 in.) or greater. The analytical procedures are generally applicable to straight pipe and portions of pipes and fittings within a distance of $(R_o t)^{1/2}$ of the weld centerline, where R_o is the pipe outside radius and t is the pipe wall thickness. This restriction is to limit the evaluation primarily to weldment areas of pipe and fittings where stresses determined by traditional piping stress analysis methods and Code procedures are most applicable. The following is the general approach in Section XI for the analytical evaluation of a flaw in a piping item.

(a) The flaw geometry from the in-service inspection results is idealized for the purpose of the analytical evaluation. The actual flaw is resolved into circumferential and axial components. The geometry of a circumferential planar flaw in a pipe is illustrated in Figure 3, and of an axial planar flaw in Figure 4.

(b) The stresses normal to the flaw at the flaw location for ASME Service Level A, B, C, and D Loadings are determined.

(c) Pipe material properties are determined.

(d) A flaw growth analysis is performed to establish the end-of-the-evaluation-period flaw dimensions. For planar flaws, flaw growth due to fatigue and stress corrosion cracking is determined as appropriate. Flaw growth can result in a change to the flaw depth divided by flaw length aspect ratio. Flaws in close proximity may need to be combined after predicted flaw growth. Except as noted later in this article, planar flaws with depth greater than 75% of the wall thickness are unacceptable. For nonplanar flaws, the end-of-the-evaluation-period minimum remaining wall thickness is determined.

(e) The allowable flaw size or allowable applied stress levels are determined.

(f) The flaw is evaluated against the acceptance criteria using the end-of-the-evaluation-period flaw dimensions.

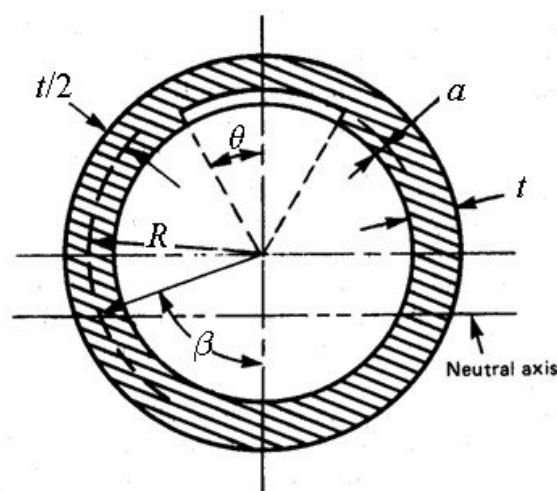


Figure 3. Circumferential Part-Through-Wall Planar Flaw

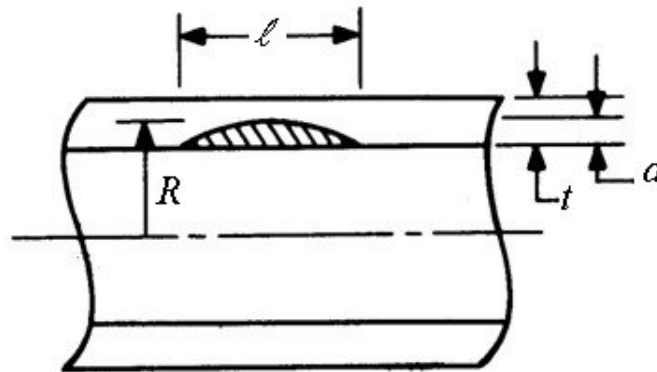


Figure 4. Axial Part-Through-Wall Planar Flaw

2.3. Piping Classes and Service Levels

Construction rules for classifying piping systems and components as Class 1, 2 or 3 are in NCA-2000 of Section III of the ASME Code. In the United States, the actual system classification process is defined by the U.S. Nuclear Regulatory Commission in 10 CFR 50.55a in the Federal Register and as described in Regulatory Guide 1.26. The ASME Code Class 1 construction rules are applicable to primary pressure boundary systems and components out to the second isolation valve to ensure the pressure boundary integrity of the components containing the nuclear fuel. In general, ASME Code Class 2 construction rules are applicable to systems and components designed for reactor shutdown, reactor residual heat removal, emergency core cooling and post-accident containment heat removal. ASME Code Class 3 construction rules are typically applicable to secondary cooling systems providing coolant to the reactor residual heat removal, emergency core cooling and post-accident containment heat removal systems.

Service loadings are classified in NCA-2000 of Section III of the ASME Code as Service Levels A, B, C and D. Service Level A Loadings are also referred to as Normal Operating, and are those that the piping item is subjected to during the normal service function. An example of a Service Level A Loading is normal Cooldown. Service Level B Loadings are also referred to as Upset, and are those that the piping item can be subjected to without damage requiring repair. Examples of a Service Level B Loading are a Turbine Trip or an Operating Basis Earthquake. Service Level C Loadings are also referred to as Emergency. When a piping item is subjected to Service Level C Loadings, there may be permanent localized deformation requiring inspection and possibly repair. Service Level C Loadings are typically system transients and postulated accidents that are anticipated to occur very infrequently. Service Level D Loadings are also referred to as Faulted. When a piping item is subjected to Service Level D Loadings, there may be permanent gross deformation requiring inspection and possibly repair. An example of a Service Level D Loading is a Safe Shutdown Earthquake.

2.4. Materials

The flaw evaluation procedures cover the following nuclear grade austenitic piping

materials: SA-312 TP304, SA-312 TP304L, SA-312 TP304N, SA-312 TP316L, SA-312 TP316LN, SA-376 TP316, SA-376 TP316N, SA-451 CF8M, as well as other similar austenitic piping materials and welds. The flaw evaluation procedures also cover the following nuclear grade ferritic piping materials: SA-333 Gr. 1, SA-106 Gr. B, SA-106 Gr. C, SA-105, as well as other similar ferritic piping materials and welds.

2.5. Loads and Stresses

Stresses resulting from primary and secondary loads, as well as residual stresses, are used in various combinations in the flaw evaluation procedures. Stresses acting normal to the flaw are used in the flaw evaluation.

For a circumferential flaw, longitudinal stresses are used. The longitudinal primary membrane stress, σ_m , longitudinal primary bending stress, σ_b , and longitudinal secondary bending stress, σ_e , are the gross nominal stresses acting over the entire cross-section of the pipe.

The longitudinal primary membrane and bending stresses are illustrated for a pipe of outside diameter D in Figure 5. The longitudinal primary membrane stress is calculated from internal pressure and other axial loads on the pipe. For an axial flaw, hoop stress is used, which is mainly due to internal pressure loading.

The stresses that are used in the flaw evaluation are the local nominal stresses as calculated in the absence of the flaw. These stresses do not contain any stress multipliers, such as stress indices or stress intensification factors. The fracture mechanics methods are based on fracture models that are used in conjunction with the local nominal stresses at the flaw location.

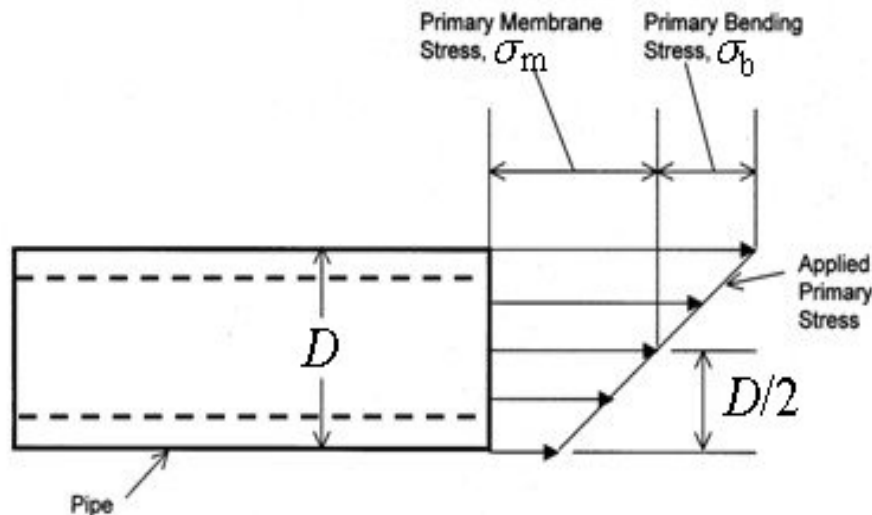


Figure 5. Illustration of Applied Longitudinal Primary Membrane and Bending Stresses. (Code Case N-513-3)

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ferritic steel piping in nuclear power plants].

Biographical Sketch

Douglas A. Scarth, Education: received a Ph.D. in Materials Science from the University of Manchester in 2002. He is with Kinectrics, Inc., Toronto, Ontario, Canada, as Technical Director - Fracture Programs. Dr. Scarth performed structural integrity evaluations of nuclear and fossil plant components containing flaws. He is involved in development of improved methodologies for evaluating flaws. He participated in development of engineering codes and standards for fitness for service assessments of plant components, including activities of *Canadian Standards Association*, and Section XI of the ASME Boiler and Pressure Vessel Code. Also he is a participant in the ASME Pressure Vessels and Piping Division.