Materials Reliability Program: Supplement 9 Draft—Qualification Requirements for Cast Stainless Steel Piping Welds (MRP-424)

2017 TECHNICAL REPORT

Materials Reliability Program: Supplement 9 Draft—Qualification Requirements for Cast Stainless Steel Piping Welds (MRP-424)

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ABSTRACT

This report includes a draft of the examination requirements for cast stainless steel piping welds. These requirements were developed with the objective of providing a framework from which the final version of ASME Section XI Appendix VIII Supplement 9 can be drafted. The U.S. Nuclear Regulatory Commission (NRC) recently affirmed that Supplement 9 needs to be adopted by January 1, 2022.

Keywords

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PRIMARY AUDIENCE: Nondestructive evaluation (NDE) practitioners and researchers

SECONDARY AUDIENCE: Code committees

KEY RESEARCH QUESTION

The U.S. Nuclear Regulatory Commission (NRC) affirmed in July 2017 the use of ASME Section XI Appendix VIII qualifications to meet the volumetric inspection requirements in cast stainless steel butt welded materials. Further, the NRC stated that these requirements are to be adopted by January 1, 2022. To meet these requirements, the industry has agreed to develop Supplement 9 to the ASME Boiler and Pressure Vessel Code Section XI Appendix VIII, and the NRC stated that it understands that the industry is committed to the development of this supplement.

RESEARCH OVERVIEW

This report describes a draft of the examination requirements for cast stainless steel piping welds. These requirements were developed to provide a framework from which the final version of ASME Section XI Appendix VIII Supplement 9 can be drafted.

In developing the requirements, technical input from Appendix VIII Supplement 2 and Supplement 10, engineering studies of flaw tolerance of piping welds fabricated with cast stainless steel, and results from cast stainless steel evaluations performed under blind protocol were used.

KEY FINDINGS

- The demonstration flaw depth distribution requirements take into account the engineering studies performed on cast stainless steel flaw tolerance.
- The detection test acceptance criterion incorporates the flaw grading units methodology used in other Appendix VIII supplements.
- The length sizing test acceptance criterion selected is likely to be acceptable from a structural point of view and was met by most of the evaluation's participating candidates.
- The depth sizing test acceptance criterion selected was not met by the evaluation's participating candidates, yet the candidates exhibited a reduced error gap compared to the criterion used in other Appendix VIII supplements.

WHY THIS MATTERS

The nuclear industry has been challenged to develop Section XI Appendix VIII qualifications for volumetric examination of cast stainless steel piping welds; these requirements need to be adopted by 2022. Because the technology for ultrasonic examination of cast stainless steel material is still under development, the convergence of the requirements with what can be achieved in practice in plant examinations is a work in progress that will involve the efforts of all the stakeholders.

HOW TO APPLY RESULTS

This work provides the framework from which the final version of Appendix VIII Supplement 9 can be developed.

LEARNING AND ENGAGEMENT OPPORTUNITIES

Stakeholders are expected to engage using the information provided in this report to develop the final version of Supplement 9.

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PROGRAM: Materials Reliability Program, P41.01.04

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UNIT CONVERSIONS

1 inch = 2.54 centimeters

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1
INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) affirmed in July 2017 the use of ASME Section XI Appendix VIII qualifications to meet the volumetric inspection requirements in cast stainless steel butt welded materials. Further, the NRC stated that these requirements are to be adopted by January 1, 2022 [1].

To meet these requirements, the industry has agreed to develop Supplement 9 to the ASME Boiler and Pressure Vessel Code Section XI Appendix VIII, and the NRC stated that it understands that the industry is committed to the development of this supplement [1].

This report provides a draft of Supplement 9 that can be used as a basis to meet the requirement set for 2022.

2 TECHNICAL INPUT

In drafting Supplement 9 Draft, the following documents were used as technical input:

- NUREG/CR-4464, Performance Demonstration Tests for Detection of Intergranular Stress Corrosion Cracking [2]
- ASME Section XI Appendix VIII Supplement 2 [3]
- ASME Section XI Appendix VIII Supplement 10 [3]
- EPRI Report 3002007383, *Technical Basis for ASME Code Case N-838: Flaw Tolerance Evaluation* (MRP-362, Rev. 1) [4]
- EPRI Report 1025217, *Cast Austenitic Stainless Steel Study Annual Report* [5]
- EPRI Report 3002010314, *Cast Austenitic Steel Round-Robin Study* [6]
- Statistical method to justify the demonstration flaw depth distribution allocation

In the next sections, the use of these documents in the draft is explained.

2.1 Use of Supplements 2 and 10

Supplement 9 Draft uses the same methodology implemented in Supplements 2 and 10 [3]. Specifically, the Supplement 9 Draft document structure mirrors that of Supplement 10: the paragraph numbers that reference the requirements are the same, and the technical justifications are embedded in the requirement sections as “Rationale.”

2.2 Detection Test and NUREG/CR-4464

Supplement 9 Draft adopted the Detection Test Grading Units methodology described in NUREG/CR-4464 [2], also used in Supplements 2 and 10. Details of this methodology are presented in Appendix A for reference.

From the adoption of the grading units methodology, the personnel performance demonstration test acceptance criteria (listed in Section 3, Table 3-2) are derived.

2.3 Flaw Distribution Requirements and MRP-362

Supplement 9 Draft uses a demonstration flaw depth distribution allocation that is a variant of that used in Supplement 10 while incorporating the flaw tolerance evaluation results included in MRP-362, as shown in Section 3.2.4.

Supplement 9 Draft uses the flaw tolerance evaluation results described in MRP-362 [4] in two ways:

1. In establishing the demonstration flaw distribution requirements, only flaws with depths greater than 25% are to be used. This minimum flaw depth requirement has its basis in the flaw tolerance acceptance tables listed in MRP-362.
2. The personnel demonstration test acceptance criteria include a requirement that all flaws with depths greater than 75% must be detected. This deep flaw detection requirement, again, has its basis in the flaw tolerance acceptance tables that require that flaws with depths greater than 75% must be repaired irrespective of the pipe geometry and load condition.

In adopting the flaw depth distribution allocation, the draft has addressed the issue that no examiner should pass the test while missing all the flaws in one of the distribution bins. Appendix E details the statistical method that provides the basis to assert this conclusion.

2.4 Sizing Tests and Examination Evaluation Reports

Supplement 9 Draft references the cast austenitic stainless steel (CASS) examination evaluation reports C*ast Austenitic Stainless Steel Study Annual Report* [5] and *Cast Austenitic Steel Round-Robin Study* [6] to compare the length sizing and depth sizing requirements with the performance exhibited by the participating candidates.

In setting the length sizing criterion to limit the measurement root-mean-square (RMS) error not to exceed 1 inch, the draft recognized the following:

- The requirement is likely to be acceptable from a structural integrity point of view because the error represents a relatively small fraction (less than 3%) of the circumference of the pipe sizes of interest and is a relatively small (0.25-inch) increase above the RMS error of 0.75 inch currently used in Supplements 2 and 10.
- Most of the participating candidates in the evaluations met the requirement.

For Supplement 9, the depth sizing acceptance criterion is a normalized RMS error not to exceed 0.1 (that is, 10% of the wall thickness at the flaw location). The normalized RMS error acceptance criterion and the absolute RMS error used in Supplements 2 and 10 were not met by any of the participating candidates in the EPRI CASS round robin.

In setting the depth sizing requirement to limit the measurement normalized RMS error (defined as the RMS of the measurement errors each divided by the wall thickness at the measurement location) not to exceed 10%, when analyzing the round-robin results, the draft recognized the following [6]:

- The normalized RMS error acceptance criterion and the absolute RMS error used in Supplements 2 and 10 were not met by any of the participating candidates in the EPRI CASS round robin:
  - The candidates’ normalized RMS depth sizing error of 23% did not meet the acceptance criterion of 10% proposed in Supplement 9 Draft, on average by a factor of 2 (see Appendix D).

  - The candidates' absolute RMS depth sizing error of 0.47 inch did not meet the acceptance criterion of 0.125 inch used in Supplements 2 and 10 of ASME Section XI Appendix VIII, on average by a factor of 4 (see Appendix D).
- These results indicate that a large gap exists between the requirement and the depth sizing capability exhibited by the participating candidates.
- The large gap suggests that an alternative depth sizing test requirement may have to be considered, one that provides a more realistic measure of examination capability. Two such alternatives are as follows:
  - A requirement that de-emphasizes depth sizing while using mostly length sizing to demonstrate structural integrity.
  - A requirement that would include biasing of the reported flaw depth to a higher value prior to evaluating the flaw for continued service or correction through repair or mitigation. This approach has precedent in relief requests that have been approved by NRC for ultrasonic testing (UT) depth sizing from the inside of pressurized water reactor (PWR) non-CASS piping welds.
- The normalized RMS depth sizing error to establish the depth sizing acceptance criterion was preferred over the absolute RMS error for three reasons:
  - From the viewpoint of structural integrity, the flaw depth relative to specimen wall thickness is more relevant than its absolute depth.
  - It exhibited a reduced error gap as a percent of the candidates' average performance.
  - By normalizing the error using the wall thickness, the absolute depth sizing error dependence on the specimen wall thickness is reduced.
- The depth sizing error gap was identified to be in large part the result of undersizing:
  - The flaw depth estimation error was found to increase with flaw depth, but this increase was mostly the result of a bias toward undersizing flaws rather than an increase in scatter for the depth sizing results. Vice versa, depth sizing accuracy was found to be better in thinner materials.
  - The differences in the candidates' normalized RMS error were mainly caused by differences in their undersizing bias, which suggests that the bias was affected by the depth sizing technique applied by each candidate.
  - Proximity to geometry, material microstructure, and flaw fabrication had little effect on the depth sizing results.

3
SUPPLEMENT 9 DRAFT

This section provides a draft of the examination requirements for cast stainless steel piping welds. These requirements were developed to provide a framework from which the final version of ASME Section XI Appendix VIII Supplement 9 can be drafted.

3.1.0 Scope

Supplement 9 is applicable to cast stainless steel piping welds examined from either the inside or outside surface. Supplement 9 is not applicable to piping welds containing supplemental corrosion-resistant cladding (CRC) applied to mitigate stress corrosion cracking (SCC).

3.2.0 Specimen Requirements

Qualification test specimens shall meet the requirements listed herein, unless a set of specimens is designed to accommodate specific limitations stated in the scope of the examination procedure (e.g., pipe size, weld joint configuration, access limitations). The same specimens may be used to demonstrate both detection and sizing qualification.

3.2.1 General

The specimen set shall conform to the following requirements:

(a) The minimum number of flaws in a specimen set shall be 10.

(b) Specimens shall have sufficient volume to minimize spurious reflections that may interfere with the interpretation process.

(c) The specimen set shall include the minimum and maximum pipe diameters and thickness for which the examination procedure is applicable. Pipe diameters within a range of ½ inch (13 mm) of the nominal diameter shall be considered equivalent. Pipe diameters larger than 24 inches (600 mm) shall be considered flat. When a range of thicknesses is to be examined, a thickness tolerance of ±25% is acceptable.

(d) The specimen set shall include examples of the following fabrication conditions:

1. Geometric conditions that normally require discrimination from flaws (e.g., counterbore or weld root conditions).
2. Typical limited scanning surface conditions shall be included as follows:
   i. For outside surface examinations, weld crowns and single-side access due to nozzle, and safe end external tapers.
   ii. For inside surface examinations, internal tapers, counterbores, and exposed weld roots.

(e) Qualification requirements shall be satisfied separately for outside surface and inside surface examinations.

Rationale: These General requirements have been used and found effective in other supplements to bound the applicability of the demonstration [2, 3, 7].

3.2.2 Flaw Location

At least 80% of the flaws shall be contained wholly in the weld material.

Rationale: For CASS, the weldments exhibit less toughness than the parent base material and are therefore more susceptible to cracking if cracking were to occur.

3.2.3 Flaw Type

(a) At least 60% of the flaws shall be cracks, and the remainder shall be alternative flaws. Specimens with in-service induced cracks shall be used when available. The alternative flaws shall meet the following requirements:

1. Alternative flaws shall provide crack-like reflective characteristics.
2. Flaws shall have a tip width of no more than 0.002 inch (0.05 mm).

(b) At least 50% of the flaws shall be in close proximity with the areas described in 3.2.1 (d).

Rationale: Alternative flaws may be used to simulate potential cracking damage as long as the listed requirements are met. These flaw fabrication requirements are consistent with those developed in the PISC II parametric studies to simulate the tip response in fatigue cracks.

3.2.4 Flaw Depth Distribution

All flaw depths shall be greater than 25% of the nominal pipe wall thickness. Flaw depths in the specimen shall be distributed as shown in Table 3-1.

Table 3-1
Flaw Depth Distribution Requirements

Flaw Depth % Wall Thickness	Minimum % of Flaws
25–50%	20%
51–75%	20%
76–100%	20%

At least 75% of the flaws shall be in the range of 25–75% of wall thickness.

Rationale: For Supplement 9, the bin depth size distribution follows the same methodology that was used for Supplement 10: once a minimum flaw depth and the number of bins are specified, the bin depth ranges are calculated so that the depth ranges are equally spaced out. Since Supplement 10 specifies three bins with the minimum number of flaws of 20% for each bin and that at least 75% shall be in the range of the first two bins, this precedent is used to justify the bin selection and flaw distribution for Supplement 9. The guidance is intentionally flexible to ensure that test “blindness” is maintained. Further, in the published flaw acceptance criteria tables for CASS, the critical flaw depth value of 25% of wall thickness bounds all the values of interest [4]. Appendix E discusses the statistical methodology used to justify the bin flaw number allocation.

3.2.5 Flaw Orientation

(a) For detection test specimen sets, at least 1 and a maximum of 10% of the flaws, rounded to the next higher whole number, shall be oriented axially. The remainder of the flaws shall be oriented circumferentially.

(b) For length sizing test specimen sets, all flaws shall be oriented circumferentially.

(c) For depth sizing test specimen sets, all flaws shall be oriented as in 3.2.5 (a).

Rationale: Test requirements listed in 3.2.5 (a), (b), and (c) are consistent with those of other supplements.

3.3.0 Performance Demonstration

Personnel and procedure performance tests shall be conducted according to the following requirements:

(a) For qualifications from the outside surface, the specimen inside surface and specimen identification shall be concealed from the candidate. When qualifications are performed from the inside surface, flaw location and specimen identification shall be obscured to maintain a “blind test.” All examinations shall be completed prior to grading the results and presenting them to the candidate. Divulgement of specimen results or candidate viewing of unmasked specimens after the performance demonstration is prohibited.

3.3.1 Detection Test

(a) The specimen set shall include detection specimens that meet the following requirements:

1. Specimens shall be divided into grading units.
    - i. Each grading unit shall include at least 3 inches (75 mm) of weld length.
    - ii. The end of each flaw shall be separated from an unflawed grading unit by at least 1 inch (25 mm of unflawed material. A flaw may be less than 3 inches (75 mm) in length.
    - iii. The segment of weld length used in one grading unit shall not be used in another grading unit.
    - iv. Grading units need not be uniformly spaced around the pipe specimen.

Rationale: The grading unit methodology described in 3.3.1 (a) 1) is consistent with other supplements and applies also to Supplement 9 because the basis is independent of material properties. The grading unit technical basis is included in Appendix A for completeness.

2. Personnel performance demonstration detection test sets shall be selected from Table 3-2. The number of unflawed grading units shall be at least 1½ times the number of flawed grading units.

3. Flawed and unflawed grading units shall be randomly mixed.

Table 3-2
Personnel Performance Demonstration Detection Test Acceptance Criteria

Detection Test Acceptance Criteria		False Call Test Acceptance Criteria	
No. of Flawed Grading Units	**Minimum Detection Criteria**	**No. of Unflawed Grading Units**	**Maximum No. of False Calls**
10	8	15	2
11	9	17	3
12	9	18	3
13	10	20	3
14	10	21	3
15	11	23	3
16	12	24	4
17	12	26	4
18	13	27	4
19	13	29	4
20	14	30	5

(b) Examination equipment and personnel are qualified for detection when

1. Personnel performance demonstrations satisfy the acceptance criteria of Table 3-2 for both detection and false calls.
2. Personnel demonstrated detection of all flaws with depths greater than 75%.

Rationale: The technical basis for Table 3-2 is included in Appendix A. This pass/fail criterion table is consistent with that of other supplements and also applies to Supplement 9 because the Appendix A derivations are independent of material properties. Supplement 9 includes the additional condition that flaws with depths greater than 75% need to be detected. This condition is based on the requirement in ASME Section XI that flaws in piping with depths greater than 75% are not acceptable for service irrespective of the flaw length and the pipe's loading condition. This requirement provides a minimum margin against pressure boundary leakage regardless of the structural margin against unstable pressure boundary rupture. Information collected to establish current personnel detection and false call examination capability is provided in Appendix B.

3.3.2 Length Sizing Test

(a) Each reported circumferential flaw in the detection test shall be length sized.

(b) When the length sizing test is conducted in conjunction with the detection test, and fewer than 10 flaws are detected, additional specimens shall be provided to the candidate such that at least 10 flaws are sized. The regions of each specimen containing a flaw to be sized may be identified to the candidate. The candidate shall determine the length of the flaw in each region.

(c) For a separate length sizing test, the regions of each specimen containing a flaw to be sized may be identified to the candidate. The candidate shall determine the length of the flaw in each region.

(d) Examination procedures, equipment, and personnel are qualified for length sizing when the RMS error of the flaw length measurements, compared to the true flaw lengths, does not exceed 1.00 inch (25 mm).

Rationale: Test requirements listed in 3.3.2 (a), (b), and (c) are consistent with those of other supplements. Axial cracks are excluded from the test because axial cracks are likely to be constrained by the weldment and their size limited to the weldment extent. Because of the lack of variability in the probable axial crack length, a pass criterion that includes axial cracks would not be meaningful. The technical basis for the pass/fail criterion listed in 3.3.2 (d) is described in Appendix C.

3.3.3 Depth Sizing Test

(a) Each reported flaw in the detection test shall be depth sized.

(b) The depth sizing test may be conducted separately or in conjunction with the detection test. For a separate depth sizing test, the regions of each specimen containing a flaw to be sized may be identified to the candidate. The candidate shall determine the maximum depth of the flaw in each region.

(c) When the depth sizing test is conducted in conjunction with the detection test, and fewer than 10 flaws are detected, additional specimens shall be provided to the candidate such that at least 10 flaws are sized. The regions of each specimen containing a flaw to be sized may be identified to the candidate. The candidate shall determine the maximum depth of the flaw in each region.

(d) Examination procedures, equipment, and personnel are qualified for depth sizing when the RMS error of the flaw depth measurements compared to the true flaw depths, divided by the wall thickness at the flaw location, do not exceed 0.10 (10%).

Rationale: Analysis of the EPRI round-robin data indicated that the depth sizing error and its dependence on the specimen wall thickness is reduced when normalizing the measurements by the wall thickness at the flaw location, as compared to the absolute depth sizing error used in Supplements 2 and 10. To date, no procedure has successfully satisfied this normalized error criterion of 10% of the wall thickness or the absolute error criterion of 0.125 inch (3 mm) of Supplements 2 and 10. Information collected to determine the current depth sizing examination capability for inspections conducted from the outside diameter surface is provided in Appendix D.

3.4.0 Procedure Qualification

Procedure qualification shall include the following requirements:

(a) The specimen set shall include the equivalent of at least three personnel performance demonstration test sets. Successful personnel performance demonstrations may be combined to satisfy these requirements.

(b) Detectability of all flaws in the procedure qualification test set that are within the scope of the procedure shall be demonstrated. Length and depth sizing shall meet the requirements of 3.3.2 and 3.3.3.

(c) At least one successful personnel performance demonstration shall be performed.

(d) To qualify new values of essential variables, at least one personnel performance demonstration set is required. The acceptance test criteria of 3.4.0 (b) shall be met.

Rationale: Stringent procedure demonstration is required, consistent with other supplements. The procedure must demonstrate that all the flaws in the test set can be detected. Otherwise, if a flaw is not detectable, it may detrimentally affect the personnel pass rates.

4
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A
DETECTION TEST GRADING UNITS TECHNICAL BASIS

For Supplement 9, the same methodology is used as was applied when formulating the Detection Test Grading Units technical basis for intergranular stress corrosion cracking (IGSCC) in austenitic piping welds implemented in other supplements [3]. In this latter case, use was made of binomial statistics as described in detail in NUREG/CR-4464 [2]. In accordance with this methodology, the primary objective of an inspector is to correctly identify cracked and blank grading units. A *blank* grading unit is interchangeably referred to as an *unflawed* grading unit. A *cracked* grading unit is considered a unit of material that contains a flaw, and a *blank* grading unit does not contain a flaw.

For Supplement 9, then, the ability for an examiner to distinguish between cracked and blank grading units is characterized by their probability of detection (POD) and probability of false call (FCP), respectively. An examiner's POD is determined based on their amount of hits (that is, identifying a crack in a cracked grading unit) and misses (that is, not identifying a crack in a cracked grading unit). An examiner's FCP is determined on their number of false calls (that is, saying that a blank grading unit contains a crack). Therefore, the detection qualification exam contains a subset of two independent tests to determine if the examiner's FCP and POD are likely to meet or surpass a given criterion. The following two tests are given simultaneously during the detection qualification exam:

- Detection test, which estimates if an examiner's POD is above a set threshold based on their number of hits and misses relative to the number of cracked grading units.
- False call test, which estimates if an examiner's FCP is below a set threshold based on their number of false calls relative to the number of blank grading units.

Based on the nature of the detection qualification exam, both the detection and false call tests are given simultaneously, with cracked and blank grading units randomly distributed throughout the test pieces. Thus, for Supplement 9, examiners are assessed on their ability to correctly characterize a grading unit as flawed or blank.

This methodology recognizes that no practical test can guarantee an examiner's proficiency. Therefore, examiners with lower than desired performance could pass the exam, and examiners with acceptable performance could fail.

Using NUREG/CR-4464 [2] as a guideline, the performance of an examiner is described using power curves. The power curves relate the probability of passing the false call and detection tests as shown in Eq. A-1 and Eq. A-2, respectively:

$$\boldsymbol{P_{FC}(FCP) = \sum_{K=0}^{C_0} \binom{N}{K} FCP^K (1 - FCP)^{N-K}} \qquad \textbf{Eq. A-1}$$

$$P_{DET}(POD) = \sum_{K=C_1}^{M} \binom{M}{K} POD^{K}(1 - POD)^{M-K} \qquad \text{Eq. A-2}$$

Where:

N = total # of blank grading units inspected

M = total # of cracked grading units inspected

C_0 = maximum number of false calls allowed

C_1 = minimum number of required detections

Eq. A-1 describes the probability of passing the false call test (P_{FC}) given a FCP, and Eq. A-2 describes the probability of passing the detection test (P_{DET}) given a POD. As seen in both Eq. A-1 and Eq. A-2, it is necessary to define variables N, M, C_0, and C_1 because they essentially define the rigor of a particular test set.

The criteria for the false call and detection tests, in terms of the variables from Eq. A-1 and Eq. A-2, will be denoted as follows:

- Detection criteria: C_1/M - POD. For example, an 8/10 - POD represents a detection test where at least 8 of the 10 cracked units must be hits.
- False call criteria: C_0/N - FCP. For example, a 3/20 - FCP represents a false call test where at most 3 false calls can occur for 20 blank grading units.

Figure A-1 shows the resulting power curves for four test cases, in which sets with 5, 10, 15, and 20 cracked units are used with twice the number of blank grading units, respectively [2].

In Figure A-1, the P_{FC} and P_{DET} curves are shown as dashed and solid color lines, respectively. These curves serve as a valuable tool for determining a test's rigor. In Table A-1, quantitative measurements from the power curves in Figure A-1 are given for an examiner with a postulated 20% FCP and 80% POD. For example, for the 0/10 - FCP test, an examiner with a 20% FCP has an 11% P_{FC}, but for the 8/40 - FCP they have over a 50% P_{FC}. Likewise, if an examiner has an 80% POD for the 5/5 - POD and 14/20 - POD tests, they have 33% and 91% P_{DET}, respectively. This shows that as the size of the test set is increased, for a fixed FCP and POD, the probability of passing each test increases. In other words, as the total number of units varies, the acceptance criteria change simultaneously. Of the test sets presented, the most drastic difference between each test set is found next to the (0/10 - FCP, 5/5 - POD) test; that is, there is greater change in the power curves between the (0/10 - FCP, 5/5 - POD) and (3/20 - FCP, 8/10 - POD) tests than between any of the other test sets. With the understanding that limited improvements in power curves are gained for test sets larger than 40 blanks and 20 cracked specimens, this trend provides an upper limit for the examinations when practical limitations such as test piece procurement and examination time are considered [2].

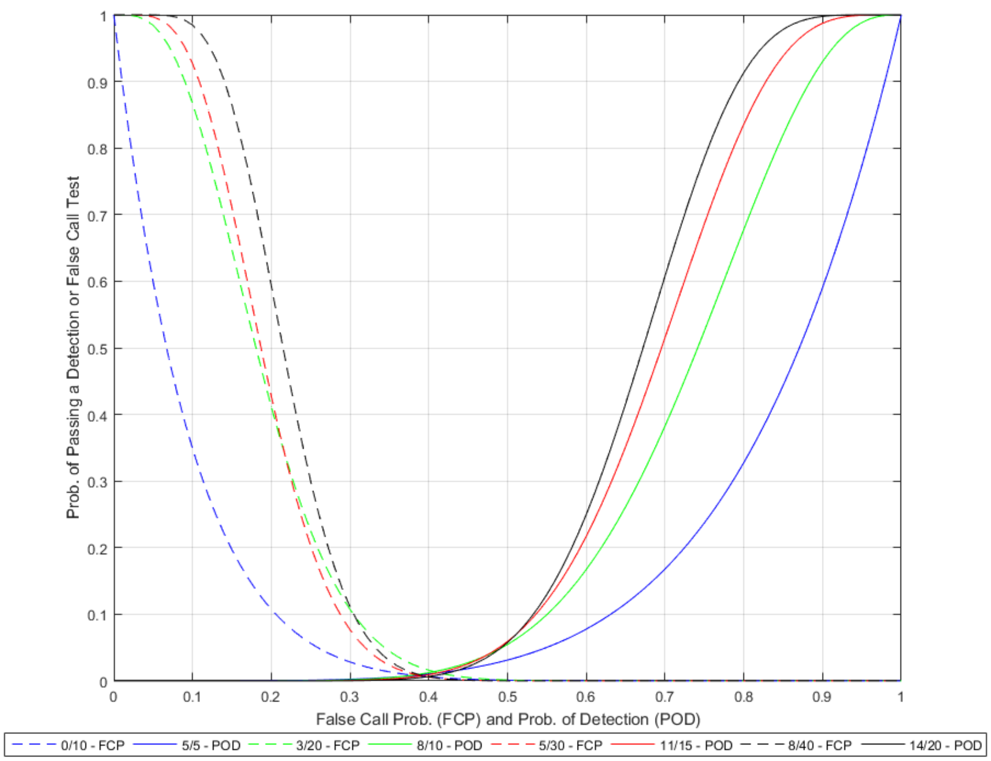

Figure A-1
Power Curves for Four Test Sets

Table A-1
Probabilities of Passing a Detection or False Call Test for Various Test Sets

Test Set	P_{FC} (FCP = 20%)	P_{DET} (POD = 80%)
(0/10 - FCP, 5/5 - POD)	11	33
(3/20 - FCP, 8/10 - POD)	41	68
(5/30 - FCP, 11/15 - POD)	43	84
(8/40 - FCP, 14/20 - POD)	59	91

Since the detection and false call tests are independent of one another, the overall probability of passing the detection qualification exam (P_{PT}) is described by Eq. A-3. The P_{PT}, for a given test, can be defined for a range of FCP and POD values. Graphically the P_{PT} for the aforementioned four test sets is shown in Figure A-2. For example, a candidate with a 20% FCP and 80% POD has less than a 5% P_{PT} for a (0/10 - FCP, 5/5 - POD) test and greater than 50% for a (8/40 - FCP, 14/20 - POD) test. When an examiner's FCP and POD become worse (that is, the FCP increases and the POD decreases), the P_{PT} will become less for any test set.

$$\boldsymbol{P_{PT}(FCP, POD) = P_{FC}(FCP) \cdot P_{DET}(POD)} \qquad \textbf{Eq. A-3}$$

Thus, the power curves analysis, as presented, allows for assessment of exam rigor based on FCP, POD, and test set design.

An examiner having "good performance" is considered as having an FCP ≤20% and a POD ≥80% [2]. This examiner taking the (8/40 - FCP, 14/20 - POD) test would have over a 50% chance of passing the test (P_{PT} >50%). An examiner with a POD of 50% and an FCP of 20% would have a less than 5% chance of passing the same test (P_{PT} <5%). Figure A-2 shows two-dimensional power curves for four test designs.

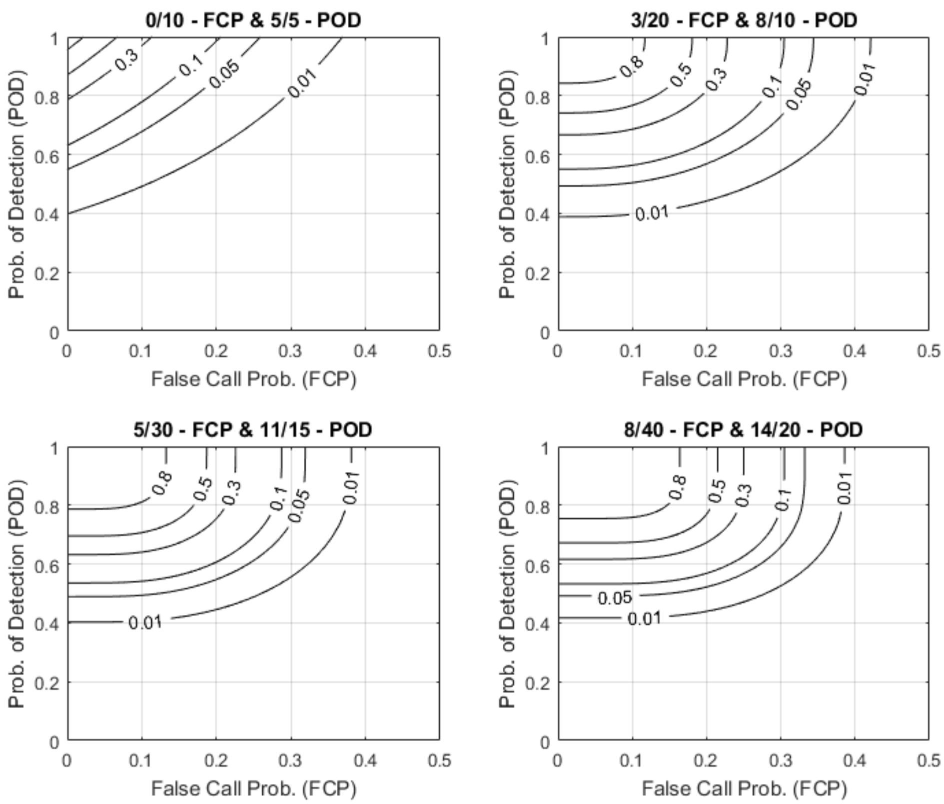

Figure A-2
Two-Dimensional Power Curves for Various Test Sets

The detection test qualification exam, as proposed for Supplement 9, provides a series of test sets for false call and detection test acceptance criteria. The determination of these test sets is based on the power curve methods, as previously described. The power curves are independent of material type, and their analysis is based on an examiner's FCP and POD; thus, if the same acceptable performance of POD ≥80% and FCP ≤20% is satisfactory for the CASS qualification, the detection test acceptance criteria are the same as those in Supplement 10 and similar to those in Supplement 2 [3]. The Supplement 10 acceptance criteria rather than Supplement 2 were applied to Supplement 9 because the material available for the CASS demonstrations is limited. The table acceptance criteria for Supplement 9 are shown in Table 3-2.

B
DETECTION TEST CURRENT INSPECTION CAPABILITY

To determine the current inspection capability of CASS material with ultrasonics, EPRI conducted a round robin with a set of mockups fabricated from various material sources and exhibiting a variety of diameters [6].

The experimental evidence provided by NDE round robin implementing an unbiased data collection methodology is used in Supplement 9 as a means of establishing the validity of the sizing pass/fail criterion. Indeed, for cast stainless steel examination, experimentally collected evidence may be the only way to infer the validity of a proposed criterion. In complex engineering problems, theoretical explanations are formulated once a large experimental body of knowledge is accumulated. For CASS material, the available engineering studies provide guidance on the maximum allowable flaw length and depth for a given pipe loading condition. This information is not useful as a means of formulating an NDE pass/fail criterion because the derived criterion would then change as a function of the pipe service conditions.

In the round robin, seven candidates participated in the capability evaluation. The grading methodology used met the requirements listed in Section 3.

None of the candidate procedures detected all the flaws in the round-robin test set; that is, none met the procedure qualification requirement 4.0 (b).

The average capability results from the personnel detection and false calls tests are shown in Table B-1 [6]. These results are presented for examinations from the outside diameter with interrogation from the upstream and downstream sides of the weld (that is, dual-side).

Table B-1
Team Average Results of Personnel Detection and False Call Tests in the CASS Capability Round Robin for Outside Diameter Dual-Side Examination and Flaw Depths Greater Than 25%

Detection Test	68%
False Call Test	37%

Figure B-1 shows the performance range for the participating candidates. In the figure, the candidate results are bounded by the blue box, with the intersection of the solid bars representing the candidate’s average results. The green box represents the PASS criterion for personnel test subject to the procedure demonstrating detection of all the test flaws.

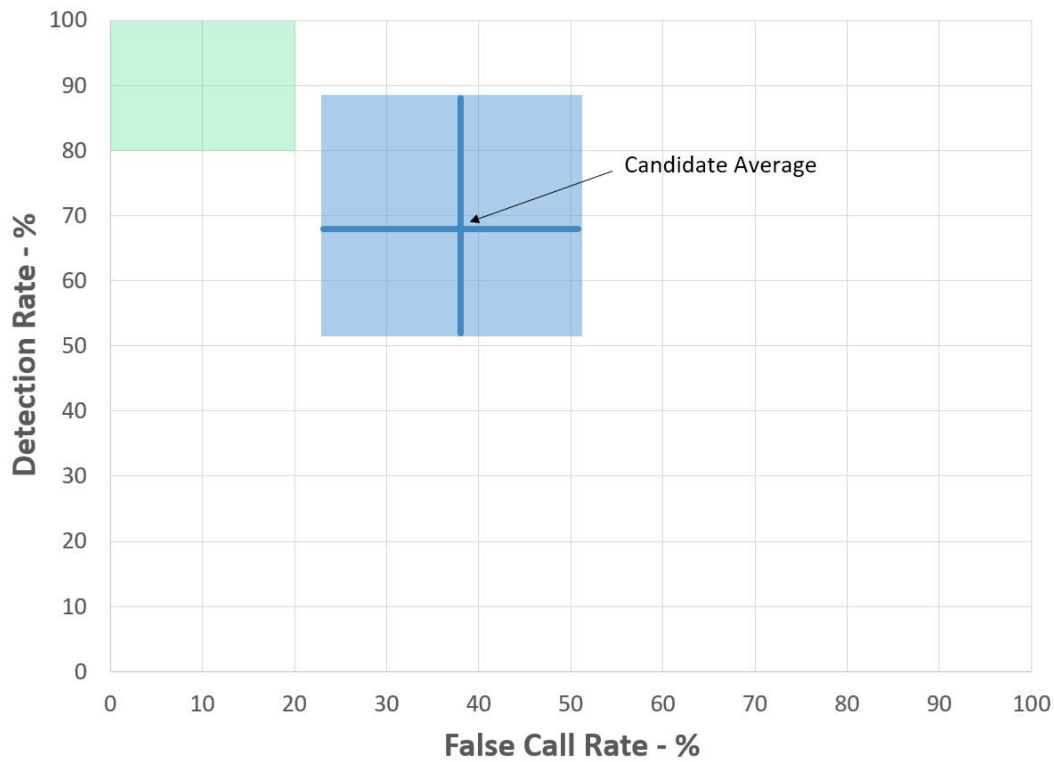

Figure B-1
Personnel Detection and False Call Capability in the CASS Round Robin for Dual-Side Examination and Flaw Depths Greater Than 25%

The figure appears to suggest that at least one of the candidate teams met the personnel detection test acceptance criteria. To pass, however, the procedure would have to demonstrate at least one detection of each individual test flaw. Also, none of the candidates met the personnel false call test acceptance criteria.

C LENGTH SIZING TEST CAPABILITY EVALUATIONS

The flaw length sizing acceptance criterion originally required a 1 inch (25 mm) of maximum over-and-under-sizing error [7] to pass the test. This flaw length sizing criterion was justified because it was deemed as reasonable, under ideal conditions [7]. The over-and-under criterion was later revised and replaced with a root-mean-square (RMS) error measurement because the over-and-under criterion was difficult to meet for low-amplitude responses [7].

Currently Supplements 2 and 10 use an acceptance criterion of 0.75 inch (19 mm) RMS error for length sizing. This criterion was established from analysis of the PDI test data [7].

For Supplement 9, the length sizing acceptance criterion is an RMS error not to exceed 1 inch (25 mm).

The basis for this criterion was established from round-robin evaluations performed using a "blind" protocol for CASS specimens examined from the inside and outside diameter.

In setting the length sizing criterion to limit the measurement RMS not to exceed 1 inch, it is recognized that:

- This requirement is likely to be acceptable from a structural integrity point of view since the error represents a relatively small fraction (less than 3%) of the circumference of the pipe sizes of interest and is a relatively small (0.25 inch) increase above the RMSE of 0.75 inch currently used in Supplements 2 and 10.
- As can be seen from Tables C-1 and C-2, an RMS error of 1.00 inch bounds most of the results obtained in the inside and outside diameter capability evaluations. Thus, most of the participating teams in the evaluations met the requirement.

C.1 Length Sizing Capability from the Inside Diameter

The inside diameter UT capability evaluations were performed using the Westinghouse Owners Group stainless steel cast specimens. The results from the three participating teams exhibited an average RMS error of 0.77 inch (20 mm) as shown in Table C-1 [5, 8].

Table C-1
Results from the Westinghouse Owners Group Stainless Steel Cast Specimens Length Sizing Evaluation from the Inside Surface

Team	UT Length Sizing RMSE (inches)
A’	0.93
B’	0.57
C’	0.82
Average	0.77

C.2 Length Sizing Capability from the Outside Diameter

The outside diameter UT capability evaluations were performed as part of the CASS round robin conducted by EPRI, as was mentioned in Appendix B. The results from the seven participating candidates exhibited an average RMS error of 1.05 inch (27 mm) for dual-side examination of flaws having depths greater than 25% of the wall thickness. The individual candidate performances are listed in Table C-2 [6].

Table C-2
Results from the EPRI CASS Round-Robin Length Sizing Capability Evaluation from the Outside Surface for Dual-Side Examination and Flaw Depths >25%

Candidate	UT Length Sizing RMS Error (inches)
A	0.85
B	0.71
C	2.36
D	0.92
E	0.79
F	0.98
G	0.71
Candidate Average	1.05

D

DEPTH SIZING TEST CAPABILITY EVALUATIONS

The outside diameter UT depth sizing capability evaluations were performed as part of the EPRI CASS round robin as was mentioned in Appendix B. The results for dual-side examination by the seven candidates of flaws having depths greater than 25% of wall thickness are listed in Table D-1 [6].

Table D-1
Results from the EPRI CASS Round-Robin Depth Sizing Capability Evaluation from the Outside Surface for Dual-Side Examination and Flaw Depths >25%

Candidates	UT Depth Sizing RMS Error (inches)	UT Depth Sizing Normalized RMS Error*
A	0.54	0.25
B	0.49	0.23
C	0.43	0.30
D	0.38	0.16
E	0.51	0.26
F	0.47	0.19
G	0.48	0.22
Candidate Average	0.47	0.23
Acceptance Criterion	0.125	0.1
Candidate Standard Deviation	0.053	0.047

*RMS of each error divided by the wall thickness at the flaw location

For Supplement 9, the depth sizing acceptance criterion is a normalized RMS error not to exceed 0.1 (that is, 10% of the wall thickness at the flaw location). This proposed acceptance criterion was not met by any of the candidates in the EPRI CASS round robin.

This normalized depth sizing RMS error acceptance criterion was preferred over the absolute RMS error because:

- From the viewpoint of structural integrity, the flaw depth relative to specimen wall thickness is more relevant than its absolute depth.
- As shown in Table D-1, it exhibited a reduced error gap as a percent of the candidates' average performance. Indeed, the absolute depth sizing acceptance criterion RMS error was not met, on average by a factor of 4, while the normalized RMS error criterion was not met, on average by a factor of 2.
- By normalizing the error using the wall thickness, the absolute depth sizing error dependence on the specimen wall thickness is reduced.

In addition, the normalized RMS error criterion of 0.1 (10%) is comparable to the absolute RMS error criterion of 0.125 inch when applied to relatively thin-wall pipe as well as to the absolute RMS error criterion of 0.25 inch applied to relatively thick-wall pipe examined from the internal pipe surface.

A more detailed analysis of the round-robin data indicated that the depth sizing error gap was due in large part to undersizing [6]. Specifically:

- The flaw depth estimation error was found to increase with flaw depth, but this increase was mostly due to a bias toward undersizing flaws rather than an increase in scatter for the depth sizing results. Vice versa, depth sizing accuracy was found to be better in thinner materials.
- The differences in the candidates' normalized RMS error was mainly due to differences in their undersizing bias, which suggests that the bias was affected by the depth sizing technique and procedure applied by each candidate.
- Proximity to geometry, material microstructure, and flaw fabrication had little effect on the depth sizing results.

E
FLAW DEPTH DISTRIBUTION

E.1 Development of Optimal Flaw Depth Bins

For Supplement 9, the bin size distribution takes into consideration the flaw acceptance criteria tables that were developed for CASS in MRP-362 [4]. In these tables, a critical flaw depth value of 25% bounds all the values of interest [4]. Using as input this minimum flaw depth of interest and the bin distribution used in Supplement 10, the bin size ranges shown in Table E-1 are obtained.

Table E-1
Detection Specimen Flaw Depth Distribution Bins for Supplement 9

Flaw Depth (% Wall Thickness)	Minimum Percentage of Flaws
25–50%	20%
51–75%	20%
76–100%	20%

*At least 75% of the flaws shall be in the range of 25% to 75% of wall thickness.

An additional consideration for the detection test design comes from the requirement within ASME Section XI that piping flaws detected and sized to be greater than 75% through-wall are always unacceptable for continued service, regardless of flaw length and stress loading. This requirement provides a minimum margin against pressure boundary leakage regardless of the structural margin against unstable pressure boundary rupture.

In the next section, technical justification for the bin size ranges is provided using a statistical allocation method that estimates an examiner's capability to detect the necessary flaw depth sizes as described by the acceptance criteria tables.

Optimal flaw distribution across the bins is assessed by looking at the number of misses that could occur within a particular bin, while still passing the detection qualification exam. In other words, the question to be addressed is: Could an examiner miss the flaws in a particular wall thickness range and still pass the qualification?

Using this statistical allocation method, it is shown that the probability of a candidate with a probability of detection (POD) of 80% of passing a 10-flaw test while missing all the flaws in a particular bin is 0.67%. Similarly, the probability of the same candidate passing a 20-flaw test while missing all flaws in a particular bin is 0.06%.

E.2 Methodology for Calculating the Detection Test Bin Size Flaw Distribution

To answer the question, the probability of detection (P_{DET}) is determined assuming that a specific number of indications are missed for a given bin. For simplicity, consider limiting the distribution to two bins as follows:

1. Bin I
2. Bin II

The two-bin example can be used to represent different scenarios, such as missing all the flaws within the wall thickness range of 25–50% (Bin I) and still passing the exam by detecting a sufficient number of flaws within the wall thickness range of 51–100% (Bin II). This methodology can be generalized to multiple bins with each bin containing a specific number of flaws.

The methodology is limited to P_{DET} and is not applicable to the probability of passing the false call test (P_{FC}) because no criteria, other than the quantity of grading units to examine, are given for a particular false call test.

The practical aspect of missing small flaws in a detection test will be answered by the following statistical question: What is the probability that an examiner, for a particular test with a given POD, will pass the detection test (P_{DET}) based on the number of missed flaws in a particular bin? For this example, the answer to the previous question will be examined by combining two probabilities. The probability of missing flaws within a particular bin will be found by using the cumulative distribution function for binomial random variables, as shown in Eq. E-1 [9, 10].

$$\boldsymbol{B(X \leq x) = B(x; n, p) = \sum_{i=0}^{x} \binom{n}{i} p^{i} (1-p)^{(n-i)}} \qquad \textbf{Eq. E-1}$$

Where:

X is a discrete random variable

x is the number of successes

n is the number of trials

p is the probability of success

B is the cumulative probability of observing up to *x* successes in *n* independent trials, given a probability of success *p*

For this example, an 8/10 detection test and a candidate with an 80 % POD will be used; therefore, the total number of flaws in the exam (M) is 10 and the total number of required detections (C_1) is 8. The examiner is allowed to miss, at most, *J* flaws—where J = M-C_1. First, the probability of missing exactly *K* flaws in Bin I ($P_{Miss\ Bin\ I}$) is found using a variety of flaw distributions within Bin I, as described by Eq. E-2.

$$\boldsymbol{P_{Miss\ Bin\ I}(X = K) = B(K; N_{Bin\ I}, 1 - POD) - B(K-1; N_{Bin\ I}, 1 - POD)} \qquad \textbf{Eq. E-2}$$

Next, the probability of missing *J-K* or fewer flaws in Bin II is found using Eq. E-3.

$$\boldsymbol{P_{Miss\ BinII}(X \leq J - K) = B(J - K; N_{Bin\ II}, 1 - POD)} \qquad \textbf{Eq. E-3}$$

Lastly, Eq. E-2 and Eq. E-3 are multiplied to determine the P_{DET} for a given flaw distribution for a given test set and its acceptance criteria as described by Eq. E-4.

$$P_{DET} = P_{Miss\ Bin\ I} \cdot P_{Miss\ Bin\ II} \qquad \textbf{Eq. E-4}$$

An illustration of Eq. E-4 is given in Figure E-1 for the 8/10 detection test and an examiner with an 80% POD. According to Table E-1, at least 2 flaws will be allocated to the 2550% Bin. Using Eq. E-4, it is determined that the probability of a candidate with an 80% POD passing an 8/10 exam while missing all the 25–50% wall thickness flaws is 0.67%. Graphically this is shown in Figure E-1, when the Number of Flaws in Bin I is 2 and the Misses in Bin I is 2. This means that there is a 0.67% chance that someone can pass the 8/10 detection exam and miss all the small flaws. This example is analogous for flaws in the 51–75% wall thickness range.

If no flaws are distributed into Bin I, the examiner has a 68% P_{DET}, meaning that all the flaws will be distributed into Bin II and, based on the acceptance criteria, the candidate has a high probability of passing the detection test (P_{DET} of 68% is also shown in Table A-1 for the 8/10 test—80% POD case). Because passing the detection test in this example requires no more than two misses, the sum of the probability values for a given number of flaws in Bin 1, as shown in Figure E-1, is the same total probability of 68%. If two flaws are allocated to Bin I, the P_{DET} for 0, 1, and 2 misses within Bin I are 51%, 16.1%, and 0.67%, respectively; the sum of these probabilities rounds to 68%.

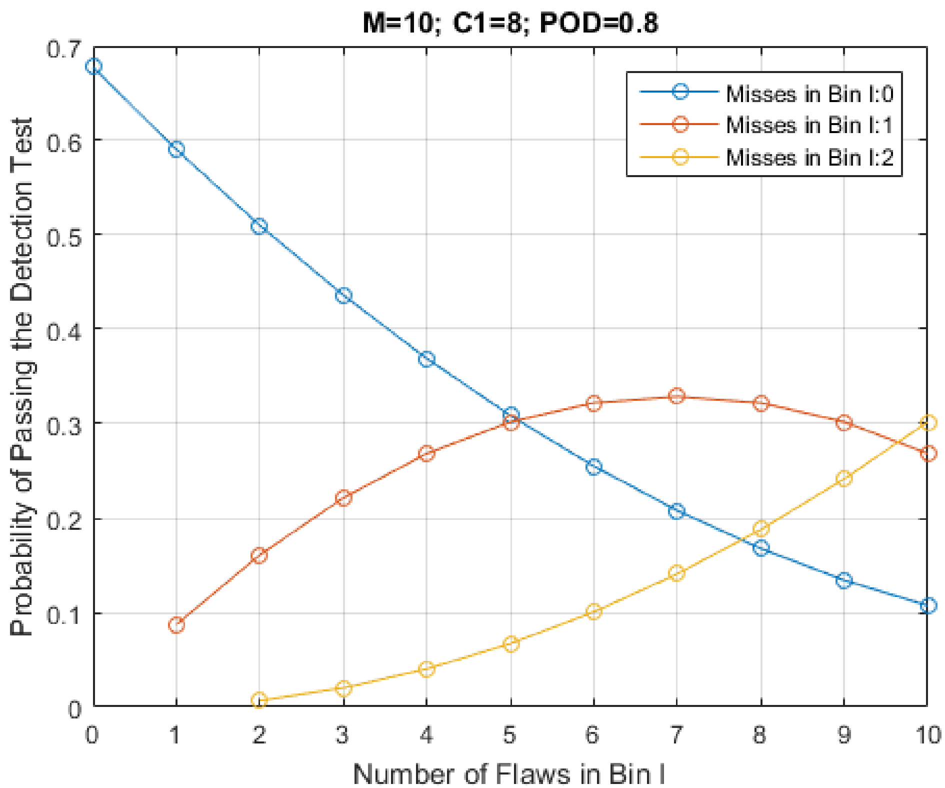

Figure E-1
Probability of Passing the Detection Test Based on Flaw Size Distributions for an 8/10 Exam

Similarly, the same question can be expanded to the 14/20 exam. In this case, it is found that a candidate has less than 0.1% chance of passing the detection test while missing all the flaws in either the 25–50% or 51–75% wall thickness bins (see Figure E-2). For the 14/20 exam, the minimum number of flaws allocated to a bin is 4. In Figure E-2, refer to Number of Flaws in Bin I as 4 and Misses in Bin I as 4. For this given scenario, the P_{DET} is 0.06%.

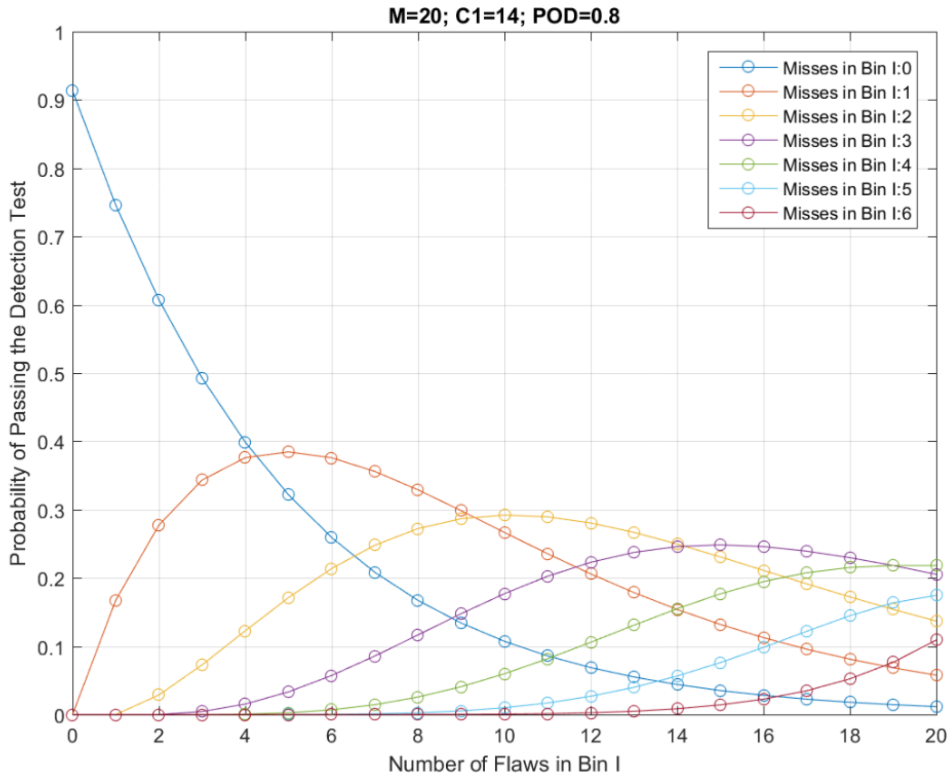

Figure E-2
Probability of Passing the Detection Test Based on Flaw Size Distributions for a 14/20 Exam

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