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Volume 1
Project 2520-7
Final Report
April 1988

Degradation and Failure of Bolting in Nuclear Power Plants

Volume 1

Prepared by
Applied Science & Technology
Poway, California

REPORT SUMMARY

SUBJECTS	Safety margins, testing, and evaluation / Nuclear component reliability	
TOPICS	Nuclear power plants Bolts Fasteners	Joints Safety engineering In-service inspection
AUDIENCE	Generation managers and engineers	

Degradation and Failure of Bolting in Nuclear Power Plants

Volumes 1 and 2

A four-year program to resolve the generic safety issue of bolting degradation and failure in nuclear power plants has developed guidelines for material selection, bolting preload control, and plant operation, as well as a realistic method for evaluating the structural integrity of bolted joints. These measures can help improve plant availability while reducing radiation exposure and costs of maintenance and inspection.

BACKGROUND In 1982, NRC issued IE Bulletin No. 82-02 and designated bolting degradation and failure in nuclear power plants as a new generic issue. To provide a technical basis for the resolution of this issue, a nuclear industry task group formed by the Atomic Industrial Forum and Materials Properties Council developed a coordinated research plan. This plan focused on identifying and developing tools and procedures for demonstrating safety margins in pressure boundary and structural joints and recommending realistic inspection and maintenance programs. EPRI carried out the research, working with industry owners groups.

OBJECTIVE To provide a basis for resolution of the generic issue of bolting degradation and failure in nuclear power plants.

APPROACH The task group outlined a comprehensive 19-point research program to ensure that no significant issue remained an open concern. A project team first collected and evaluated the service history of pressure boundary and structural joints. The task group then assigned tasks to several project teams, which studied the problems and recommended solutions. These tasks focused on procurement specifications, material selection and testing, design procedures and bolt preload control, in-service inspection, plant operation and maintenance, and evaluation of the structural integrity of degraded bolted joints.

RESULTS This two-volume report provides a single-source document to help utility engineers address plant-specific bolting and fastener problems. Volume 1 contains background information, the approach to issue resolution, a

summary of findings for each of the 19 tasks, and specific conclusions and recommendations. Volume 2 compiles detailed research results—a vast amount of data organized for ready use. Specific task groups produced the following:

- Guidelines for the purchase of bolts and threaded fasteners, including recommendations for bolting materials that resist boric acid wastage and stress corrosion cracking
- Analyses of the role of bolt preload in bolted joint problems
- Guidelines on the use of lubricants and leak sealants
- Recommendations for improvements to nondestructive examination of threaded fasteners
- Suggested revisions to ASME and ASTM codes and standards
- Methods for assessing the significance of degraded or failed bolts
- Training materials for plant mechanical maintenance personnel, including videotapes and reference manuals

Analyses determined that the structural redundancy of a bolted joint can tolerate considerable degradation before safety is compromised. Furthermore, in the absence of leaking coolant, low-alloy steel fasteners have demonstrated exemplary performance. The report confirms the importance of fastener material selection, bolt preload control, and elimination of leaking joints.

EPRI PERSPECTIVE This report provides the technical basis for resolution of the generic issue of bolting degradation and failure in nuclear power plants. The task group, utility personnel who contributed their time and expertise, provided invaluable coordination with ASTM, ASME code bodies, the Institute of Nuclear Power Operations, and NRC.

PROJECT RP2520-7
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NP-5769, Volume 1
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ABSTRACT

These two volumes provide the documentation for industry resolution of the U.S. Nuclear Regulatory Commission (NRC) generic issue B-29, Degradation and Failure of Bolting in Nuclear Power Plants. The issue was identified as a consequence of concerns about the structural integrity of component supports circa 1980. When bolting integrity became a separate issue in 1982, the utility industry responded by forming a Task Group on Bolting under the aegis of the Atomic Industrial Forum (AIF) and the Materials Properties Council (MPC). The AIF/MPC Task Group on Bolting formulated a comprehensive nineteen-task action plan aimed at resolution of the issue, with implementation of the plan, the responsibility of EPRI and the affected Owner's Groups. EPRI organized a matrix-managed Generic Bolted Joint Integrity Program to carry out the research, with the results reported herein.

The scope of the EPRI Generic Bolted Joint Integrity Program was broad, in order to assure that no significant aspect of the issue remained as an open concern. The scope included:

- Documentation of the service history of pressure boundary and structural bolts;
- Recommendations for ASME and ASTM codes and standards;
- Guidelines for purchase specifications and receipt inspection of bolts and threaded fasteners;
- Recommendations for the selection of bolting materials to resist boric acid wastage and stress-corrosion cracking;
- Guidelines on the use of lubricants and leak sealants;
- Training materials for plant mechanical maintenance personnel, including videotapes and reference manuals;
- Improvements in the nondestructive examination of threaded fasteners; and
- Methods for assessing the safety significance of degraded or failed fasteners, in the context of the complete bolted joint.

The format of the two volumes is such that the results of the research are easily referenced. This format was chosen intentionally in order to aid the utility engineer in addressing plant-specific bolting and fastener problems by providing a single source document. Volume 1 consists of background information, a description of the AIF/MPC Task Group on Bolting action plan, the issue resolution outline, summary material on each of the issue resolution topics (i.e., lubricants), and the conclusions and recommendations. Volume 2 provides the more complete reference source and data for the topics. An index is included to assist the reader in using the two volumes as a reference.

ACKNOWLEDGMENTS

A body of work as comprehensive as these two volumes is due to the efforts of many individuals and organizations over the past six years. Major credit must go to the Chairman of the AIF/MPC Task Group on Bolting throughout its existence, Mr. Edwin A. Merrick of the Tennessee Valley Authority. His purposeful approach to the bolting degradation and failure issue was a principal force in the creation of the EPRI Generic Bolting Integrity Program. Dr. Martin Prager of the Materials Properties Council (MPC) was an enthusiastic supporter of the combined industry effort, and brought specialized expertise to bear on the issue as needed. The EPRI Generic Bolting Integrity Program was managed in an interdisciplinary matrix form, with continuity provided by Dr. Theodore U. Marston. At the time of the creation of the AIF/MPC Task Group on Bolting in mid-1982, he was the Manager of the Structural Integrity (later the Structural Mechanics) Subprogram and the Matrix Manager of the Generic Bolting Program. Presently, he is Director of the Nuclear Engineering and Operations Department.

Significant contributions to the Generic Bolting Program were due to the efforts of Dr. Arthur F. Billy of EPRI's Nuclear Safety Analysis Center, who developed an historical and documentary record of the issue that was sorely needed, and who provided EPRI staff support to the AIF/MPC Task Group during a critical period. Similar support for the Task Group came from Nuclear Steam Supply System (NSSS) vendors -- in particular, Ken Moore from Babcock & Wilcox, Walt Bak from Combustion Engineering, and Ed Landerman from Westinghouse. Key technical contributors are readily recognized in the material contained in these two volumes. Added recognition should go to Russ Cipolla of Aptech Engineering Services, who helped to define the industry strategy for dealing with the bolting issue.

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Section 1

INTRODUCTION

BACKGROUND

EPRI became involved actively in bolting degradation and failure concerns as a consequence of the generic Unresolved Safety Issue (USI) A-12, which addressed the potential for low fracture toughness in nuclear power plant component support materials. The Atomic Industrial Forum (AIF), through its Committee on Power Plant Design, Construction and Operation, began to develop an industry response to USI A-12 by creating a Subcommittee on Material Requirements in March 1981, with EPRI staff coordinating the research activities and the Subcommittee integrating this research together with utility owner's group technical work. Bolting concerns were originally limited to stress corrosion cracking of high-strength support bolts, the results of which were officially submitted to the NRC as part of the initial proposed resolution to USI A-12 in June 1981.

USI A-12 came about principally as the result of technical concerns raised by the NRC during the construction and licensing of the North Anna Nuclear Power Station, Units 1 and 2. At issue was the ability of the steam generator and reactor coolant pump supports, which included bolting, to maintain their structural integrity under accident conditions. The NRC identified the potential for low fracture toughness of steam generator and reactor coolant pump support materials, including bolting and threaded fasteners, as a generic issue (1). Procedures and evaluation criteria were published in NUREG-0577 (2) in October 1979. Subsequent augmenting letters by the NRC (3,4) amended NUREG-0577 to include all PWRs as well as BWRs; plants under construction, not just operating units; reactor pressure vessel and pressurizer supports; stress corrosion cracking assessment of high-strength materials, including bolting; and failure consequence analysis for many supports.

The NRC required the industry to comply with an action plan that contained two distinct parts for materials and bolting, a toughness review plan under Part I and a stress corrosion review plan under Part II. Part II of the NRC's review proce-

dure required materials with a specified minimum yield strength greater than 120 ksi (827 MPa) to be reviewed for stress corrosion cracking resistance. This established guidelines for loading of high strength bolting materials susceptible to stress corrosion cracking using a fracture mechanics approach.

The NRC further clarified its position on 6 October 1980 (5) and on 26 November 1980 (6). Twenty-four plants were eventually identified by the NRC as requiring plant-specific action. Component support materials were separated into three groups consisting of structural materials, weld consumables and bolting materials. Three categories of materials susceptible to brittle failure -- highest, intermediate and least susceptible -- were also established.

The identification of bolting integrity as a separate issue received impetus from the Advisory Committee on Reactor Safeguards (ACRS) in October 1981, who recommended that the NRC staff expand the concerns about stress corrosion cracking of high-strength, low-alloy steel bolts to include a more comprehensive approach to bolting and threaded fastener degradation and failure. NRC staff responded with IE Bulletin No. 82-02, "Degradation of Threaded Fasteners in the Reactor Coolant Pressure Boundary of PWR Plants", issued in June 1982 (7). The AIF Subcommittee on Material Requirements responded to the NRC's intensification of emphasis on the bolting issue by joining with the Materials Properties Council (MPC) to form the Joint AIF/MPC Task Group on Bolting, also in June 1982. The Task Group was composed of representatives from AIF member organizations -- utilities, vendors, and architect-engineers -- plus representatives from EPRI and MPC. Edwin A. Merrick of the Tennessee Valley Authority was designated as the Chairman.

The original charter of the Task Group was oriented toward a coordinated industry response to IE Bulletin No. 82-02, and to the bolting aspects of the earlier but related NUREG-0577 (2). The emphasis was to be placed on a bolting survey, on stress corrosion cracking susceptibility criteria, and on corrective actions to deal with the problem. However, over the next several months, through meetings of the Task Group by itself and with NRC staff, a more comprehensive industry program evolved. This nineteen-task Generic Bolting Program was presented to the parent AIF Subcommittee on Material Requirements in February 1983, for their review and comments, and was officially transmitted by the AIF to NRC in July 1983. During the period of development of the industry's Generic Bolting Program, the NRC designated bolting degradation and failure in nuclear power plants as a new generic

issue -- No. B-29 -- with a high priority safety rating (November 1982) (8). The NRC's concerns can be illustrated by the following paragraphs taken from NUREG-0943 (9):

> "Numerous threaded fasteners, for example, bolts, studs and capscrews, are used in a nuclear power plant. The most important applications are those constituting an integral part of the reactor coolant pressure boundary, such as pressure-retaining closures in reactor vessels, pressurizers, reactor coolant pumps, and steam generators. In recent years, an increasing number of incidents of degraded threaded fasteners have been reported in both operating reactors and reactors under construction. A large number of reported degraded threaded-fastener incidents involve the reactor coolant pressure boundary and major component supports. Although these incidents have not resulted in an immediate safety concern in regard to the requirements of General Design Criterion 14 of Appendix A to 10 CFR 50 (Title 10 of the Code of Federal Regulations), they do reflect an undesirable level of degradation of the reactor coolant pressure boundary in operating nuclear power plants and they impair the structural integrity of component supports."

These comments in NUREG-0943, and the high priority safety classification given to the issue by NRC staff, were a consequence of an increasing number of reported failures in high strength bolting in Class 1 component supports and other safety-related equipment since 1964. Common characteristics among the reported incidents included materials that were overly hard and out of specification, high sustained tensile stresses, out-of-specification pretorquing, an aqueous environment caused by high humidity, primary water leakage, and borated water leakage. The most frequently observed failure mode for the structural bolting was stress corrosion cracking. Low alloy, quenched and tempered steels and maraging steel types have also been degraded by stress corrosion cracking. A small number of overstress failures has been traced to improper heat treatment or low strength material. Pressure retaining bolts have also failed through corrosion wastage. Reactor coolant pressure boundary components affected included steam generator manway closures, reactor coolant pumps, pressurizer manway closures, reactor vessel closures, chemical and volume control system isolation valves, safety injection check valves and other check valves. Reactor vessel internals, mainly the lower thermal shield bolts and upper core barrel bolts, have been degraded in nine plants requiring extensive and expensive replacement of bolts in some plants.

The following summarizes the documented generic experience of bolting failures during the 1964-1983 period and the AIF/MPC Task Group on Bolting position on these

failures. Tables 1-1 through 1-8, taken from NUREG-0943, provide the detailed information on the failures.

- GROUP I - Degradation or Failure of Pressure Boundary Bolting due to General Borated Water Corrosion (Wastage or Erosion/Corrosion). Group I failures are a concern due to potential compromise of the pressure boundary. This type of degradation is the subject of NRC IE Bulletin 82-02. It is our position that degradation due to wastage is primarily a maintenance problem. Without the presence of reactor coolant leakage, no significant corrosion would occur. Methods for minimizing leakage can be applied. While the materials now in use in flanged connections are fully adequate for the intended application, material changes can also mitigate this problem.

- GROUP II - Degradation or Failure of Pressure Boundary Bolting due to Stress Corrosion Cracking. Group II failures are a concern due to potential compromise of the pressure boundary. Some bolts in flanged joints have failed due to stress corrosion cracking (SCC). The cause of these failures can be attributed to an undesirable combination of stress, environment, and material condition. Generally these types of failures can be tied to leaking gaskets and certain lubricants or sealants. Lubricants containing MoS_2 have been implicated and may contribute to SCC under certain conditions. The failure of pressure boundary bolts can be eliminated through proper use of tensioning techniques, lubricants and sealants. For bolting currently in service, assessment of material condition may be accomplished by NDE inspection. It must be noted that out-of-specification material has not been implicated as a cause for stress corrosion cracking of pressure boundary materials.

- GROUP III - Degradation or Failure of Internals Bolting due to Fatigue and Stress Corrosion Cracking. Group III failures are a concern due to the uncertain influence of loose parts on system integrity. Bolting used in primary components internals applications has failed due to either fatigue, stress corrosion cracking or some combination of the two mechanisms. Generally, failures are related to materials, heat treatment, forming technique, high steady state stresses, and/or fatigue life. Failures can be eliminated by alternate materials selection and design modification.

- GROUP IV - Degradation or Failure of Supports and Embedment Bolting due to Stress Corrosion Cracking. Group IV failures are a concern because degraded bolting may not be adequate for service. Component support and embedded bolts have failed due to stress corrosion cracking. Failures can be attributed to a combination of high stress, susceptible material condition, and a wet environment. Materials which have failed can basically be divided into two categories:

  (1) Materials which are specified as high strength (greater than 150,000 psi specified minimum yield strength) which are susceptible to stress corrosion cracking.

  (2) Materials which are specified as moderate strength (lower than 150,000 psi specified minimum yield strength) and which have

been supplied in a condition (greater than 180,000 psi actual yield strength) which may then be susceptible to stress corrosion cracking.

The AIF/MPC Task Group on Bolting assigned the responsibility for work related to Group III failures to the individual vendor owner's groups. The remainder of the topics were included in the Generic Bolting Program, with EPRI taking the lead role in technical integration and research support.

The question of fastener integrity involves many disciplines (e.g., metallurgy, fracture mechanics, nondestructive examination, design, specifications and standards, quality assurance, manufacturing or quality control, corrosion engineering, tensioning control). The approach taken by the Task Group considered all of these disciplines. Priorities were established for the various fastener applications, with the Task Group recommending that action focus on primary pressure boundary components. The action plan put forth by the Task Group encompassed nineteen tasks, as outlined below.

TASKS ASSOCIATED WITH ALL BOLTING

Task 1 - Assessment of Priorities and Safety Significance

Task 1.1. This task was conducted to monitor bolting priority ranking. Work under this task involved an assessment of the failure and success history for each of the four failure groups. The contractor was Aptech Engineering Services.

Task 1.2. EPRI conducted a pilot scoping study on the use of decision analysis for bolting. The objective of the pilot study was to develop a methodology for determining the technical parameters that influenced the likelihood of bolt failure. The work was conducted in house, with the help of consultants.

Task 2 - EPRI "Literature Survey of Carbon and Alloy Steel Fastener Corrosion in PWR Plants", RP2058-7

A literature survey of carbon and alloy steel fasteners corrosion in PWR plants was completed. The contractor was Combustion Engineering, Inc.

Task 3 - Stress Corrosion Cracking of Low Alloy Quenched and Tempered Bolting Materials in Water Environments

EPRI contracted with Battelle's Columbus Laboratories for this work.

Task 3.1 - Fracture Mechanics Analysis. This task was aimed at developing stress intensity factors for realistic flaw shapes and loading conditions in bolts. Realistic stress intensity factors (K_I) were to be derived for the load/flaw geometry configurations for the bolt head fillet, the thread termination point and at the groove of the first thread engaged in the nut. K_{IC} was also to be determined for the case of failure in the thread away from the nut and bolt head.

Task 3.2 - Data Review. Detailed descriptions of failures involving stress corrosion of high strength low alloy material were to be provided from hitherto unpublished accounts.

Task 4 - Inclusion of Hardness Test Data into the Bolting Database

Several utilities have conducted hardness surveys of installed bolting and spares. These data were to be included in a bolting database, and their impact on the issue assessed. Aptech Engineering Services was the contractor on this task.

Task 5 - Bolting Database

A database containing hardness and other materials data was to be maintained and updated as necessary to support industry efforts. The contractor was Materials Research and Computer Simulation.

Task 6 - Bolting Specification Requirements Recommended to ASTM for Nuclear Power Plant Applications and Recommendations for Receipt or Preinstallation Inspection

Task 6.1. The Task Group developed a general specification on bolting for nuclear requirements that eventually could be adopted by utilities.

Task 6.2. The Task Group initiated action in ASTM Committee F-16 (responsible for structural bolting) to revise sampling requirements in the specifications to be more consistent with end-product expectations.

Task 6.3. The Equotip hardness tester appeared to be viable for in-place hardness measurements, within certain limitations. A draft specification was prepared for ASTM entitled, "Standard Test Method for Leeb Hardness Testing of Metallic Materials".

Task 7 - ASME Bolting Requirements

Task 7.1. The Task Group prepared a critique regarding ASME bolting requirements, particularly as related to pretensioning of both pressure boundary and structural bolting joints. The contractors were Raymond Engineering, Inc., together with consultants.

Task 7.2. An Industrial Fasteners Institute (IFI) Task Group is currently reviewing ASME Section III Code bolting requirements to determine a need for revision or improvement. The results of Task 7.1 were to be included in the recommendations to IFI and to the ASME Code bodies.

Task 8 - EPRI Development of Field NDE Techniques to Detect Wastage and Stress Corrosion Cracking

EPRI has conducted pilot studies utilizing advanced ultrasonic techniques to detect wastage and/or stress corrosion cracking in pressure boundary and supports applications. The Task Group advised EPRI to focus these efforts on the development of a field technique. The contractors were Southwest Research Institute and Randomdec Computers.

Task 9 - Information Exchange

Task 9.1. EPRI workshops on bolting were held in November 1983 and November 1985. The workshop provided an exchange of information on industry efforts regarding bolting integrity.

Task 9.2. A videotape on the behavior and maintenance of flanged pressure boundary connections was produced and distributed to utilities as an aid to improving bolting design, as well as installation and maintenance techniques.

Task 9.3. Based on results from Task 16, a decision was to be made on whether to provide a videotape on design, behavior, and tensioning practices as applicable to structural joints.

TASKS ASSOCIATED WITH PRESSURE BOUNDARY BOLTING

Task 10 - Screening Strategy and Corrective Action for Pressure Boundary Bolting

The Task Group developed a strategy for identifying bolts in pressure boundary applications that may be susceptible to boric acid corrosion or stress corrosion cracking. Corrective actions were to be recommended. The contractor was Aptech Engineering Services, Inc.

Task 11 - Recommendations for ASME Section XI Changes

The Task Group prepared comments regarding Section XI requirements. These comments were forwarded to ASME Section XI for action and included the following: (i) appropriateness of Section XI size limits for inspection requirements; (ii) provisions to assure that adequate visual inspection is accomplished; and (iii) provisions to assure that NDE inspections are effective in detecting corrosion wastage and stress corrosion cracking. The contractors were Aptech Engineering Services, Inc., plus consultants.

Task 12 - Recommendations to EPRI on Degradation of Fasteners Research Programs

The Task Group recommended to EPRI three projects aimed at increasing the understanding of: (1) accelerated boric acid attack of carbon and alloy steel fasteners, (2) the effect of MoS_2, and (3) sealants for PWR primary system components. These recommendations led to a change in direction for the contracted work under Task 3.

Task 13 - Recommendations for Materials Substitutions and Coatings

Improvements in choice of materials, and perhaps use of certain coatings, can eliminate concern with borated water corrosion. The objective of this task was to recommend alternative materials and coatings and provide guidance regarding application. The efforts of this task were included in the work contracted under Task 3.

TASKS ASSOCIATED WITH COMPONENT SUPPORT BOLTING

Task 14 - Screening Criteria for Bolting Utilized in Component Support Applications

This task was to develop a strategy for identifying bolts in component support applications that may be susceptible to stress corrosion cracking. Methods for disposition of materials that require review on a plant-specific basis were to be recommended. Aptech Engineering Services, Inc. was the contractor.

Task 15 - Fracture Mechanics Based Methodology for Assessing Integrity of Fasteners

A report on the evaluation of bolting material integrity in component support applications described an acceptable technique for assessing the integrity of fasteners. The contractor for this work was Aptech Engineering Services, Inc.

Task 16 - Preload Technology Assessment

This task consisted of: (1) evaluating the need for high preloads, (2) identifying potential relief in preload requirements, and (3) investigating preload application

techniques and variability in preload. Optimum techniques were to be recommended. Methodologies for estimation of existing preloads based on knowledge of the tensioning techniques, sampling, or some combination of techniques and risks of detensioning existing joints were to be discussed. The contractor was Combustion Engineering, Inc., together with its consultants.

Task 17 - Development of UT Procedure for Inspection of Ultra High Strength Low Alloy and Maraging Steels

The Westinghouse Owners' Group funded a program element to develop a field procedure for UT inspection of ultra high strength bolts in the Westinghouse designed steam generator lower support feet.

TASKS ASSOCIATED WITH INTERNALS BOLTING

Task 18 - EPRI Work on High Strength Bolting (A286, X750, etc.)

EPRI conducted research projects to improve the stress corrosion resistance of high strength age hardenable Ni-Cr-Fe alloys and A453Gr 660 (A286) bolting materials. The influence of irradiation and stress/strain on the behavior of structural materials was also investigated. The contractors were Westinghouse Electric Corporation and Babcock & Wilcox Company.

Task 19 - Liaison with Owners' Groups

Liaison will be maintained with owners' groups to insure that duplication of effort is minimized and that pertinent information is exchanged on the efforts of the Task Group.

These nineteen tasks were subject to some modification and adaptation during the progress of the program. Some tasks received a considerably greater emphasis, while some of the sub-tasks were of a lesser priority. The results of these tasks are described in the next section, representing the industry resolution of the bolting issue. In those cases where the differences between the planned and the executed tasks are substantial, an explanation is provided.

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2. R.P. Snaider, et al. NUREG-0577 (Issued for Comment). "Potential for Low Fracture Toughness and Lamellar Tearing of PWR Steam Generator and Reactor Coolant Pump Supports." Office of Nuclear Reactor Regulation, USNRC, Washington, D.C., October 1979.

3. Letter of May 19, 1980. Darrell G. Eisenhut to All Power Reactor Licensees. Subject: Amendment to NUREG-0577, Concerning Linear Elastic Fracture Mechanics Analysis to Demonstrate Adequate Structural Integrity.

4. Letter of May 20, 1980. Darrell G. Eisenhut to All Pending Operator Licensees and Construction Permit Applicants, All Licensees of Plants Under Construction. Subject: Amendment to NUREG-0577, Concerning Linear Elastic Fracture Mechanics Analysis to Demonstrate Adequate Structural Integrity, and Additional Guidance of "Potential for Low Fracture Toughness and Lamellar Tearing of PWR Steam Generator and Reactor Coolant Pump Supports." NUREG-0577.

5. Letter of October 6, 1980. Darrell G. Eisenhut to All Power Reactor Licensees and Applicants. Subject: Implementation of Guidance for Unresolved Safety Issue A-12, Potential for Low Fracture Toughness and Lamellar Tearing of Component Supports.

6. Letter of November 26, 1980. Darrell G. Eisenhut, NRC's Director, Division of Licensing to All Power Reactor Licensees and Applicants. Subject: Implementation of Guidance for Unresolved Safety Issue (USI) A-12, Potential for Low Fracture Toughness and Lamellar Tearing of Component Supports. Attachment Summary of the 11/12/80 Meeting of the NRC, EPRI Staff and Interested Licensees, License Applicants and Consultant Organizations.

7. IE Bulletin No. 82-02. "Degradation of Threaded Fasteners in the Reactor Coolant Pressure Boundary of PWR Plants." USNRC, Office of Inspection and Enforcement, SSINS No. 6820, OMB No. 3150-0086, Expiration Date 05/30/86, Washington, D.C., June 2, 1982.

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9. NUREG-0943. "Threaded-Fastener Experience in Nuclear Power Plants." W.H. Koo, USNRC, January 1983.

Table 1-1

SUMMARY OF DEGRADED THREADED-FASTENER INCIDENTS INVOLVING REACTOR COOLANT PRESSURE BOUNDARY (RCPB)[1]

Degraded RCPB Threaded Fasteners	Number of Reported Incidents	Plants	Year Reported	Reactor Vendor*	Mode of Failure**
Steam Generator Manway Closure Studs	8	San Onofre 1	1977	W	SC
		St. Lucie 1	1977	CE	BC
		Arkansas 1	1978 1980	B&W	SC
		Calvert Cliffs 1	1980	CE	BC
		Oconee 3	1980	B&W	SC
		Arkansas 1	1981	B&W	BC
		Maine Yankee	1982	CE	SC
Reactor Coolant Pump Closure Studs	5	Calvert Cliffs 1	1980	CE	BC
		Ft. Calhoun	1980	CE	BC
		Calvert Cliffs 2	1981	CE	BC
		Oconee 2	1981	B&W	BC
		Oconee 3	1981	B&W	BC
Pressurizer Manway Closure Studs	2	St. Lucie 1	1978	CE	BC
		Calvert Cliffs 2	1981	CE	BC
Reactor Vessel Closure Studs	1	LaCrosse	1970	AC	SC
Chemical and Volume Control System Isolation Valve Bolts	1	Zion 1	1979	W	Erosion-Corrosion
Safety Injection Check Valve Studs	1	Calvert Cliffs 2	1981	CE	BC
Check Valve Studs	1	D.C. Cook 2	1981	W	BC

* W = Westinghouse; CE = Combustion Engineering; B&W = Babcock & Wilcox; AC = Allis Chalmers

** Key for mode of failure; SC = Stress Corrosion; BC = Borated Water Corrosion

1. The information in this table is taken from NUREG-0943 (9).

Table 1-2

SUMMARY OF DEGRADED THREADED-FASTENER INCIDENTS INVOLVING COMPONENTS SUPPORTS[1]

Degraded Threaded Fasteners in Component Supports	Number of Plants	Plants	Year Reported
Steam Generator Support Bolts	6	Surry 1	1974
		Surry 2	1974
		Sequoyah 1	1977
		Sequoyah 2	1977
		Prairie Island 1	1980
		Prairie Island 2	1980
Steam Generator Support Imbedded Anchor Studs	2	Ginna	1970
		Haddam Neck	1973
Reactor Vessel Imbedded Anchor Studs	1	Midland	1979
Piping Restraint Imbedded Anchor Bolts	1	Palo Verde	1981
Reactor Coolant Pump Support Bolts	1	Waterford	1981

Note: Total Number of Plants = 11; Total Number of Incidents = 11

Table 1-3

SUMMARY OF DEGRADED THREADED-FASTENER INCIDENTS INVOLVING COMPONENT INTERNALS[1]

Degraded Threaded Fasteners in Component Internals	Number of Plants	Plants	Year Reported
Reactor Vessel Internals - Thermal Shield Bolts	4	Big Rock Point	1968
		Yankee Rowe	1968
		Oconee 1	1981
		Oconee 2	1982
Reactor Vessel Internals - Holddown Bolts for Ring Shim	1	Palisades	1972
Main Steam Isolation Valve Internals - Studs	1	D.C. Cook 1	1981
Service Water Pump Internals - Impeller Capscrew	1	Surry 2	1981

Note: Total Number of Plants = 7; Total Number of Incidents = 7

1. The information in these tables is taken from NUREG-0943 (9).

Table 1-4

INCIDENTS OF STRESS CORROSION OF THREADED FASTENERS[1]

Plants	Year Reported	Components & Parts	Materials of Parts	Contributing Factors	Corrective Action
LaCrosse (BWR)	1970	Reactor Vessel Closure Studs (3.5" Diam.)	12% Cr Martensitic Stainless Steel (ASTM A437-B4B)	• Aqueous Environment During Outage • Improper Heat Treatment of Material • Galvanic Action Resulting from Silver Plating Breakdown • Pretension	• Replaced with Studs Made from A540-B23, Class 4 Material • Augmented Inservice Inspection Ultrasonic Test Surveillance
Ginna	1970	Steam Generator Support Anchor Studs (1-3/8" Diam)	Low Alloy Steel (AISI 4140)	• 160 ksi Pretension • Humid/Wet Borated Water	• Replaced with Studs Made from A490 Material • No Pretension
Haddam Neck	1973	Steam Generator Support Anchor Bolts (2" Diam.)	Low Alloy Steel	• Pretension • Water Leakage	• 24 of 256 Bolts Replaced • Pretension Reduced on Replaced Bolts • Microswitch Installed on All Bolts for Monitoring
Surry 1	1975	Steam Generator Support Bolts	Maraging Steel (Vascomax 250)		• Replaced with Cd-Plated Vascomax 250 Bolts
Surry 2	1975	Steam Generator Support Bolts	Maraging Steel (Vascomax 250)		• Replaced with Cd-Plated Vascomax 250 Bolts
San Onofre 1	1977	Steam Generator Manway Studs	Low Alloy Steel (AISI 4140)(A193-B7)		• 8 Studs Replaced
Midland 1	1979	Reactor Vessel Skirt Flange Imbed Anchor Studs (2-1/2" Diam.)	Low Alloy Steel (AISI 4140, 4145)	• Improper Heat Treatment of Material • Excessive Preload of 87-92 ksi	• Remaining Studs Detensioned to 6 ksi • Upper Lateral Support Installed on Vessel

Table 1-4 (Continued)

INCIDENTS OF STRESS CORROSION OF THREADED FASTENERS[1]

Plants	Year Reported	Components & Parts	Materials of Parts	Contributing Factors	Corrective Action
Arkansas 1	1978	Steam Generator Manway Closure Studs	Low Alloy Steel (AISI 4340)		• 2 Cracked Studs Replaced
	1980	Steam Generator Manway Closure	Low Alloy Steel (AISI 4340)	• Use of Thread Lubricant Containing Molybdenum Disulfide • Preload	• 3 Cracked Studs Replaced Surveillance
Oconee 3	1980	Steam Generator Manway Closure Studs (2" Diam.)	Low Alloy Steel (SA320, Grade L-43) (AISI 4340)	• Use of Thread • Lubricant Containing Molybdenum Disulfide • Trapped Moisture	• All Studs Replaced (Thread Lubricant Containing Molyb-denum disulfide was applied)
Prairie Island 1	1980	Steam Generator Column Support Bolts (1-1/2" Diam)	Maraging Steel (Vascomax 250) (A538, Grade B)	• Excessive Preload (1400 ft-lb torque)	• Replaced with Studs Made from Same Material • Pretension Reduced
Prairie Island 2	1980	Steam Generator Column Support Bolts (1-1/2" Diam)	Maraging Steel (Vascomax 250) (A538, Grade B)	• Excessive Preload (1400 ft-lb torque)	• Replaced with Studs Made from Same Material • Pretension Reduced
Rancho Seco	1980	Valve Studs	Stainless Steel Type 410 (A193-B6)	• Improper Heat Treat-ment of Material	
D.C. Cook	1981	Main Steam Isolation Valve Internals - Studs	Low Alloy Steel (AISI 4340)	• Primary Steam • Possible Use of Thread Lubricant Containing Molybdenum Disulfide • Possible Over-Torque	

Table 1-4 (Continued)

INCIDENTS OF STRESS CORROSION OF THREADED FASTENERS[1]

Plants	Year Reported	Components & Parts	Materials of Parts	Contributing Factors	Corrective Action
Oconee 1	1981	Reactor Vessel Internals - Thermal Shield Bolts	A286 Stainless Steel	• Borated Water Environment • Preload of 32 ksi and 32 ksi Bending	• Lower Thermal Shield Redesigned • Use of Inconel X-750 Studs and Nuts
Oconee 2	1981	Reactor Vessel Internals - Thermal Shield Bolts	A286 Stainless Steel	• Borated-Water Environment • Preload of 32 ksi and 32 ksi Bending	• Lower Thermal Shield Redesigned • Use of Inconel X-750 Studs and Nuts
Palo Verde	1981	Piping Restraint Imbedded Anchor Bolts (1-1/2" Diam)	Low Alloy Steel (AISI 4140) (A354 Grade BD)	• Improper Heat Treatment of Material	
Maine Yankee	1982	Steam Generator Manway Closure Studs (1-1/2" Diam)	Low Alloy Steel (SA540-B24)	• Gasket Leakage of Borated Water • Use of Furmanite Sealing Compound • Use of Thread Lubricant Containing Molybdenum Disulfide • Preload of 900 - 1100 ft-lb	• 10 Failed Studs Replaced with Studs of the Same Stock
		6" Gate Valve Bonnet-to-Body Studs (5/8" Diam)	Stainless Steel	• Valve Body-to-Bonnet Gasket Leakage of Borated Water	• Proposed Short-Term Action - Replace with AISI 4140 (A193-B7) Studs • Proposed Long-Term Action - Use 17-4 PH Studs

1. The information in this table is taken from NUREG-0943 (9).

Table 1-5

INCIDENTS OF FATIGUE OF THREADED FASTENERS[1]

Plants	Year Reported	Components & Parts	Materials of Parts	Contributing Factors	Corrective Action
Big Rock Point (BWR)	1964	Reactor Vessel Internals - Thermal Shield Bolts	Type 316 Stainless Steel (ASTM A276)	• Flow-Induced Vibration	• Support and Flow Pattern Modified
Yankee Rowe	1968	Reactor Vessel Internals - Thermal Shield Bolts	Type 316 Stainless Steel	• Flow-Induced Vibration	• Clamp Added to Each Thermal Shield Joint
Palisades	1982	Reactor Vessel Internals - Hold-down Bolts for Ring Shim (1/2" Diam.)	Type 304 Stainless Steel	• Improper Torque	• Broken Bolts Replaced • Proper Torque and Clearance

1. The information in this table is taken from NUREG-0943 (9).

Table 1-6

INCIDENTS OF BORATED-WATER CORROSION OF THREADED FASTENERS[1]

Plants	Year Reported	Components & Parts	Materials of Parts	Contributing Factors	Corrective Action
St. Lucie	1977	Steam Generator Manway Closure Studs (1-1/2" Diam)	Low Carbon Low Alloy Steel (SA540-B24)	• Manway Gasket Leakage of Borated Water	• 3 Studs Replaced • Gasket Replaced
	1978	Pressurizer Manway Closure Studs	Low Carbon Low Alloy Steel (SA540-B24)	• Manway Leakage of Borated Water	• 5 Corroded Studs Replaced
Calvert Cliffs 1	1980	Reactor Coolant Pump Closure Studs	Low Alloy Steel	• Possible Gasket Leakage of Borated Water	• 27 Studs Replaced
	1980	Steam Generator Manway Studs	Low Alloy Steel	• Gasket Leakage of Borated Water	• 11 Studs Replaced
Ft. Calhoun	1980	Reactor Coolant Pump Closure Studs (3-1/2" Diam.)	Low Alloy Steel (AISI 4140) (SA193-B7)	• Flexitallic Flange Gasket Leakage	• 9 Studs Replaced
	1981	Reactor Coolant Pump Closure Studs (3-1/2" Diam.)	Low Alloy Steel (AISI 4140) (SA193-B7)		• Corroded Studs Replaced
Arkansas 1	1981	Steam Generator Manway Closure Studs	Low Alloy Steel	• Closure Gasket Leakage of Borated Water	• Corroded Studs Replaced
Calvert Cliffs 2	1981	Reactor Coolant Pump Closure Studs	Low Alloy Steel	• Possible Gasket Leakage of Borated Water	• 12 Studs Replaced
	1981	Pressurizer Manway Studs	Low Alloy Steel	• Seal Leakage of Borated Water	• 2 Studs Replaced
D.C. Cook 2	1981	Check Valve Bonnet Bolts	Low Alloy Steel (AISI 4140) (SA193-B7)	• Valve Body-to-Bonnet Gasket Leakage of Borated Water	• All Studs Replaced

Table 1-6 (Continued)

INCIDENTS OF BORATED-WATER CORROSION OF THREADED FASTENERS[1]

Plants	Year Reported	Components & Parts	Materials of Parts	Contributing Factors	Corrective Action
Kewaunee	1981	8" Motor-Operated Valve Body-to-Bonnet Studs	Low Alloy Steel	• Valve Body-to-Bonnet Gasket Leakage of Concentrated (12%) Borated Water	• Corroded Studs Replaced
Oconee 2	1981	Reactor Coolant Pump Closure Studs	Low Alloy Steel	• Closure Gasket Leakage of Borated Water	• 1 Stud Replaced
Oconee 3	1981	Reactor Coolant Pump Closure Studs	Low Alloy Steel	• Closure Gasket Leakage of Borated Water	• 1 Stud Replaced

1. The information in this table is taken from NUREG-0943 (9).

Table 1-7

INCIDENTS OF EROSION-CORROSION OF THREADED FASTENERS[1]

Plants	Year Reported	Components & Parts	Materials of Parts	Contributing Factors	Corrective Action
Zion 1	1979	Chemical and Volume Control System Valve Bolts	Low Alloy Steel (AISI 4140) (SA193-B7)	• Valve Gasket Leakage of Borated Water	• Degraded Bolts Replaced • Valve Bonnet Reassembled

1. The information in this table is taken from NUREG-0943 (9).

Table 1-8

INCIDENTS OF OTHER TYPES OF DEGRADATION OF THREADED FASTENERS[1]

Plants	Year Reported	Components & Parts	Materials of Parts	Contributing Factors	Corrective Action
Sequoyah 1	1977	Steam Generator Support Bolts (1-1/2" Diam.)		• Quench Cracks	• Bolts Replaced
Sequoyah 2	1977	Steam Generator Support Bolts (1-1/2" Diam.)		• Quench Cracks	• Bolts Replaced
Arkansas 1	1980	Emergency Feed-water Turbine Steam Inlet Bolts	Carbon Steel (AISI 1215)	• Wrong Material (Understrength) • Waterhammer Loading	• All Bolts Replaced with Low Alloy Steel (AISI 4140) Bolts
Pilgrim 1 (BWR)	1981	Valve Limit-Torque Operator Motor Holddown Bolts			• Bolts Replaced
Surry 2	1981	Service Water Pump Impeller Capscrew	Carbon Steel		• Broken Capscrew Replaced • All Impeller Capscrews to Be Replaced with Stainless Steel Capscrews
Vermont Yankee	1981	Valve Limit-Torque Operator Motor Mounting Bolts			• 4 Mounting Bolts Replaced
Waterford	1981	Reactor Coolant Pump Support Bolts	A490 Alloy Steel	• Improper Torque • Some Bolts Too Short	• Failed & Short Bolts Replaced • Bolts Retorqued with Cali-brated Torque Equipment • Quality Assurance Plan for Bolting Improved

1. The information in this table is taken from NUREG-0943 (9).

Section 2

INDUSTRY RESOLUTION OF THE BOLTING ISSUE

INTRODUCTION

The AIF/MPC Task Group on Bolting, with assistance from EPRI and other industry groups, formulated a comprehensive Generic Bolting Program to address the issue of degradation and failure of threaded fasteners in nuclear power plants. The goals of this program were to provide definition of the critical aspects of the issue, and to consolidate industry resources in order to supply an appropriate response to the bolting integrity question. Work under this program ranged from corrosion and fracture mechanics studies to nondestructive examination (NDE) methods development to codes and standards activities to maintenance and training tasks. Technology exchange between program participants and with general utility engineering and operations staff members has been emphasized in order to assure resolution of the issue. Nothing has been discovered during the course of the program that would raise undue concern with respect to bolting integrity, primarily because of the redundant nature of bolting in critical closure joints.

This section will provide an overall summary of the program tasks, including essential results, and will identify the recommendations that evolved from the work. Later sections will amplify upon these results.

BOLTING EXPERIENCE IN U.S. NUCLEAR PLANTS

There are millions of bolts used in commercial nuclear plants. In each unit, two or three thousand of these are used in the primary reactor coolant pressure boundary components, their internals and supports. While the number of reported bolting failures has increased over recent years, there is some evidence which indicates that the increase is a function of the increased number of installed bolts. It appears also that, as plant maintenance personnel gain experience during early plant operation, the incidents of leaking joints and reported failures decrease. The success history of fasteners is excellent when compared to the number of failures. There are four distinct bolting topics grouped by application and apparent failure cause, as described in Section 1 of Volume 1 of this report.

Failure Groups I, II, and IV have been addressed generically under the auspices of the Joint AIF/MPC Task Group on Bolting. Pressure boundary bolting (Groups I and II) has a greater influence on system integrity and, therefore, had the highest priority in the industry program. Internals bolting (Group III) was effectively addressed by component vendors and owners' groups and was not considered generically. Supports/embedment bolting (Group IV) had a secondary priority in the industry program. The remainder of this section focuses on the elements of the pressure boundary and supports/embedment generic program.

GENERIC INDUSTRY PROGRAM ON PRESSURE BOUNDARY AND SUPPORTS BOLTING

The question of fastener integrity is very complex and involves many disciplines (e.g., metallurgy, fracture mechanics, mechanical and corrosion engineering) and activities such as bolt tension control, NDE, design, specifications and standards, manufacturing, and quality assurance/control. Research activities have focused on understanding, identifying and implementing solutions to the various topics. The research work on bolting is in three key areas: structural integrity analysis (including nondestructive examination), corrosion studies, and maintenance improvements.

EPRI has completed a Generic Bolted Joint Integrity Program which addressed both pressure boundary and structural support bolted connections. The program also provided technical support to the Joint AIF/MPC Task Group on Bolting and was integrated with the larger industry program. A major contribution of the program was a methodology for evaluating the safety significance of individual fastener degradation or failure on the overall bolted connection. The consequences of joint degradation in terms of leakage and leak-before-break margin for pressure boundary joints was examined. This approach was an alternative to individual fastener integrity assessment. Since one of the principal design features of a bolted connection is its structural redundancy, this alternative seemed more realistic, provided that acceptance criteria for both safety and reliability could be met.

The ultimate goal was to use the generic analytical methodologies developed by EPRI for bolted joint integrity assessment, supplemented by industry experience and data - both nuclear and non-nuclear - to demonstrate the safety margins in both pressure boundary and structural joints, and to recommend realistic inspection or maintenance programs for utilities.

PROGRAM ACCOMPLISHMENTS

The EPRI Generic Bolted Joint Integrity Program has now been completed, with the highlights to be discussed in this section. For convenience, these highlights will be referred to the nineteen tasks in the Joint AIF/MPC Task Group on Bolting action plan.

Task 1 - Assessment of Priorities and Safety Significance, Aptech Engineering

An experience base of bolt failures and/or problems was generated and analyzed under Task 1.1. Of the five types of pressure boundary closures studied -- from pressurizer manways, steam generator manways, reactor coolant pump seals, reactor coolant pump flanges, and valves -- steam generator manway bolting exhibited the highest total reject rate. Irrespective of the basis for the rejection rate calculation, either based on the total number of bolts at risk or on the total service years for the bolts at risk, the steam generator manway bolting still had the highest rate. The complete evaluation is contained in Section 3 of Volume 2 of this report. Task 1.2 involved the use of decision analysis techniques to identify the technical parameters influencing bolting degradation and failure. This study was preliminary and scoping in nature, and did not result in a formal report.

Task 2 - Literature Survey of Carbon and Alloy Steel Fastener Corrosion in PWR Plants, Combustion Engineering, Inc.

This report was published separately from these volumes as an EPRI report (1) in December 1984. Much of the work is also discussed in Section 8 (Lubricants and Sealants) and Section 9 (Alternative Materials) of Volume 1.

Task 3 - Stress Corrosion Cracking of Low Alloy Quenched and Tempered Bolting Materials in Water Environment, Battelle-Columbus Laboratories

A final report has been written by R. Rungta and B.S. Majumdar of Battelle-Columbus Laboratories, "Stress-Corrosion Cracking of Alternative Bolting Alloys", March 1986 (2). The major elements of this report are given in Sections 8 (Lubricants and Sealants) and 9 (Alternative Materials) of Volume 1. The scope of the report was changed from the descriptions of Subtasks 3.1 (Fracture Mechanics Analysis) and 3.2 (Data Review), with the emphasis on the latter. Both laboratory and service experience were reviewed. Fracture mechanics considerations were emphasized in Task 15.

Task 4 - Inclusion of Hardness Test Data into the Bolting Database, Aptech Engineering

The results from this task are documented in the topical report, "Assessment of Field Hardness Measurements on Low Alloy Quenched and Tempered Bolting Materials", by E.L. Capener, R.C. Cipolla, and T.J. Feiereisen, Aptech Engineering Services, Inc., September 1986 (3). The report is contained in Section 7 (Field Hardness Testing Assessment) of Volume 2. These hardness measurements were also transmitted to the contractor integrating data into a bolting database.

Task 5 - Bolting Database

The results of an industry survey by the Materials Properties Council (MPC) gave rise to the BOLTS Database, which is discussed in Section 6 (Bolting Data Base) of Volume 2. The work was carried out by Materials Research and Computer Simulation of Goleta, California. MPC has acquired the database and the associated software from the contractor, and the system resides at Stanford University.

Task 6 - Bolting Specification Requirements Recommended to ASTM for Nuclear Power Plant Applications and Recommendations for Receipt or Preinstallation Inspection

Section 1 of Volume 2 contains "Utility Recommendations and Guidelines for the Purchase Specification and Receipt/Preinstallation Inspection Requirements for ASME Section III, AISC, ANSI/ASME B31.1, and ANSI B31.5 Bolts and Threaded Fasteners", which was developed as a result of this task. Section 2 of Volume 2 consists of the draft standard, "Standard Test Method for Equotip Hardness Testing of Metallic Materials", submitted to ASTM subcommittee E28.06. Actions are still pending with ASTM F16.02 (Structural Bolting) regarding quality control modifications.

Task 7 - ASME Bolting Requirements

Section 9 (ASME Code Reference Book) of Volume 2 contains the results of this task effort. One of the contributions is due to R.W. Schneider and M.E. Looram. The other contribution is due to M.E. Looram and J.H. Bickford. This section explains the current code rules, together with recommendations for clarification and amplification of existing requirements. These recommendations were also provided to the Industrial Fastener Institute for their review and possible use.

Task 8 - EPRI Development of Field NDE Techniques to Detect Wastage and Stress Corrosion Cracking

EPRI has completed an assessment of advanced ultrasonic techniques to detect wastage and/or stress corrosion cracking in pressure boundary and supports applica-

tions. The results of these efforts are contained in Section 7 (NDE of Bolting) of Volume 1, and are due to Southwest Research Inc. and Randomdec Computers.

Task 9 - Information Exchange

An EPRI/MEAC workshop was held in November 1985 in Charlotte, North Carolina to enhance technology transfer. This workshop was aimed primarily at informing maintenance personnel to the practical tools being developed in the bolting research program to aid in achieving leak-free joints. The workshop was a tremendous success, with participants agreeing that additional workshops would be useful. The videotapes that have been developed under the EPRI program to respond to Subtasks 9.2 and 9.3 are described in Section 10 (Training Package) of Volume 1.

Task 10 - Screening Strategy and Corrective Action for Pressure Boundary Bolting

The results of this task are covered in Section 3 (Pressure Boundary Bolting), and are due to the efforts of Aptech Engineering Services, Inc.

Task 11 - Recommendations for ASME Section XI Changes

ANSI/ASME Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components, is considering a rationalization of bolting inspection requirements to focus on "at-risk" applications in service-sensitive primary coolant boundary components. A Code case (presented in draft form in Section 6 of Volume 1) is being developed, as an outcome of the EPRI Generic Bolted Joint Integrity Program, that contains empirical rules for inspection frequency and acceptance requirements.

Task 12 - Recommendations to EPRI on Degradation of Fasteners Research Program

The results of this task caused a change in direction for the research effort described under Task 3. The Battelle-Columbus Laboratories project was altered in work scope to reflect the concerns of the Joint AIF/MPC Task Group on Bolting with respect to accelerated boric acid attack of carbon and low-alloy steel fasteners, molybdenum disulfide lubricant effects, and leak sealants for PWR primary system components.

Task 13 - Recommendations for Material Substitutions and Coatings

The results for this task are contained in Section 9 (Alternative Materials) of Volume 1. These results were adapted from the Battelle-Columbus Laboratories research report (2) described under Task 3.

Task 14 - Screening Criteria for Bolting Utilized in Component Support Applications

The results of this task are contained in Section 4 (Structural and Support Bolting) of Volume 1, and are due to the efforts of Aptech Engineering Services, Inc.

Task 15 - Fracture Mechanics Based Methodology for Assessing Integrity of Fasteners

The results of this task are contained in Section 10 (Fracture Mechanics of Structural Bolts) of Volume 2, and are based upon a report by Aptech Engineering (4).

Task 16 - Preload Technology Assessment

The results for this task are contained in Section 5 (Required Preload) of Volume 1, and are due to the efforts of Combustion Engineering, Inc.

Task 17 - Development of UT Procedure for Inspection of Ultra High Strength Low Alloy and Maraging Steels

This task was assigned to the Westinghouse Owners' Group. A summary of owners' group activities is provided in Section 5 (Owners' Group Summary) of Volume 1.

Task 18 - EPRI Work on High Strength Bolting

The results of this task are represented by a Babcock & Wilcox Company research project with EPRI, "Improved Stress Corrosion Resistance of High-Strength, Age-Hardenable Ni-Cr-Fe Alloys", RP2181-1; and by a Westinghouse Electric Company research project with EPRI, "Improved Stress Corrosion Resistance of Ni-Cr-Fe Alloys", RP2181-2. The reports from these projects are not contained in their entirety in these two volumes, since the work will be published separately. However, abstracts of these projects are provided in Volume 2.

Task 19 - Liaison with Owners' Groups

The Joint AIF/MPC Task Group on Bolting provided a convenient mechanism for maintaining the liaison between the EPRI Generic Bolted Joint Integrity Program and the various owners' group efforts.

Generalized Closure Integrity Model

Probably the most significant contribution of the EPRI Generic Bolted Joint Integrity Program was the development of the generalized closure integrity model, wherein the closure is modeled accurately, incorporating the load shedding and

redundancy inherent to bolted connections. With the evaluation based upon the overall closure, the details of individual fastener degradation are not required. As a result, the complexity of the calculations and data burdens are substantially reduced, and many of the areas of greatest uncertainty are avoided. Either wastage or stress corrosion cracking can be accommodated in the model.

The philosophy behind the model is analogous to the leak-before-break philosophy used in fracture mechanics evaluations of other pressure boundary components. The steps required to achieve the desired result, i.e., demonstrate that a degraded joint (due to wastage, cracking, etc.) has ample margin against catastrophic failure when the leakage from the joint reaches levels that have a very high probability of detection, include: knowledge of the degree of load shedding to adjacent fasteners due to fastener degradation, knowledge of the joint opening profile accounting for gasket spring back and flange distortion, realistic calculation of leak rates through the degraded joints, margin demonstration in load-carrying capability of degraded joint and margin definition.

This philosophy was initially successfully applied to a steam generator manway cover to show its load carrying capability. Example calculations indicated that, for a typical sixteen bolt joint, about three bolts must fail before a "detectable" leak (1 gpm) would occur. The stresses in the adjacent bolts increased by less than 30% (well below the yield strength of the bolts).

This work has been used as the basis for an ASME Section XI Code Case, where leak rate margins and nondestructive examination limits for bolting materials commonly used in primary pressure boundary closures are recommended (see Section 6 of Volume 1). Analytic methods for determining the structural behavior and leakage of a bolted closure for various amounts of bolt degradation have also been used for several additional essential components (check valve flanges, reactor coolant pump, main flange, and pressurizer manway flange). Initial results indicated that leak rates between 1 gpm and 10 gpm are possible without compromising the closure integrity. These analyses should provide sufficient basis for recommending revisions to present Code NDE requirements. Use of a leak-before-break criterion is considered an effective method of assuring closure integrity while reducing demands on NDE. This calculation clearly demonstrated the degradation tolerance of bolted connections.

Leak Tightness

Another significant result of the bolting program was the finding that the most desirable attribute of a bolted joint is its leak tightness. A recent NRC survey (6) demonstrated that over 90% of all bolted connections in the primary pressure boundary are leak tight. The key elements that contribute to leak tightness are: adequate joint design, proper cleanliness, proper gasketing, uniform and sufficient preload. It should be noted that all but the first element are controlled by station maintenance. The integrated bolted joint program addressed two aspects: the uniformity of preload, and evaluation of thread lubricants. The program findings indicated that a joint could be prepared with uniform preload in the bolts even with simple torque wrenches, if particular attention were paid to bolt-up. Recommendations included stepped torque values with multiple passes and verification of proper preload by ultrasonic or other methods. Studs are to be preferred over bolts for many applications. Leak tightness can be assured with proper care.

The second program finding was related to thread lubricants. The work included laboratory and field tests and indicated that the nickel-based lubricants can be substituted for those using molybdenum disulphides (MoS_2), with an upward adjustment of the nut factor and torque values (7). A recommendation was made to avoid these MoS_2-based lubricants when dissociation is even suspected, i.e., when the joint will be exposed to water and high temperatures. Reviews by Rungta and Majumdar (8) also included work in this area. The Materials Properties Council has done extensive studies on various thread lubricants and their contribution to SCC (9).

EPRI has developed two reference manuals (10,11) to address the selection of appropriate procedures for assembly and disassembly, inspection and verification of bolted joint performance. These manuals will serve as a repository of useful information learned from EPRI experimental and analytical programs and will give the utility industry guidelines for bolted joints. Several utilities are already using drafts of these guidelines in their efforts to enhance their bolting program. It is believed that the bolting reference manuals will satisfy the industry's need for guidance in this area.

On 20 September 1984, the Institute of Nuclear Power Operations (INPO) issued SOER No. 84-5 entitled, "Bolting Degradation or Failures in Nuclear Power Plants". INPO conducted an independent review of the issues and arrived at conclusions which

reinforced previous AIF recommendations. The SOER serves to highlight and provide a "road map through the issues to utilities". The INPO SOER depends heavily on AIF/MPC and EPRI programs.

CONCLUSIONS

The purpose of the Joint AIF/MPC Task Group on Bolting was to develop and execute the AIF program for resolution of the generic bolting issue. Since this has been accomplished and the work is complete, the Task Group was disbanded in November 1985. The AIF Subcommittee on Materials Requirements will be available to handle any residual problems.

This volume is one of two comprehensive documents on pressure boundary bolts and structural bolts for use by utilities. These are considered the final products from the program. They will be reviewed and approved by the AIF Subcommittee on Materials Requirements, then distributed to utilities and the NRC for their use and information in resolution of the issues.

The technical program underlying these volumes is an example of a cooperative effort between the utilities, the vendors and the NRC to resolve an issue with potential safety significance. Shortcomings in design, material specification, procurement and maintenance were identified. Fixes to alleviate concerns regarding pressure boundary bolt integrity were formulated and are being implemented. The implementation of the recommendations will result in improved plant availability and reliability, with reduced maintenance, man-rem exposure, and inspection costs.

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Section 3

PRESSURE BOUNDARY BOLTING

INTRODUCTION

Recent service experience with primary pressure boundary bolting in pressurized water reactors (PWR) indicated carbon steel fasteners can become degraded as a result of prolonged contact with primary coolant water at elevated temperatures (1,2,3). The closures in which bolting degradation has been observed include primary side manway covers of steam generators and pressurizers, coolant pump main flanges, and some primary valve flanges. Of the closures listed, the steam generator manway covers have been the most troublesome (4).

Individual fasteners have been observed to suffer from general corrosion (wastage) at the shank or threaded sections, or from stress corrosion cracking (SCC) at the thread root. Although degradation of individual fasteners has raised some questions with regard to closure integrity, operating experience also suggests that only a small number of closures have actually degraded while in service. It was believed that, by focusing on these "service sensitive" closures, a generic plan for addressing the integrity of a joint could be developed. Such a plan would also provide a rational basis for integrating appropriate mitigating measures, e.g., preload control, nondestructive examination (NDE), and leak detection capabilities, which could ensure the integrity of the primary pressure boundary.

A Bolted Joint Integrity Program has been sponsored by the Electric Power Research Institute (EPRI) with the main objective of obtaining a better understanding of the behavior of bolted closures. Primary emphasis was placed on the safety acceptance of the degraded bolted closure, but it was expected that improvements in closure reliability would occur as well. The purpose of this section is to present a leak-before-break strategy for resolving bolted closure integrity issues as a continuation of past work (5) and to show how this approach could be implemented through the ASME Boiler and Pressure Vessel Code (6).

LEAK-BEFORE-BREAK EVALUATIONS FOR CLOSURES

The leak-before-break criterion was originally proposed in the late 1960's as a means of estimating the necessary toughness of pressure vessel steels so that a surface crack could grow through a vessel wall, causing leakage to reach detectable levels before fracturing. This approach has been effectively used in the assessment of integrity issues for welded pressure vessels and piping components fabricated from ductile materials. If a component exhibits a leakage failure mode prior to the point where the actual integrity becomes questionable, then the demands on NDE methods other than leak detection can be reduced. Hence, the objective of any leak-before-break analysis is to show that leakage will always precede failure by a suitably safe margin.

The basic similarities between a bolted closure and a welded joint with respect to material selection, design requirements, control of fabrication processes, and preservice inspection suggest that an assessment plan for closures could make use of a leak-before-break criterion in much the same fashion as with welded pipes or vessels. Since one of the principal design features of a bolted connection is its structural redundancy, it seems plausible that a bolted closure, even with some degraded or failed fasteners, could meet acceptance criteria consistent with current industry practice, provided that ample safety margins and closure reliability could be demonstrated. As an alternative to current emphasis within the ASME Code on individual fastener integrity, an assessment strategy is proposed that will establish the acceptance of a closure provided that the following conditions are met:

- Leak-before-break of the closure is assured under the design basis conditions for the plant
- The safety consequences of closure leakage are acceptable
- The margin against break at the point when the leakage becomes detectable exceeds an acceptance level

A proposed assessment method for bolted closures based upon leak-before-break philosophy is depicted in Figure 3-1. The suitability of this methodology to closure evaluations will depend on available margins as dictated by the conditions required for closure failure, the amount of external leakage from the closure, and the availability of leak detection instrumentation. Clearly, the characteristics of joint behavior in terms of load redistribution and gasket unloading followed by flange separation must be quantified for valid and accurate determination of safety

margins. Load changes within the joint resulting from postulated bolt degradation (wastage or cracking due to corrosion) will cause the degraded regions of the closure to unload at the expense of neighboring regions which must carry a greater portion of the pressure loadings.

The parameters that govern bolt degradation and ultimately the integrity of a closure include the material condition, the closure loads, and the environment being contained. Because the SCC susceptibility of low alloy steels increases with increasing strength, the parameters that affect variability in strength are the most important, specifically: material specification, heat treatment, and nominal strength level. In this regard, a quality control plan that includes both routine fastener receipt inspection checks, with an appropriate sampling procedure, and a verification plan element using destructive examination techniques (for mechanical and chemical properties), based on a different sampling procedure, would help to address strength variability concerns. The stress-related variables include preloading method, preload level, anticipated service loadings, and the joint stiffness and load redistribution characteristics of the closure. Given suitable numerical methods, the closure displacements and bolt stresses can be computed for a wide range of degraded bolt conditions. Finally, the environmental variables include temperature, humidity, and the presence of corrosive agents. A range of possible initial degraded bolting conditions caused by these environmental effects should be parametrically considered, using service experience as a guide. The combination of material condition, closure loads, and initial degraded state can then be studied parametrically. From the results of these studies, acceptance requirements for service and inservice inspection can be recommended, based upon leak rates and available safety margins for given closure designs.

SERVICE SENSITIVE CLOSURES

The focusing of inspection and maintenance activities on service sensitive closures will allow for more effective resolution of equipment leakage problems. During the investigation of primary pressure boundary bolting problems, the AIF/MPC Task Group on Bolting and EPRI developed a statistical approach for analyzing bolt failure data, with a specific objective of identifying troublesome closures. The failure data were compiled primarily from utility responses to IE Bulletin 82-02 and Licensee Event Reports up to September 1984. It was the intention of the AIF/MPC Task Group that this field information, along with historical data on plant specific closure performance from preservice and hydrotesting, would identify the service sensitive closures.

The bolting failure data was used to estimate rejection rates for fasteners used in five closures (4): steam generator manways, pressurizer manways, valves, reactor coolant pump (RCP) seals, and RCP flanges. A summary of bolt rejection rates for all reported causes including boric acid corrosion, mechanical damage, cracking, etc., is given in Table 3-1. The rejection rates were computed on two bases: first on the total number of bolts at risk; and again, on the total service years for the bolts at risk. On either basis, the ranking of closure types is the same with the steam generator manways exhibiting the highest frequency of fastener replacements. The RCP main flange, pressurizer manway, and valves greater than 6 inches (15 cm) in diameter also were troublesome, but all exhibited rejection rates less than half that for the steam generator manway. The cause for rejection of generator manway studs was principally related to boric acid corrosion, as shown in Table 3-2. Galling and mechanical damage to threads were also major contributors to stud rejection, suggesting thread lubrication problems. It is important to note that SCC was only a small percentage (10.3%) of the causes for rejection.

Although one may question conclusions drawn from such limited data, the information does help to focus on the types of components requiring utility attention for improved maintenance practice, as well as identifying candidate closure designs for evaluation by leak-before-break analysis methods.

ANALYSIS OF TYPICAL CLOSURES

Primary Manway Cover

Although there are more than 300 primary manway covers on operational steam generators and pressurizers in United States nuclear plants, the basic design is very similar for all applications. Most covers are typically 27-inch (69 cm) diameter circular plates covering a 16-inch (40.6 cm) opening. The cover is 5.75 inches (14.6 cm) thick and held to the vessel by 16 studs. The 16 studs are fabricated from AISI 4340 steel according to either ASTM A193-B7 or A320-L43 specifications and are 1.875 inches (4.76 cm) in diameter. A 20-stud manway cover of similar geometry is also used by one PWR vendor. The 20 studs are smaller in size, typically 1.3 inches (3.3 cm) in diameter and fabricated from similar materials.

A three-dimensional finite element model was developed to study the deformation behavior of both cover designs as a function of stud preload and different degrees of stud degradation. A general purpose finite element computer program called ANSYS (7) was used to solve for cover displacements as a function of circumferential position, and the conditions under which the cover would separate from the

gasket. The finite element mesh for the 16-stud cover is shown in perspective view in Figure 3-2. The studs were modeled by beam elements which were connected directly to the solid elements. Orthogonal rigid links were connected to the beam element end nodes to induce stud bending when cover and flange surfaces do not remain perpendicular to the stud during loading. To simplify the analysis, the gasket was modeled as an elastic foundation represented by discrete uniaxial elastic springs. The elastic loading and unloading behavior of a spiral wound asbestos filled gasket was inferred from experimental cyclic stress deflection curves (8) and used to define the spring element stiffnesses. The deflections from the tests were matched to the actual manway by relating the gasket properties through ratios involving stress area and gasket thickness. Because of the massiveness of the vessel flanges, the flange surface was assumed to be rigid. Stud preload was established in the model by imposing a differential temperature between the studs and the cover. A nominal preload stress in each stud of approximately 30 ksi (207 MPa) and internal pressure of 2235 psi (15.4 MPa) were used in the study. Stud degradation was modeled by changing the area of individual bolt elements to simulate partial wastage or by removing bolt elements to model complete fastener failure. Greater reductions in area correspond to greater degrees of wastage.

The model shown is a 180° segment of the closure and its components. This model implies that the most severely degraded fastener lies on the plane of symmetry, and that the studs on either side of this most severely degraded fastener have the same degree of degradation, if any. It should be pointed out that the modeling of degradation that is not symmetric about the most severely degraded fastener would require a complete 360° representation. Also, a 90° model would imply symmetric degradation at 0° and 180°. Service experience shows that boric acid wastage is associated with leakage of primary coolant, typically at a single location in the circumferential direction (the bottom stud). Therefore, this 180° symmetric model is both reasonable and simple. Cover separation was predicted in the 20-stud model when approximately two studs were assumed to have failed; whereas, in the 16-stud manway, the cover first lifted away from the gasket when one stud was assumed to have failed. When increased amounts of degradation were permitted, including multiple stud failures, a redistribution in both gasket and stud loads was observed. The change in gasket load in a 20-stud manway from the "preload only" case through to various degrees of stud failures under internal pressure of 2235 psi (15.4 MPa) is shown in Figure 3-3. The uniform gasket load becomes nonlinear as the studs degrade, and eccentric pressure loading causes gasket compression to shift. The angular position at zero gasket load indicates the extent of cover separation.

Stud load redistribution was most significant for the five studs nearest to the degraded region. Figure 3-4 illustrates the load shedding and redistribution characteristics of the 20-stud manway for a range of conditions including a worst case of seven adjacent or contiguous studs completely failed (100% degraded). It was observed that the two studs nearest to the failed region received the greatest increase in load, while the second and third nearest neighbors received a smaller fraction. The load in the fourth and fifth closest stud decreased with the unloading caused by the reduced stiffness of the cover/flange joint. The applied pressure loading performed a greater amount of work in deforming the more flexible (degraded) portions of the closure, while slightly less work was done on the greater stiffness of the undegraded portions of the closure.

A similar trend in load change was observed in the 16-stud design, except that the load increase in the stud nearest the failed region was greater due to the fewer number of studs and greater angular distance between the fasteners. The load redistribution was most significant for the three nearest studs to the degraded region, as shown in Figure 3-5. Only the two nearest studs share an increased load, whereas the third nearest was observed to unload. The stud stress increased proportionately faster in the 16-stud manway for a given amount of closure damage; also, larger amounts of leakage would be expected.

Reactor Coolant Pump Main Flange

The main flange and cover of a Type E RCP was evaluated in the same manner as the manway closure. The pump cover consists of an insert plate and bolting ring with a bolt circle diameter of approximately 58 inches (147 cm). The insert and ring are held to the pump casing by 16 studs, 4.75 inches (12 cm) in diameter and approximately 36 inches (91 cm) long. The opening of the pump casing is 48 inches (122 cm) in diameter and the outside diameter of the ring is approximately 80 inches (203 cm). The studs are fabricated from AISI 4340 steel. Because the mating flange on the casing is of comparable size to the cover, the pump casing was also modeled so that the compliance of the mating flange was well represented.

The finite element model representing a 180° segment of the pump casing, flange, and cover is shown in Figure 3-6. The model was comprised of 1200 solid elements, with the studs being represented by beam elements attached to the solid body in the same manner as in the manway model. Two pressure retaining gaskets were used in the actual assembly of this pump; however, a single line of gasket (spring) elements of equivalent area and location was employed to simplify the model geometry.

The studs were preloaded by a differential temperature between the studs (beams) and the cover/body to give an approximate stretch of 25 mils (0.64 mm) translating to a stud stress of about 25 ksi (172 MPa). Internal pump pressure was assumed to be 2250 psi (15.5 MPa).

The unloading of the flange as studs were removed was similar to that observed for the manway cover, except that gasket unloading was more uniform with little or no increase in gasket compressive load. The ring/insert plate is expected to separate when only one stud was assumed to have failed. The increase in stud stress for various degrees of stud degradation is shown in Figure 3-7. The four closest studs to the degraded region were observed to carry increased amounts of load above their original level of approximately 35 ksi (240 MPa). The increase from the stud prestress of 25 ksi is due to prying action on the stud element (bending). This prying is caused by rotation (flexibility) in the insert plate and bolting ring. As with the manway cover, the two studs adjacent to the degraded region received the largest increase in load. The load ratios were greater than those of the manway cover studs because the pressure load is about nine times greater for the pump cover; that is, roughly the same pressure is acting over a considerably greater area.

Check Valves

Two bolted flange check valves, one small 6-inch (15 cm) swing check and another larger 10-inch (25 cm) check, were analyzed in a similar manner as the previous closures. The valve flanges complied with ANSI B16.5 steel pipe flange design, 1500 lb class. Check valves were selected for evaluation because they exhibited the most flange leakage problems, as documented in the analysis of bolting failure data (Section 3, Volume 2).

The 6-inch (15.2-cm) valve has a 14.25-inch (36.2-cm) diameter cover with a neck diameter of 7.825 inches (19.9 cm). Twelve 1.25-inch (3.2-cm) diameter studs hold the cover to the body with a specified preload torque of 500 ft-lbs (680 J). The 10-inch (25-cm) valve has a 19.875-inch (50.5-cm) bonnet covering an 11-inch (28-cm) diameter opening. Sixteen studs, 1.625 inches (4.1 cm) in diameter, are used in this design. The stud material is the same for both valves, specifically ASTM A193-B7.

The 3D finite element models of the two valves are shown in Figures 3-8 and 3-9. Both models are 180° symmetric representations containing approximately 700 elements in each. Because of the importance of flange stiffness on stud load, the

valve bodies also were modeled. The basic modeling of the studs and gasket followed that of the previous analyses. A uniform preload of approximately 35 ksi (240 MPa) was applied to the studs and the internal pressure was 2250 psi (15.5 MPa).

The unloading of the flange due to stud degradation was similar to the manway cover analysis except that the 10-inch (25 cm) valve was less uniform, probably because of the nonsymmetric valve flange body geometry. The redistribution of the original 37 ksi (255 MPa) bolt stress is shown in Figures 3-10 and 3-11. Cover separation would be expected somewhere after two contiguous studs fail, although the specific analysis to show conditions for bonnet liftoff was not performed. The load redistribution in the 10-inch (25-cm) valve was relatively uneven between two and four contiguous stud failures. Nevertheless, the stress ratios are reasonably similar for the two valves, considering the greater density of studs (i.e., 16 studs compared to 12) in the larger valve.

LEAK RATE PREDICTIONS

Model Description

Selection of an appropriate model for predicting flow through a slit will depend on the fluid conditions and geometric characteristics of the crack (Figure 3-12). In this case, the slit is represented by the gap between the unloaded portion of the gasket and the previously mating flange surface. The ratio of flow path length to characteristic dimension (i.e., hydraulic diameter) defined as L/D, is used to specify the degree of thermal nonequilibrium of the escaping fluid. A leak rate model following this approach based on Henry's homogeneous nonequilibrium critical flow model (9) was developed by Collier, et al. (10), and subsequently modified by Abdollahian and Chexal (11). The general features of the discharge of initially subcooled to saturated liquid through a slit is shown in Figure 3-12. In the region: $0 < L/D < 3$, a liquid jet surrounded by a vapor annulus is formed. For lengths between $L/D = 3$ and $L/D = 12$, the liquid jet breaks up into droplets at the surface and small bubbles are entrained within the jet. It is assumed that no mass or heat transfer takes place between entrance and $L/D = 12$ and also that the friction pressure drop in this region is negligible.

The flow is assumed to be isoenthalpic and homogeneous, and all nonequilibrium effects are introduced through a single parameter which is a function of equilibrium quality and flow path length to diameter ratio L/D. The one-dimensional mixture mass and momentum conservation equations are used to evaluate the pressure drop components. The continuity equation is:

$$\frac{dG}{dZ} + \frac{G}{A}\frac{dA}{dZ} = 0 \quad , \tag{3-1}$$

where G is the mass flux, A is the slip opening area, and Z is the direction of flow coordinate. The momentum equation is:

$$- \frac{dP}{dZ} = \frac{1}{g_c} \left[\frac{1}{A}\frac{d}{dZ} \left(\frac{G^2A}{\rho'}\right)\right] + \frac{f}{2D}\frac{c^2}{\rho_m} \quad , \tag{3-2}$$

where P is the pressure, g_c is the gravitational acceleration, ρ' is the momentum density equal to the mixture density (ρ_m) for the homogeneous flow assumption, f is a friction factor, and c is the sonic velocity. Eq. 3-2 can be integrated along the flow path to evaluate the overall pressure drop across the slit as the sum of individual drop components to give:

$$\Delta P_{total} = \Delta P_e + \Delta P_{ae} + \Delta P_{aa} + \Delta P_f \quad , \tag{3-3}$$

where ΔP_e is the entrance pressure loss, ΔP_{ae} and ΔP_{aa} are the acceleration pressure drops due to fluid phase change and area change, respectively, and ΔP_f is the friction pressure loss.

The solution of the above expressions requires an iterative process for a given set of stagnation conditions and slit geometry. The details of the numerical procedure are given elsewhere (11,12). For situations where the flow is not choked, the leak rate is calculated from single phase relations with friction included:

$$G = 2g_c \frac{(P_o - P_B)^{1/2}}{v_o} \tag{3-4}$$

where P_o and v_o are the pressure and the specific volume at stagnation, respectively, and P_B is the back pressure. Calculated leak rates by the above methods have agreed well with experimental studies (10).

Computed Closure Leakages

The leak rate for each closure was calculated by the computer program PICEP (12), which was modified to accommodate the expected slot openings for the bolted flange connections as determined from the finite element results. The subcooled fluid conditions for a pressure of 2235 psi (15.4 MPa) and 2250 psi (15.5 MPa) at a tem-

perature of 600°F (316°C) were assumed. Leak rate estimates for all the previously analyzed closures are presented in Figure 3-13. The RC pump main flange showed the greatest capacity for producing large leak rates owing to the large diameter of the sealing surface and smaller number of studs per arc length. The manway covers and valve bonnets exhibited similar leak rates and trends. Being a smaller closure with somewhat stiffer mating surfaces, the 6-inch (15-cm) valve was predicted to produce smaller leak rates for the lesser levels of stud degradation. It should be pointed out that while the reduced number of studs in the small valve did not reflect itself in a greater shift in load to adjacent studs following stud failure, the same cannot be said for the leak rate. The stiffness of the mating surfaces helps adjacent studs share the redistributed load, but the reduced density of studs can lead to significant leakage as the degradation becomes more severe.

For the closures analyzed, a leak rate of one gallon per minute (1 GPM = 0.042 kg/s) is achieved when approximately one to three studs have failed. The available margins at 1 GPM (0.042 kg/s) are shown in Table 3-3, where the safety factor is based on load required to fail one of the studs adjacent to the degraded region by net section tensile overload. In this determination the direct (σ_m) and bending (σ_b) stresses were conservatively added and compared with specified minimum strength properties. The 6-inch (15.2-cm) valve exhibited the smallest margin for the condition where about 28% of the studs have failed but, because of the smaller pressure load, a safety factor of 2.2 still existed. The pump and manway covers all exhibited reasonable margins at the 1 GPM (0.042 kg/s) leak rate.

IMPACT OF CLOSURE INTEGRITY ASSESSMENTS ON NONDESTRUCTIVE EXAMINATION

With reference to the requirements in Section XI of the ASME Code, two areas where closure integrity assessments would affect NDE are the extent of examinations (IWB-2000) and the flaw acceptance standards (IWB-3000). The extent of examination for pressure retaining bolting is divided into two categories as dictated by bolt size. Category B-G-1 covers principally volumetric examination of bolting whose diameter is greater than 2 inches (5.1 cm). Category B-G-2, for bolting 2 inches (5.1 cm) in diameter or less, specifies visual surface examination only. The NDE requirements were developed from conventional bolted joint fabrication applications; however, the nuclear power plant field experience previously presented called the volumetric/visual examination cutoff at 2 inches (5.1 cm) into question. If the field data provided a statistically representative measure of primary pressure boundary closure performance, service sensitive closures could be identified and appropriately ranked and NDE requirements established based on known closure performance and on likely failure modes. The NDE requirements developed from such

an approach would not necessarily be the same as those in the 1983 edition of the Code. It would be expected that any alternative approach would emphasize volumetric examination with supplemental visual/volumetric NDE for those situations where leakage from the closure has occurred during service.

An added consideration relating to the extent of examinations is the level of personnel radiation exposure that accrues to NDE. Service experience in nuclear power plants may indicate that service sensitive closures should be subject to enhanced NDE, and the repair of degraded bolted joints should reduce personnel radiation dose levels. Leak-before-break analysis, on the other hand, permits the trade-off between NDE personnel exposure and plant operational personnel exposure to be treated on a rational basis.

Category B-G-1 acceptance standards for nonaxial flaws are 0.250 inch (0.64 cm) and 1 inch (2.5 cm) for axially oriented flaws. Closure assessment based on leak-before-break will provide a relationship between leak rate and closure integrity as measured in terms of bolt degradation. By selecting a minimum required safety margin, which may vary for different service loading levels, the results from a closure assessment would give the basis for establishing NDE requirements. The logic of integrating a leak-before-break approach into a determination of requirements and criteria for NDE is shown in Figure 3-14. From an established set of safety margins, a range of degraded conditions would be postulated that maintains a constant level of closure safety. Leak rates would be computed for the range of postulated conditions and the minimum leak rate used to establish detectability limits. Likewise, the type and extent of degradation used in the analysis for leak rates would provide the basis for selecting NDE requirements and levels of acceptance. Clearly, the sample analyses presented herein provide sufficient bases for initiating Code revision.

SUMMARY AND CONCLUSIONS

Closure integrity assessments can provide a rational basis for recommending revisions to the present ASME Code NDE requirements. Satisfying a leak-before-break criterion is an effective strategy for assuring closure integrity, while at the same time balancing the demands on NDE and minimizing personnel radiation exposure. Preliminary analyses of various primary pressure boundary closures (steam generator and pressurizer manways, RCP main flanges, and check valves) suggested that integrity can be assured by monitoring closure leakage in excess of operational limits. Large leak rates were calculated when a few fasteners were assumed to have failed.

Adequate safety margins can be demonstrated provided that the closure damage is localized. A proposed ASME Section XI Code Case based on this work is provided in Section 6 of Volume 1.

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Table 3-1

REJECTION RATES FOR BOLTING IN PRIMARY PRESSURE BOUNDARY CLOSURES (ALL CAUSES)

Closure Type	Total Bolts at Risk (%)	Total Bolt Service Years (%)
Steam Generator Manways	5.81	3.98
Reactor Coolant Pump Main Flange	2.85	2.48
Pressurizer Manways	2.28	1.20
Valves [>6-Inch (>15.2 cm) Diameter]	2.10*	--
Reactor Coolant Pump Seal Flange	0.82	0.85

*Estimated for all primary valves by statistical analysis (4). Note, bolts at risk is the total population of bolts inservice for the given closure during reporting period.

Table 3-2

STEAM GENERATOR MANWAY STUD REJECTIONS BY CAUSE

Cause for Rejection	Bolts Rejected	% of Total
Boric Acid Corrosion	116	37.1
Galled/Mechanical Damage/ Thread Damage/Removal Damage	65	21.3
Pitting/Removal Damage	65*	21.0
Stress Corrosion Cracking	32	10.3
Linear Indications	16	5.5
Cracks	5	1.6
Corrosion/Erosion/Steam Cut	4	1.2
Corrosion/Mechanical Damage	3	1.0
Other	4	1.0
	310	100.0

*61 at one facility for one event (Calvert Cliffs 2); Source IE Bulletin No. 82-02

Table 3-3

ASSESSMENT OF MARGINS AT 1 GPM (0.042 kg/s) LEAKAGE

Closure Type	Assumed Bolting Material	Percentage Failed Studs for 1 GPM Leak	Computed Factor of Safety at 1 GPM Leakage
16 Stud Manway Cover	A320-L43	15.9	3.2
20 Stud Manway Cover	A540-B24	14.5	3.0
RC Pump Flange	A193-B7	7.8	3.3
6-Inch (15 cm) Check Valve	A193-B7	27.5	2.2
10-Inch (25 cm) Check Valve	A193-B7	17.8	2.6

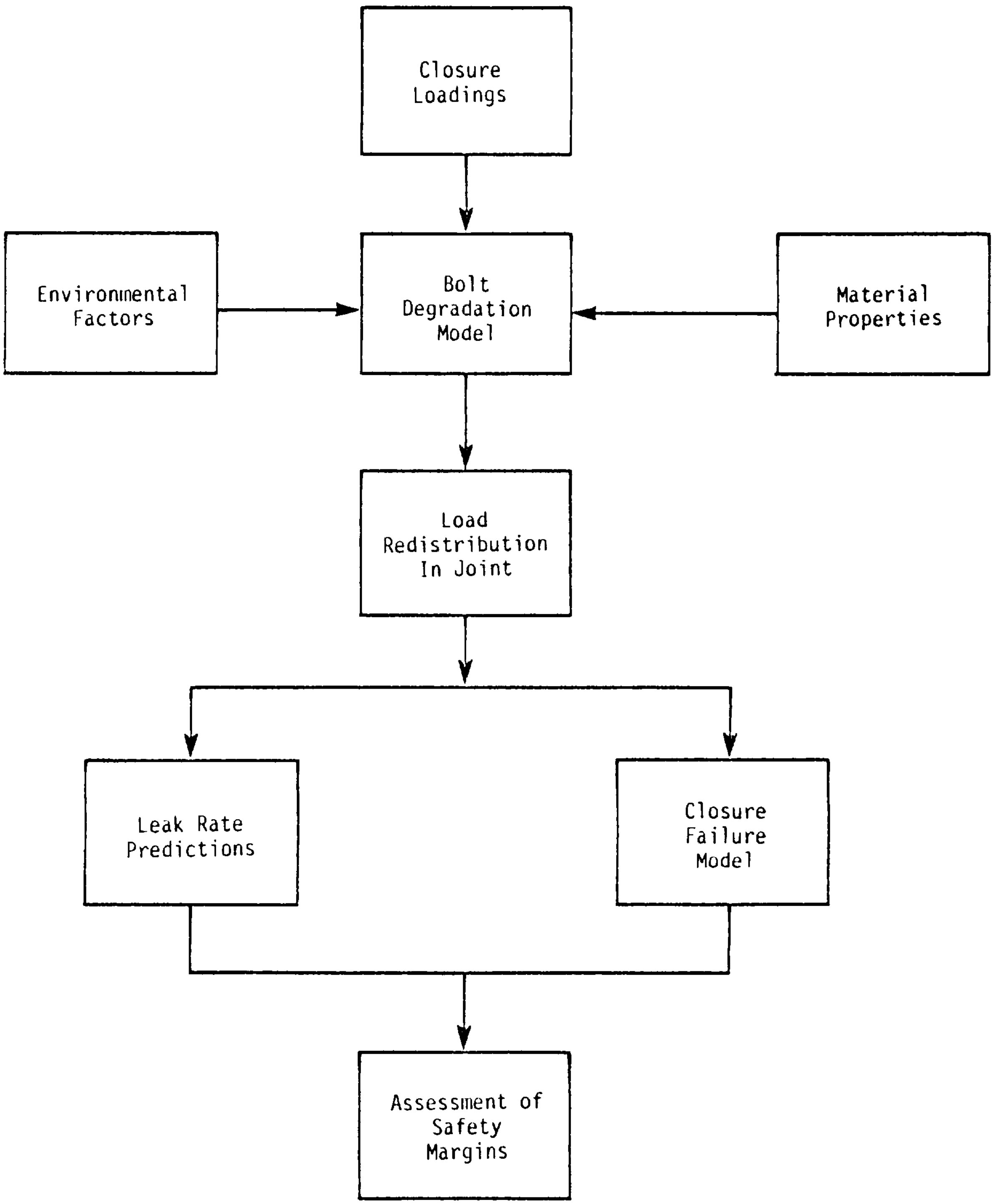


Figure 3-1. Closure Integrity Assessment Strategy

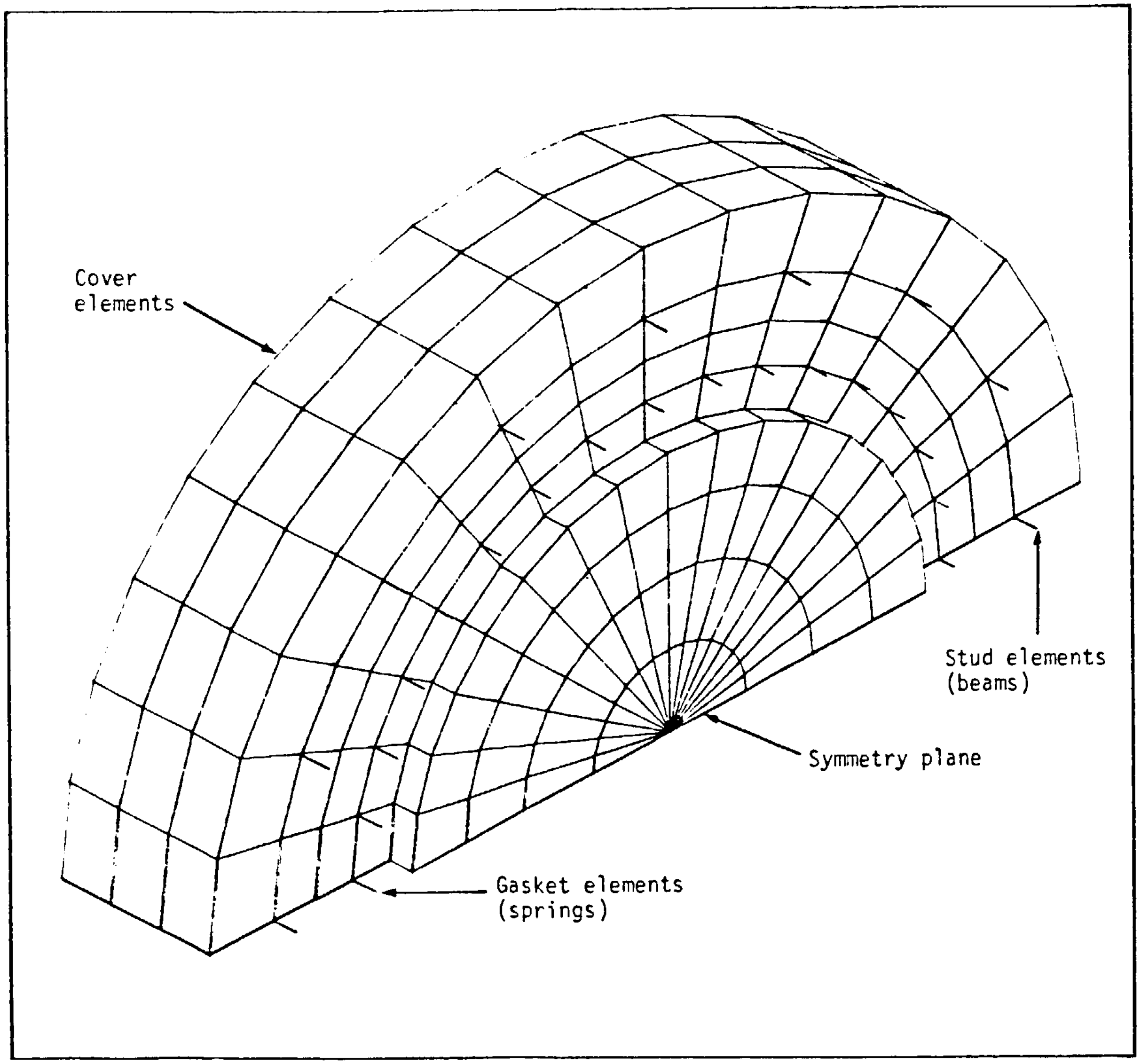


Figure 3-2. Sixteen-Stud Manway Cover Model

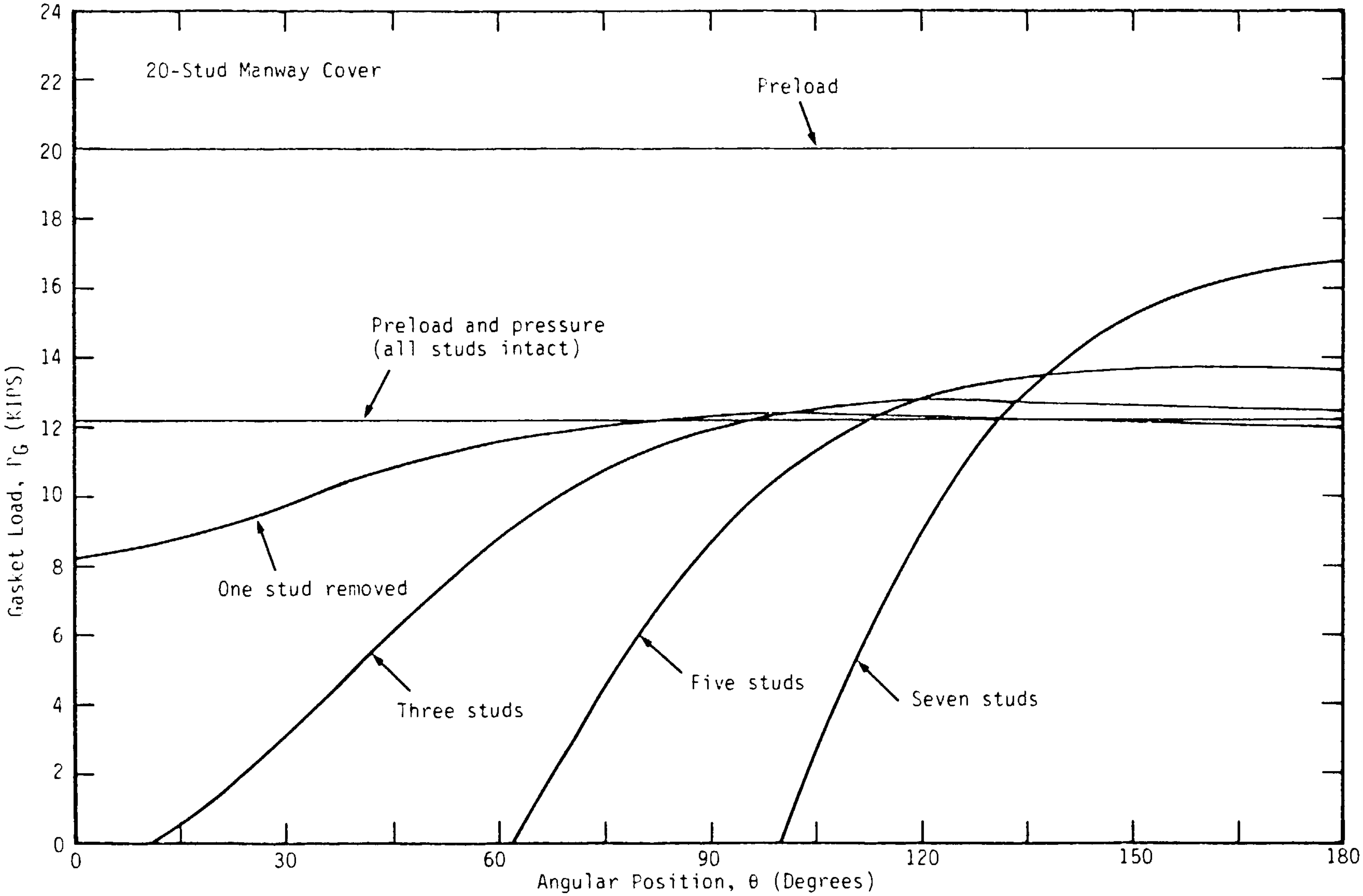


Figure 3-3. Gasket Load Redistribution for Different Stud Failure Conditions (Note: 1 Kip = 4.45 kN)

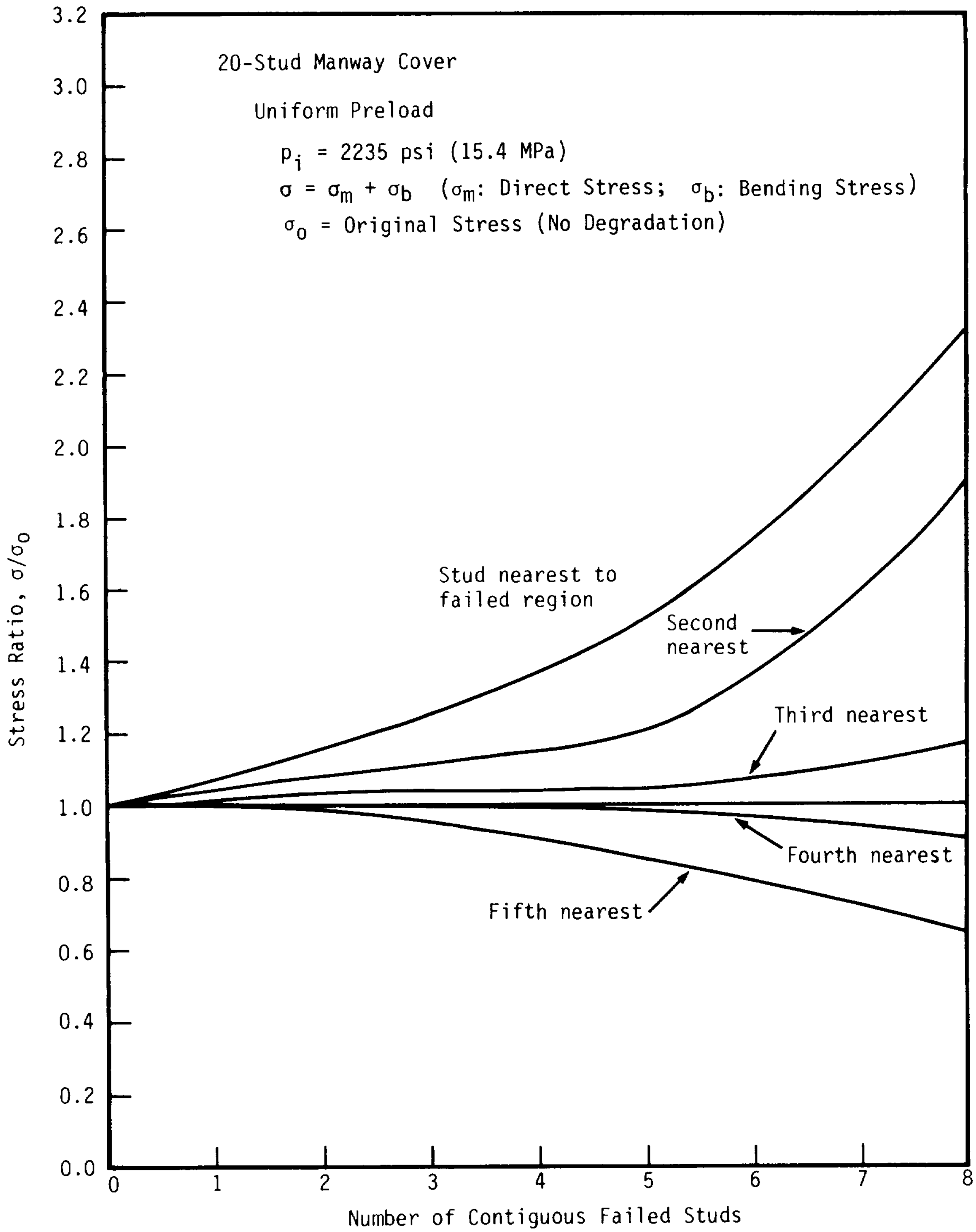


Figure 3-4. Load Redistribution in Five Nearest Studs to Degraded Region in a 20-Stud Manway

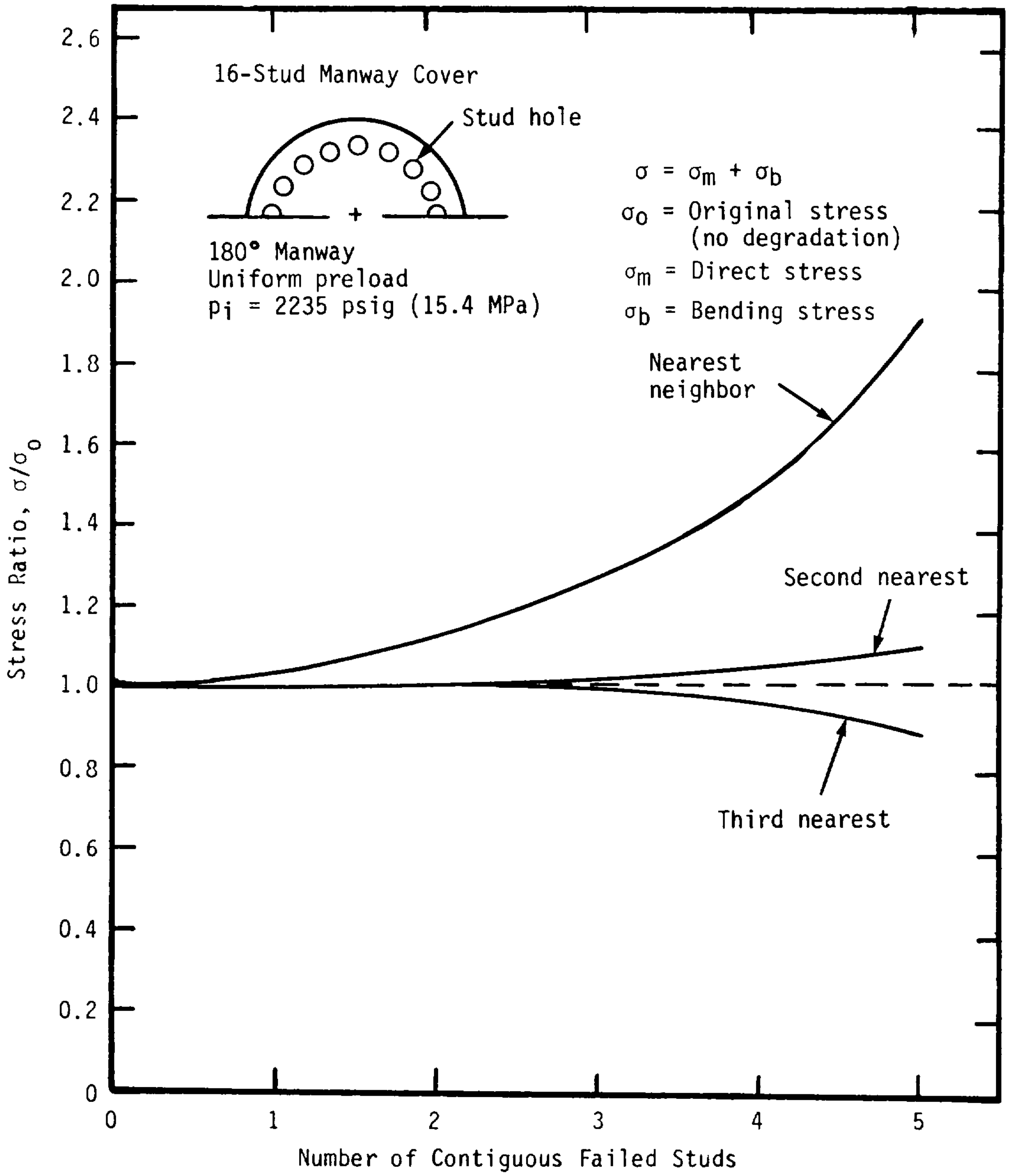


Figure 3-5. Load Redistribution in the Three Nearest Studs Due to Stud Degradation in a 16-Stud Manway

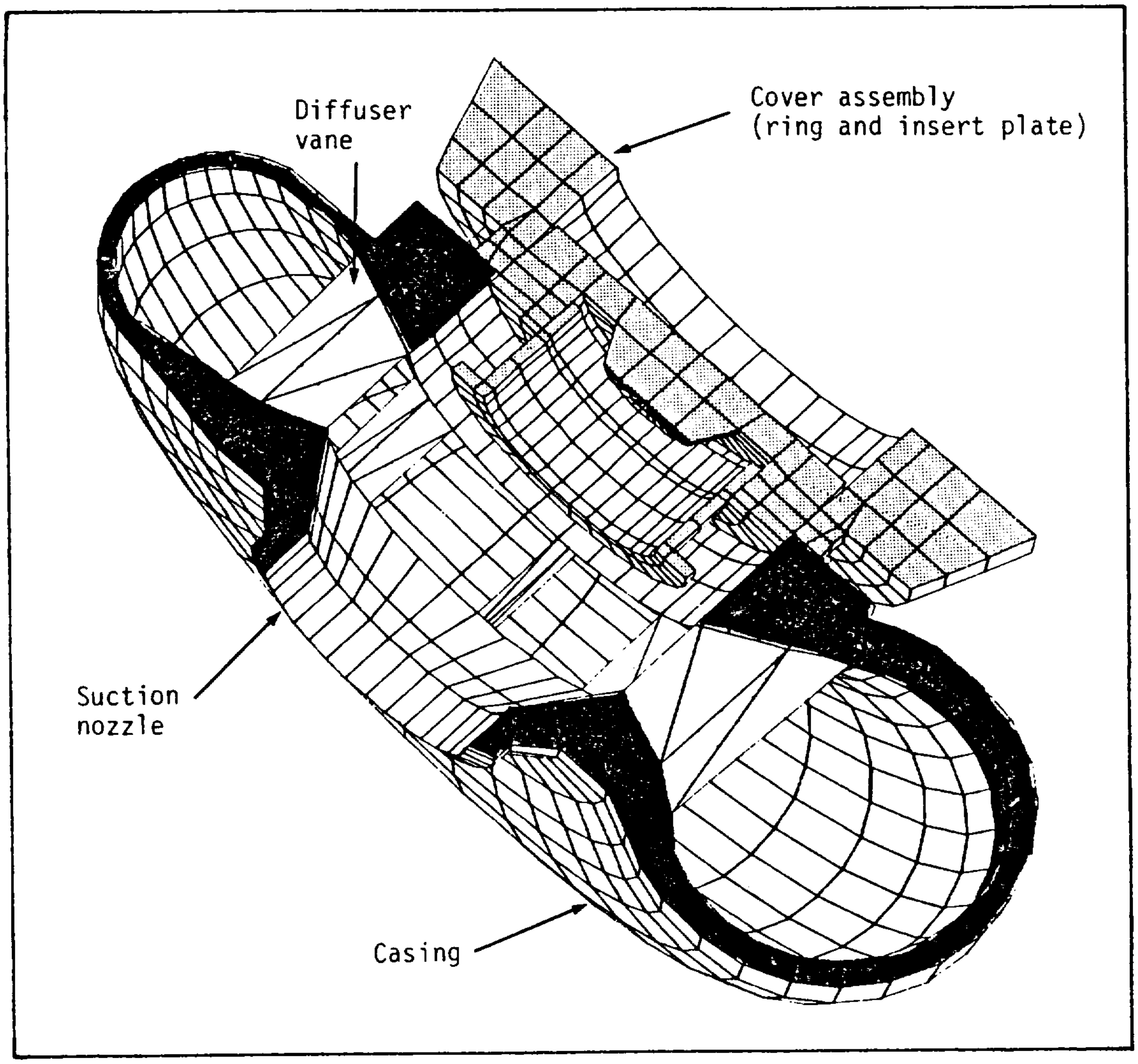


Figure 3-6. Reactor Coolant Pump Model

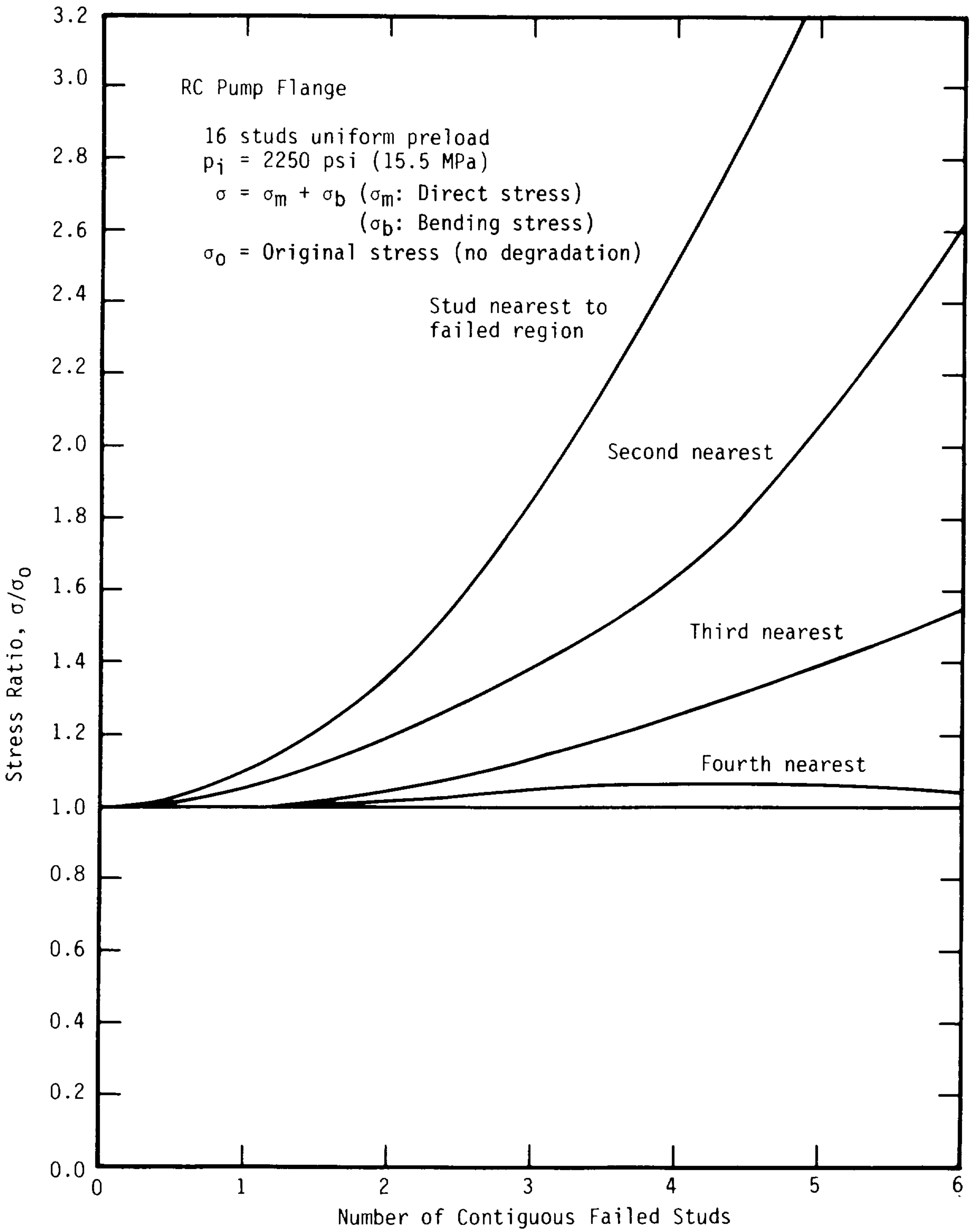


Figure 3-7. Load Redistribution in Reactor Coolant Pump Main Flange

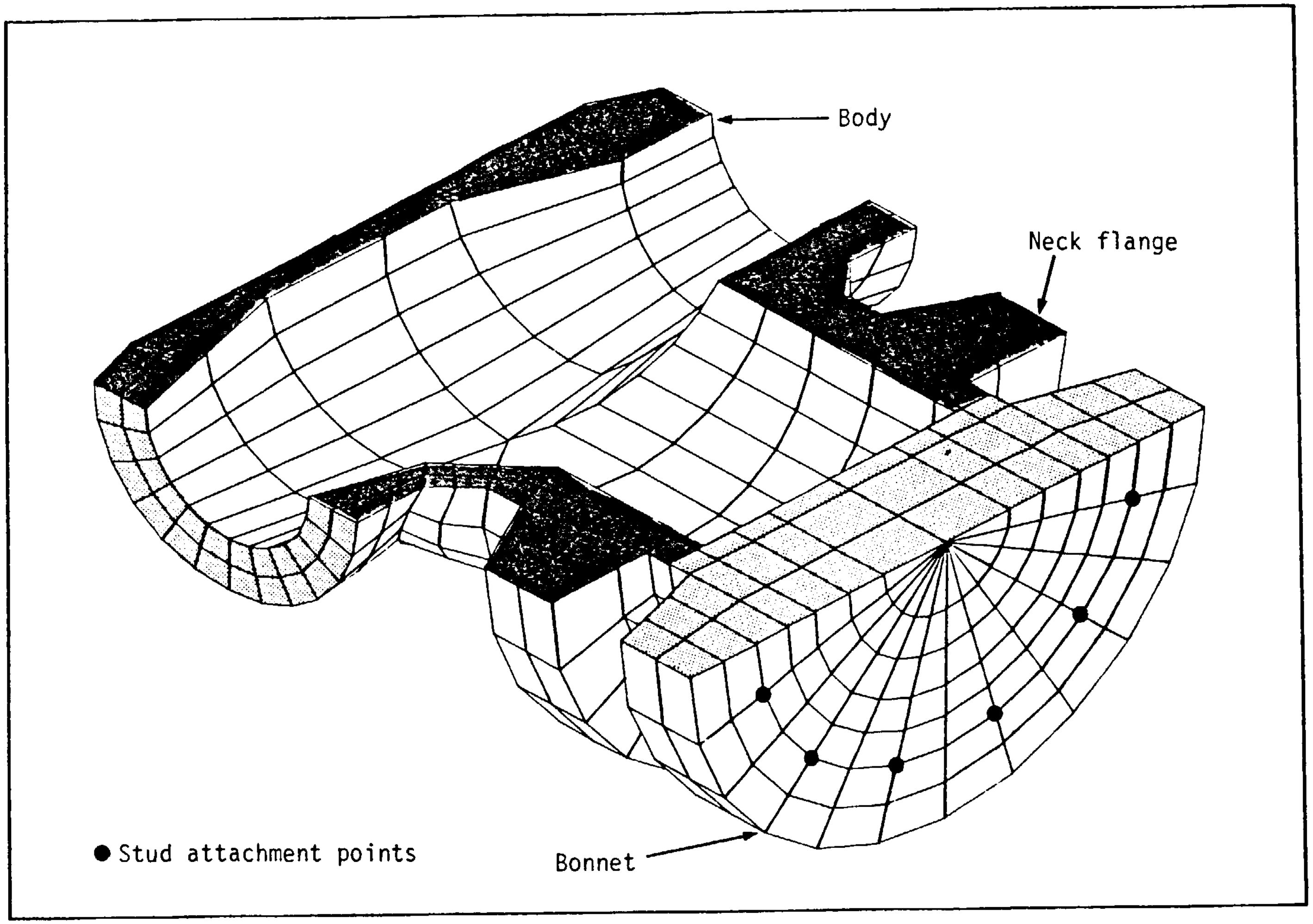


Figure 3-8. Six-Inch (15 cm) Check Valve Model

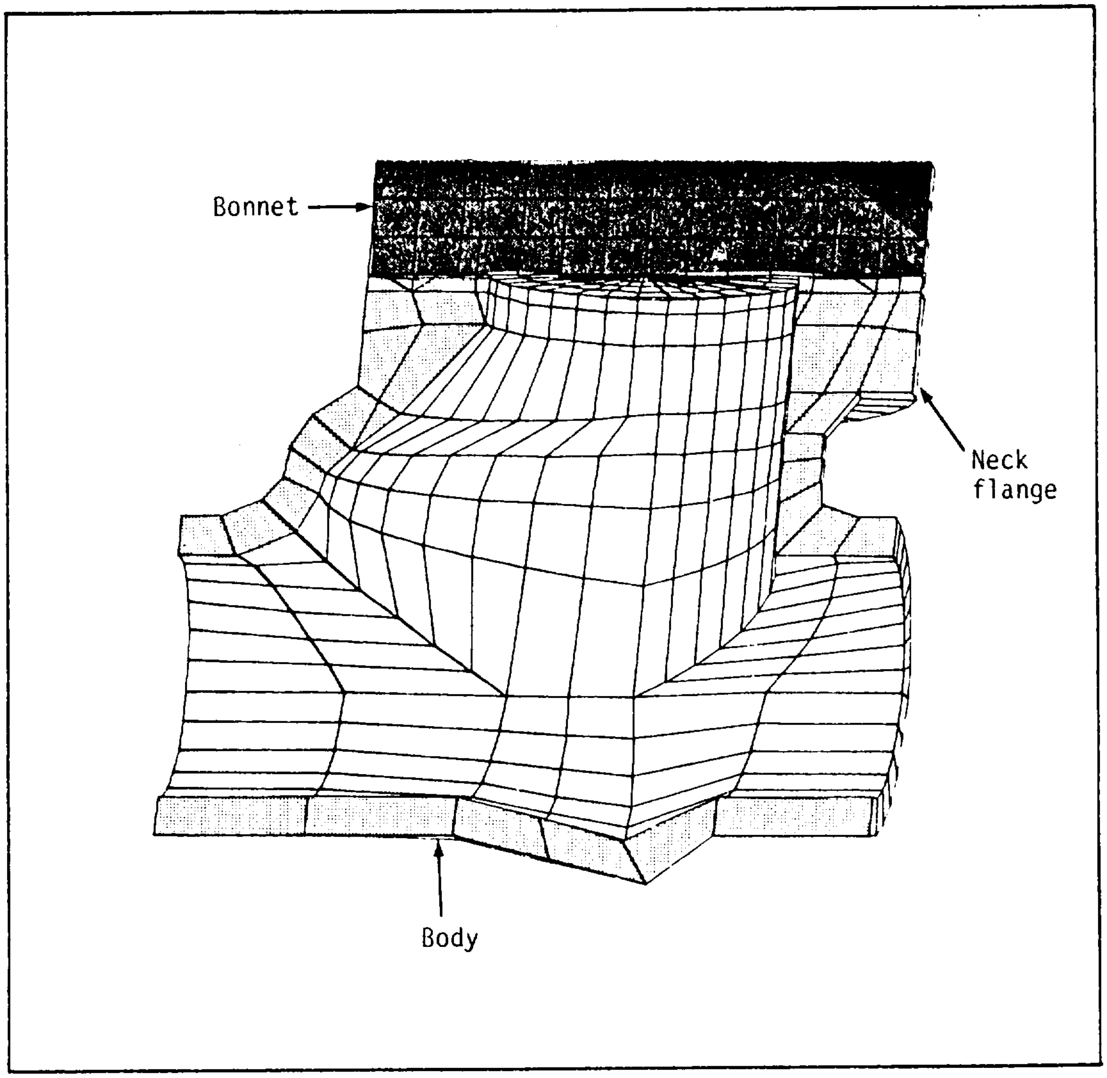


Figure 3-9. Ten-Inch (25 cm) Check Valve Model

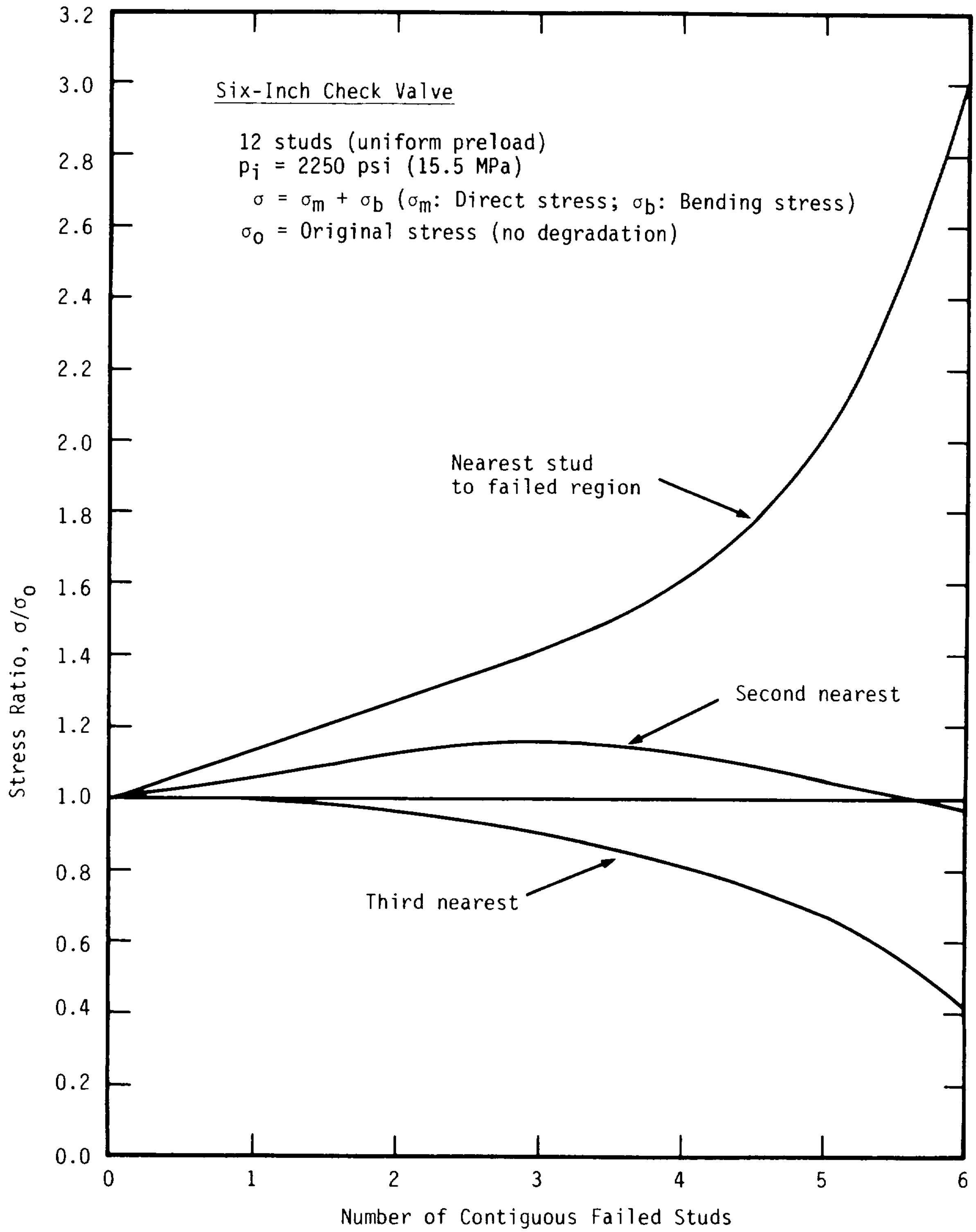


Figure 3-10. Load Redistribution in Three Nearest Studs to Degraded Region in a 6-inch (15-cm) Check Valve

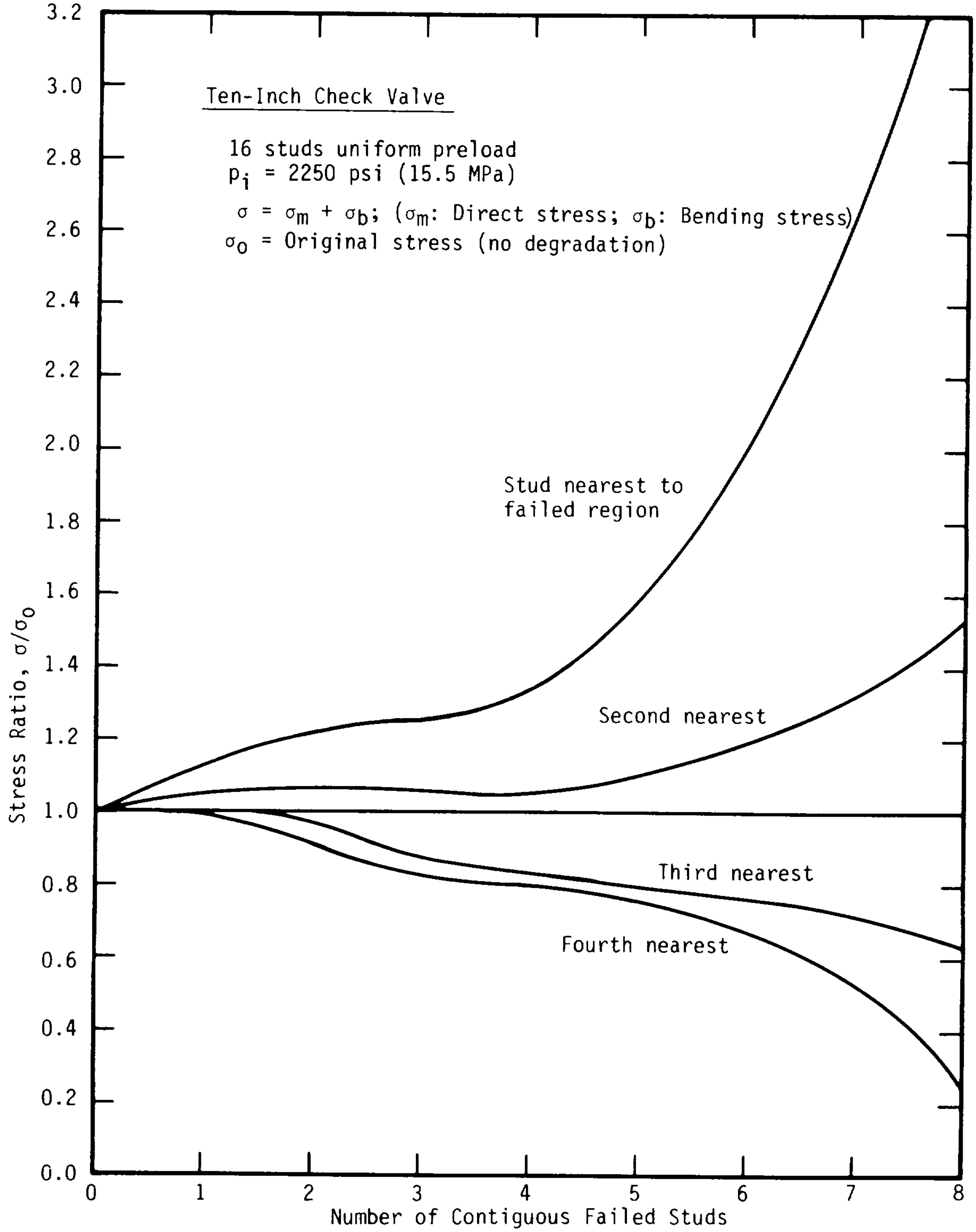
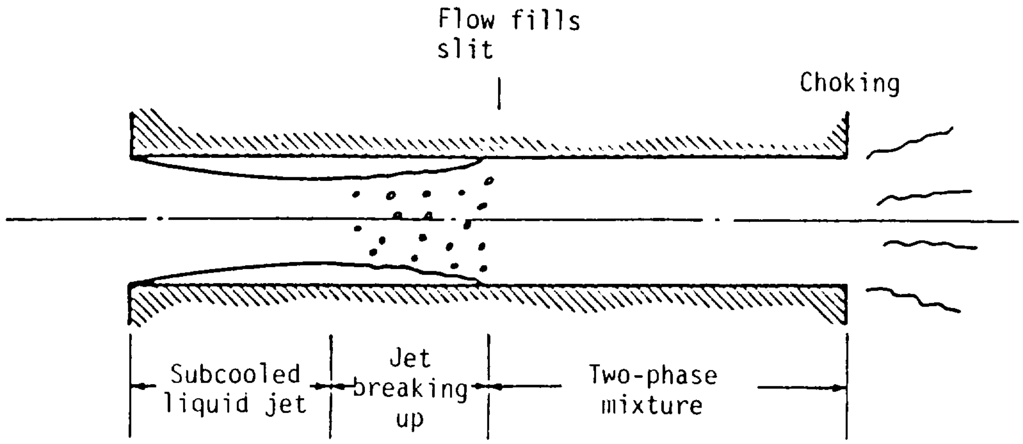
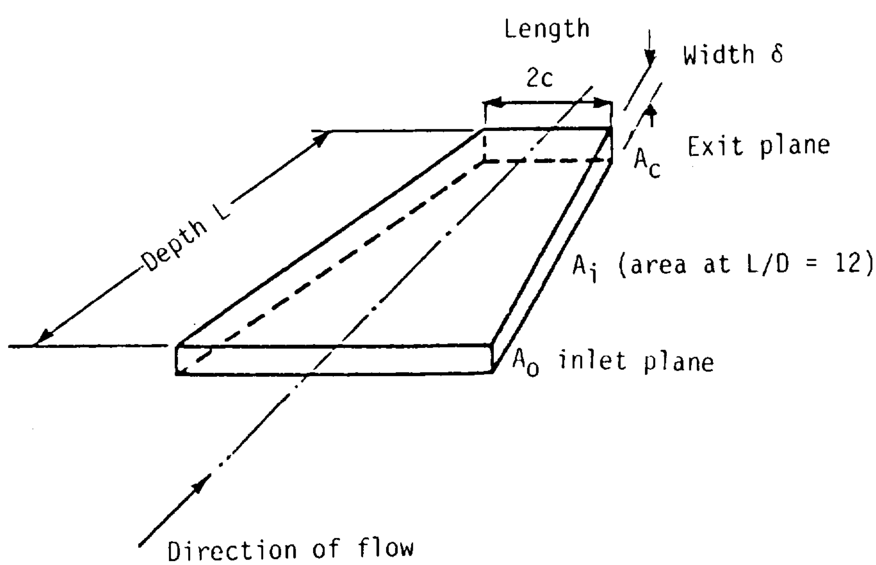


Figure 3-11. Load Redistribution in a 10-inch (25-cm) Check Valve



(a) Two-Phase Flow Through a Long, Narrow Crack.



(b) Geometry of a Convergent Crack.

Figure 3-12. Critical Flow Model for Leakage through a Crack

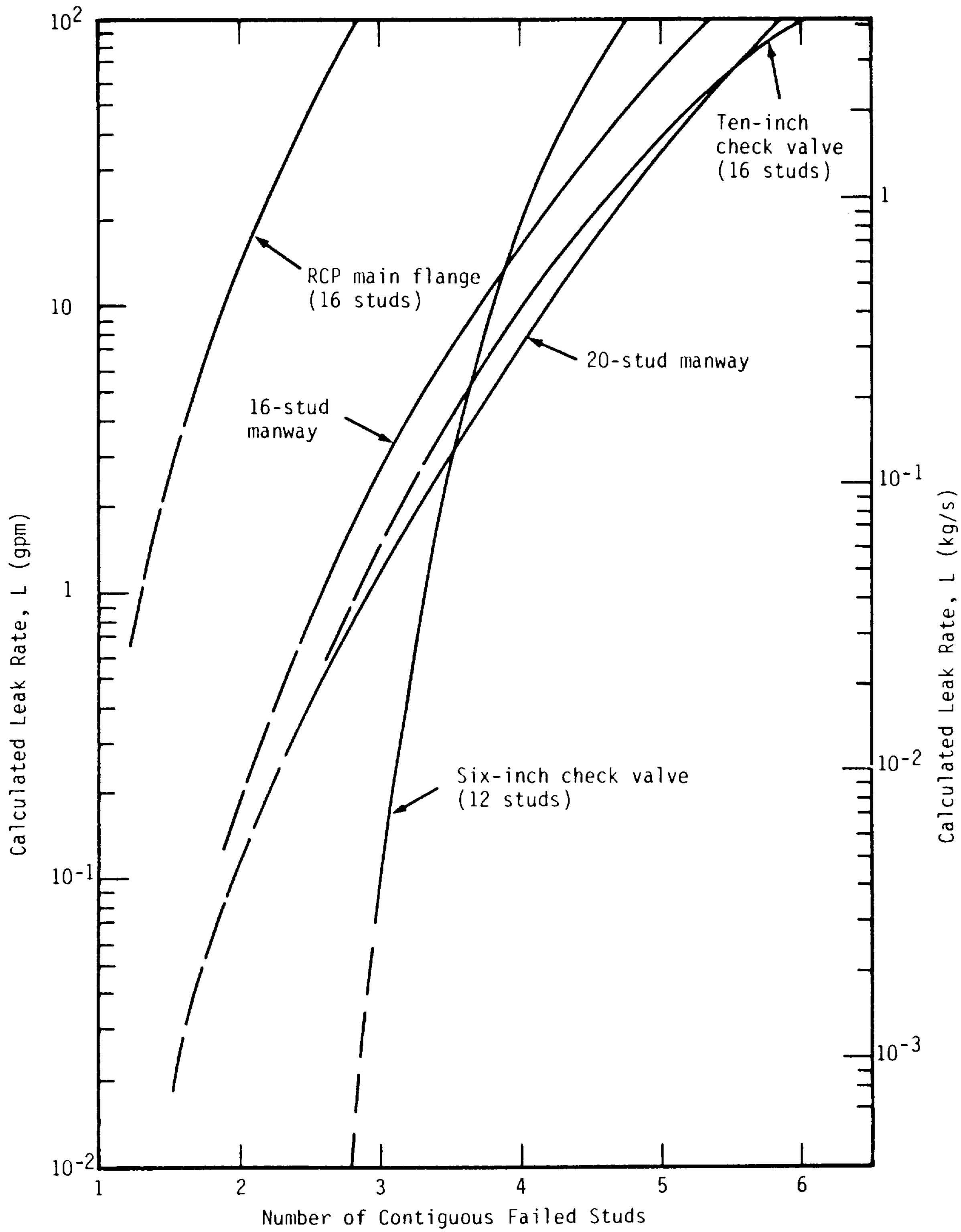


Figure 3-13. Leak Rate Predictions for Different Primary System Closures

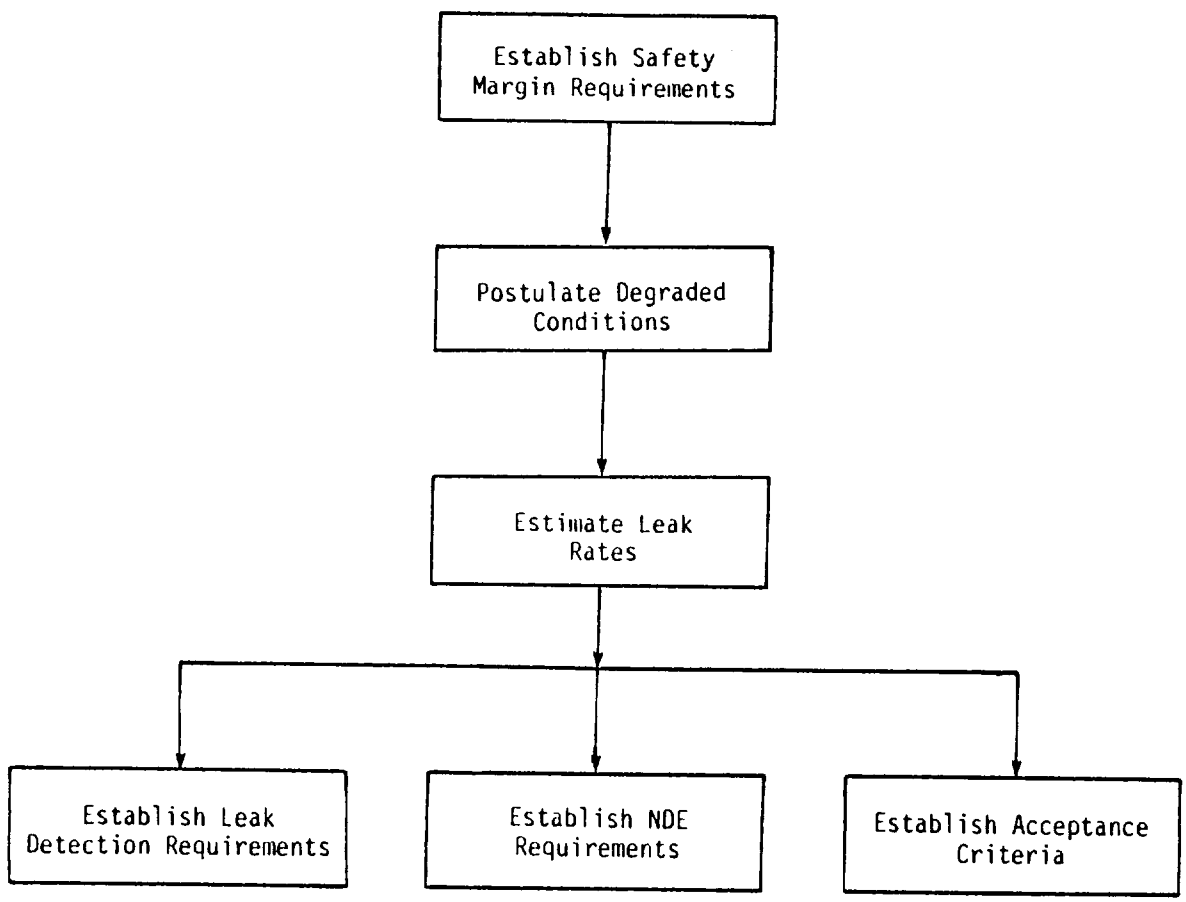


Figure 3-14. Flowchart Showing the Determination of NDE Performance Requirements and Acceptance Criteria

Section 4

STRUCTURAL AND COMPONENT SUPPORT BOLTING

INTRODUCTION

Background

Failures of structural bolting used in Class 1 component supports have been reported by some plants. A listing of reported failure events is provided in Table 4-1, compiled from an industry survey and from (1). In most cases, the failure events have been attributed to stress corrosion cracking (SCC); however, incidents also have been reported where bolts have failed by tensile ductile overload related to an understrength material condition. Common features of the failures by SCC were that high strength or overly hard materials were used in moist environments under high sustained tensile stresses. A key observation was that some materials were above the specified maximum hardness, and it is known that SCC susceptibility of the materials in question increases with increasing strength. Although some failures did not occur until the plant was under commercial operation, most events occurred during plant construction; all failures involving understrength materials were detected during the construction phase.

Recognizing the safety implications of these failure events, the U.S. Nuclear Regulatory Commission (USNRC) proposed an issue entitled, "Bolting Degradation or Failure in Nuclear Power Plants", and designated it as Generic Issue 29. This issue covers the NRC staff's concern with both pressure boundary and component support bolting. Although the primary concern of the NRC has focused on pressure boundary integrity, the reliability of component support structures under postulated accident conditions also is being considered.

Scope and Objectives

The scope of Task 14 of the AIF/MPC Task Group on Bolting action plan (see Section 1 of this volume) was to identify component support bolting which may be susceptible to SCC, and to recommend both generic and plant-specific review procedures. Therefore, this section addresses the plan for resolution of Generic Issue 29 with regard to component support bolting. The work reported in this section is based on

a review of field failure experiences and judgements with regard to purchase specifications, material performance, and past proposed regulatory requirements as they affect SCC susceptibility. Based on the review, a screening procedure was proposed that defined the structural bolting categories (i.e., application, size, materials, etc.) that may warrant generic industry scrutiny in this regard. Also contained in this section are recommendations for disposition of materials that are flagged by the screening procedure. These strategies for disposition are provided for guidance to utilities in developing plant-specific plans.

DEFINITION OF STRUCTURAL BOLTING ISSUES

Strategy

A strategy was developed which could serve as a procedure for resolving the structural (component support applications) safety aspects of the USNRC Generic Issue 29. The strategy focused on those structural bolting aspects with generic interest or impact. The scope of the recommended general evaluation procedure involved review of the following:

- An inventory of component support applications in which failures have occurred;
- The material specification requirements regarding product size, strength, hardness, and quality control sampling;
- Established Code requirements for bolting materials and product size, with attention paid to how well the requirements are met or what exemptions are employed;
- The use of relevant features of the SCC review plan proposed by the USNRC when the bolting issue was part of Unresolved Safety Issue (USI) A-12 (2,3);
- The evaluation (engineering analysis) of hardness data from field measurements made on installed and surplus bolting (4); Ref. (4) represents the completion of Task 4 of the AIF/MPC Task Group on Bolting action plan; the work is also presented in Section 7, Volume 2, of this report.

The results of a review of the above aspects of design and operation can be used to screen plant bolting. Susceptible bolting can be evaluated using analyses involving fracture mechanics concepts (including fracture toughness and SCC experimental results) and operating loads (service stresses for normal and accident conditions). The strategy allows the engineer to develop a plant-specific plan to evaluate bolting materials in component support structures that are included in USNRC Generic Issue 29. Adequacy (fitness for continued service) is established by demonstrating that the bolting exhibits resistance to both brittle fracture and SCC.

Support Applications

In reviewing component support applications in order to discriminate between those applications requiring attention and those that do not, field failure experience was used to create the historical record of component support bolting failures. These component supports are listed in Table 4-1. It should be noted that none of the observed field failures impaired the normal operation of the component being supported; hence, attention should be focused on the supports of critical primary system components subject to accident loadings. Since damage to Class 1 components due to support failure under postulated earthquake or LOCA is a concern for the primary pressure boundary, although of low probability, the generic review should emphasize the supports of Class 1 components. Field experience has shown that steam generator supports and their anchor bolting, and the anchor bolting of reactor coolant pumps and of reactor pressure vessels support skirts have suffered from degradation by SCC. Therefore, it seems reasonable that these bolting applications should be examined. It is recommended that pressurizer support bolting also be included in the review, since primary pressure boundary integrity concerns are similar for the pressurizer and other Class 1 components.

Sizes

The review procedures for toughness and SCC proposed by the USNRC (3) included the exclusions given in NF-2300 and NC-2300, which can be applied to bolting materials for the purpose of exempting certain materials and product sizes. Bolts and studs with a nominal diameter of one inch and less were exempt from both fracture toughness and SCC review under the proposed USI A-12 resolution. Since none of the failures occurred in bolts of less than 1.25-inch diameter, it is also recommended herein that only bolts or studs greater than one inch nominal diameter be considered in the review.

Materials

Bolting failure experience summarized in Table 4-1 indicates that two general classes of steel have been involved with the reported events -- high-nickel maraging steels and low-alloy, quenched and tempered (LAQT) steels. The field experience involving these bolting materials can be categorized into four groups:

1. Materials specified as high strength or ultra-high strength (S_y > 150 ksi, where S_y is the yield strength) that failed by SCC under a combination of stress and environmental factors.

2. Materials specified as medium strength (120 ksi < S_y < 150 ksi) that failed by SCC because poor heat treatment and material variability resulted in overly hard (high strength) material condition.

3. Materials specified as medium strength that failed by tensile ductile overload because of poor heat treatment practice (over tempering).

4. Low strength (S_y < 120 ksi) materials supplied to a medium strength requirement.

The selection of 120 ksi yield strength as a lower limit for medium strength materials was based on the 120 ksi cutoff limit in the proposed USNRC SCC review plan (3). In the above categorization, the Group 1 experience involved materials with intentionally high strength requirements, and the integrity of these materials is directly questioned by the field experience. These failure events included both maraging and LAQT type steels. All failure events occurred during service; multiple fastener failures have been observed. Therefore, it seems appropriate for the industry to examine the use of materials with specified minimum yield strengths greater than 150 ksi. Note that this recommendation is 30 ksi less than that recommended in NUREG/CR-3009 (5).

In contrast, the failure events associated with Group 2 involved unintentionally high strength materials. These failure events are related to poor quality control, with all bolt failures occurring and being detected during plant construction. Although it is possible that bolt degradation of these materials might not occur until the plant became operational, it seems less likely, in general, to expect failures within this classification, because of the small percentage of material that would exhibit high strength characteristics. There is a high probability that most failures in this group would be detected during plant construction because of the long lead times from initial component installation to commercial operation. It is proposed that materials in the range of 120 ksi to 150 ksi specified minimum yield strength be conditionally exempt from generic industry review. Several utilities are conducting field hardness studies to assess materials in this Group 2 category. Upon completion of these programs, the industry position with regard to the Group 2 materials may require reassessment. However, it is believed that these programs will demonstrate that most materials supplied in this strength range are within acceptable limits of strength based on SCC considerations. In the interim, problems with the Group 2 category should be handled on a case-by-case basis.

Group 3 and Group 4 can be referred to as problems associated with an understrength condition. This aspect of the field failure experience can be viewed as nongeneric because understrength material should be screened by the act of installation. For example, preload requirements of the American Institute of Steel Construction

(AISC) for structural applications (6) are stringent enough to uncover weak materials during installation. Furthermore, other preload requirements often establish minimum preload levels to ensure tight connections, and the live loads carried by the connection do not significantly increase the stress in the bolt above its initial preload level. Hence, it is expected that many connections will develop the highest stress at or near the initial preload stress. The reported failure events involving understrength materials all occurred during the construction phase and were detected during the installation process. Therefore, no generic concern exists for these situations.

PROPOSED SCREENING PROCEDURE

General

Based on the preceding considerations, a screening procedure was proposed to define the bolting applications requiring review. The proposed screening procedure was subdivided into two categories -- those situations requiring generic review and those situations requiring review on a case-by-case basis.

Generic Review

Structural bolting that requires generic industry review are those bolting applications that satisfy the conditions listed below. Bolting materials used as externally threaded fasteners in support of Class 1 components -- the specific Class 1 component support applications are:

- Steam generator support and anchor bolts or studs
- Reactor coolant pump support and anchor bolts or studs
- Reactor pressure vessel support and anchor bolts or studs
- Pressurizer support and anchor bolts or studs
- Only bolts or studs in sizes greater than one inch nominal diameter
- Materials with specified minimum yield strengths greater than 150 ksi

Recommendations for disposition of materials that satisfy the above conditions are provided later.

Case-by-Case Review

Bolts or studs fabricated from steels with specified minimum yield strengths less than or equal to 150 ksi are exempt from generic review. Where a utility has

experienced failures of these bolting materials, resolution of this situation shall be accomplished on a case-by-case basis by a plant-specific plan. Specific recommendations for disposition of such situations are given next.

RECOMMENDATIONS FOR DISPOSITION

Scope

It is anticipated that the materials remaining after the proposed screening procedure is completed must be addressed by plant-specific actions. The proper course of action will depend on many factors, including the material type, accessibility in the plant to the material, availability of surplus materials, etc. In view of these limitations, only general strategies for disposition have been developed.

Disposition Based on Mechanical Testing

Direct measurement of the mechanical properties that provide a measure of SCC susceptibility could be performed in a plant-specific plan. In this circumstance, it is clearly desirable to select a single property that is measured relatively easily in situ, is nondestructive, and will provide sufficient information to dispose reliably the material under scrutiny. In addition, the measurement program should be planned in such a way to ensure that reliable statistics are developed which can be exploited to minimize the need for measurement of all products under examination.

The hardness test is the principal candidate, because it is relatively simple to perform and, with proper procedures, can be performed in the field. From hardness measurements, estimates of tensile strengths are possible; from a knowledge of the mechanical behavior of individual materials, yield strength levels may be implied. From such considerations, it can be established reliably that proper strength levels have been achieved. Satisfactory hardness and strength properties serve to confirm proper heat treatment and, hence, microstructure. Furthermore, it is generally accepted that susceptibility to SCC correlates with yield strength, so that statements with regard to necessary levels of SCC resistance can be formulated.

Alternatively, on the basis of statistically significant data, a limited destructive testing program could be undertaken where strength and SCC resistance parameters (K_{ISCC}, e.g.) are measured directly. The scope of such a program would depend on the plant-specific requirements for disposition. Such programs, however, may be more costly and time-consuming to execute and complete, so that hardness testing is likely to be the preferred choice.

Disposition Based on Analysis

Analysis may provide a technical basis for ensuring bolt integrity by demonstrating either that (1) sufficient redundancy exists in the support design so that structural integrity will not be lost even if some bolts fail, or (2) SCC is not likely to occur under the service conditions to which the bolting is exposed. In either case, it may be demonstrated that even under a set of conservative assumptions, the component support design is adequate for the intended service.

The first evaluation approach would involve analysis of the support design to determine the consequences from degradation of bolting materials within the support system. A similar evaluation procedure was allowed under the proposed NRC review plan for USI A-12 (3). Such an evaluation would proceed by assuming that some support bolts or anchor studs have failed. An analysis of the remaining support bolting would establish the residual load carrying capacity of the structure under postulated accident conditions. Acceptability of a given component support design would, therefore, be based on the criterion that the component being supported will not be damaged to the point where it could not perform its design function or damage other components critical to the safe operation of the plant. It should be noted that this approach would be very appealing in a plant-specific plan since it is anticipated that the postulated LOCA loading will be significantly reduced under the pending decision to remove the double-ended pipe break as a design condition. The anticipated changes to the LOCA condition will greatly increase the likelihood of success for the consequence analysis in many bolting applications.

The second evaluation approach would involve an assessment of the SCC susceptibility based on material condition, steady-state stress level, and environment. An evaluation procedure based on fracture mechanics concepts has been developed (6) by which one can determine the allowable bolt stress below which SCC is predicted not to occur. This evaluation approach could be used to demonstrate that actual bolt stresses are below the allowable stress to avoid SCC. Given such a conclusion, the material under review would be judged acceptable for service and no further action would be required. If steady-state stresses are above the calculated allowable stress, then a strategy could be considered to lower the bolt stress by preload reduction. The calculated allowable stress would, therefore, be a maximum limit to the bolt steady-state stress condition.

The evaluation procedure presented in Ref. (6) is simple and straightforward in application. Although there may be some cases where in situ testing will not be

required to demonstrate service fitness, general application of the procedure requires sampling the material in a field hardness testing program to estimate the material properties. This type of analysis could be implemented together with the disposition strategy based on testing described earlier. The procedure is described in greater detail in Section 11 of Volume 2 of this report.

Disposition Based on Inspection

Inspection of bolting materials on a regular interval also could serve as a means to assure that SCC is not operative. This method of disposition was included in the proposed USNRC SCC review plan (3) as a way of resolving the issue. It would be expected that the NRC would require verification of the inspection system and procedures by model or mockup to ensure that the system could indeed detect SCC in bolting geometries.

Other Means for Disposition

There are other strategies that could be used in a plant-specific plan to resolve the issue. Some approaches could consider review and evaluation of material test reports, immediate material replacement, or reheat treatment to achieve desired material properties and, hence, performance. There are other strategies that could be developed; such strategies will depend on the given plant-specific issue.

CONCLUSIONS AND RECOMMENDATIONS

Task 14 of the AIF/MPC Task Group on Bolting action plan (see Section 1 of this volume) addressed the identification of component support bolting which may be susceptible to SCC, and to recommend both generic and plant-specific review procedures. A set of screening conditions have been proposed in order to identify susceptible component support bolting, based on preservice and inservice failure data, material specifications, and bolting sizes. Disposition of bolting that fails to meet the screening conditions can be carried out by mechanical testing, most likely in terms of hardness; failure consequence analysis; fracture mechanics evaluation; or inservice inspection. From a plant-specific perspective, a detailed review of bolting material test reports, followed by reheat treatment or material replacement, could be considered.

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3. D.G. Eisenhut, NRC Division of Licensing. Letters to all power licensees (May 19, 1980), to all pending operating licensees, permit applicants, and plants under construction (May 20, 1980).

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5. G.A. Knorovski, et al. "Fracture Toughness of PWR Component Supports." NUREG/CR-3009, SAND 78-2347, February 1983, p. 13.

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7. "Specification for Structural Joints Using ASTM A325 or A490 Bolts." American Institute of Steel Construction (AISC), Chicago, 1986.
"Specification for the Design, Fabrication and Erection of Structural Steel for Buildings." AISC, Chicago, November 1, 1978.
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Table 4-1

SUMMARY OF STRUCTURAL SUPPORT BOLTING FAILURES

Plants	Year	Application	Nom. Bolt Size	Relevant Material Specification	Specified Min. Yield Strength	Material Supplied	Failure Mode	Failure Contributors
Ginna	1970	RCP Embedment Anchor Studs	1-3/8"	A490[1]	200 ksi[2]	4140	SCC	High Preload & Borated Water Environment
Haddam Neck	1973	SG Support Embedment Anchor Studs	2-5/8"		160 ksi	4340	SCC	High Preload & Moisture Environment
Surrey 1 & 2	1974	SG Support Bolts				Vascomax 250	SCC	
Sequoyah 1 & 2	1977	SG Support Holddown Bolts	1-1/2"	A564 XM16 (H900)	220 ksi	Custom 455	SCC	Improper Fabrication
Midland 1	1979	RPV Embedment Studs	2-1/2"	A354 Gr. BD	130 ksi	4140	SCC	Improper Heat Treatment (Under Tempered)
Midland 1	1980	Pipe Whip Restraint Connection Bolts	1-1/4"	A490 Type 3	130 ksi	4140	Ductile Fracture	Improper Heat Treatment (Over Tempered)
Midland 1	1980	Pipe Whip Restraint Connection Bolts	1-1/8"	A540 Gr. B23		1018	Ductile Fracture	Wrong Material Supplied
Prairie Island 1&2	1980	SG Support Bolts	1-1/2"	A538 Gr. B	230 to 260 ksi[3]	Vascomax 250	SCC	High Local Stress and Moisture Environment
Palo Verde	1981	Piping Restraint Embedment Anchor Bolts	1-1/2"	A354 Gr. BD	130 ksi	4140	SCC	Improper Heat Treatment (Under Tempered)

Table 4-1 (Continued)

SUMMARY OF STRUCTURAL SUPPORT BOLTING FAILURES

Plants	Year	Application	Nom. Bolt Size	Relevant Material Specification	Specified Min. Yield Strength	Material Supplied	Failure Mode	Failure Contributors
Palo Verde	1981	Piping Restraint	1-1/2"	A354 Gr. BC	130 ksi	1020	[4]	Wrong Material Supplied
Waterford	1981	RCP Support Bolts		A490	130 ksi			Improper Torque

[1] This specification was reported to be used for heat treatment requirements.

[2] Based on specified minimum hardness of $45R_C$.

[3] This value corresponds to 0.2% offset yield and strength. Specified minimum tensile strength is 240 ksi.

[4] During the investigation of the SCC-related failures, at least one bolt was found to be a low strength material.

Section 5

OWNERS' GROUPS SUMMARY

BABCOCK & WILCOX OWNERS' GROUP PRIMARY PRESSURE BOUNDARY BOLTING PROGRAM

The Babcock & Wilcox Co. (B&W), sponsored by the B&W Owners' Group Material Committee, has been an active participant in the AIF/MPC Task Group on Bolting since its formation. A decision was made by the B&W Owners' Group in August 1983 to become more actively involved in the bolting issue. Realizing its importance, they initiated a program to evaluate the structural integrity impact of corrosion of primary pressure boundary closure fasteners.

During the program planning process, a concept evolved that provided a realistic means for dealing with the primary pressure boundary bolting issue. This concept involved evaluating the load-carrying capability of closures containing failed (or missing) fasteners against the leak detection capability available in the plant, an approach analogous to the "leak-before-break" concept. This concept was presented to the AIF/MPC Task Group on Bolting in December 1983. It has since been embraced by EPRI. The AIF/MPC Task Group presented the concept to the ASME Subcommittee on Nuclear Inservice Inspection (Section XI) as a means of establishing bolted closure inspection criteria.

Upon receiving industry concurrence, the B&W Owners' Group Program, "Primary Pressure Boundary Closure Evaluation", was initiated during the first quarter 1984.

The objectives of the program were as follows: (1) to demonstrate that the primary pressure boundary closures in each B&W plant can safely carry existing and/or required loads for the defined service life considering environmental effects not previously covered in ASME Code stress evaluations; and (2) where the first objective cannot be met due to the identification of problem areas or unanswered questions, to specify the measures required to significantly increase the confidence that the integrity of the closures can be maintained for the defined service life.

The tasks designed to meet these objectives were as follows:

- Task 1 - Collect and Document Pertinent Closure Data

  --Materials Data

  --Service Experience

  --Inspection Results

  --Design Information

- Task 2 - Establish Screening Criteria

  --SCC and Wastage

- Task 3 - Identify Service Sensitive Closures

- Task 4 - Define Short Range Corrective Actions

  --Provide Recommendations for Procedure and Specification Upgrades

- Task 5 - Define Long Range Corrective Actions

  --Hardware Evaluation

  --Hardware Upgrades

Two representative closures were selected for this effort. The steam generator manway closure was selected because stress corrosion cracking (SCC) was observed in studs removed from these manways in two plants. The reactor coolant pump main closure was selected because corrosion wastage was observed in pump studs in several plants. The number of closures to be evaluated in the future depends on the results of the work in progress.

Tasks 1-3 involved detailed analyses, the results of which were documented in Ref. (1). A leak-before-break approach was applied in stress, fracture mechanics, and limit load analyses performed on the steam generator manway and reactor coolant pump closures. Conservative failure criteria were established to evaluate the integrity of the closures with adjacent studs missing. Closure integrity was assured if two conditions were met: (1) the leak rate was detectable, and (2) all load criteria were met by the remaining studs.

The evaluation demonstrated that the leak rate criterion and all but one load criterion were met in the manway closure when three of 16 adjacent studs were missing from the closure. The load criterion based on stress corrosion cracking in a H_2S environment was not met. This very conservative criterion was based on the potential decomposition of a MoS_2 lubricant in leaking reactor coolant. The

evaluation performed on the reactor coolant pump closure demonstrated that all criteria were met when up to 7 of 20 adjacent studs were missing. The violation of the SCC load criterion in the presence of decomposing MoS_2 lubricant has led to the recommendation of a phased replacement of that lubricant.

Task 4 of this program also has been completed and documented in Ref. (2). The report included recommendations on closure maintenance, NDE, gasket and stud material ordering requirements, and the phased replacement of MoS_2 lubricants.

Task 5, "Definition of Long Range Corrective Actions", is in progress. The output of this work will consist of an assessment of closure component modifications and replacements, together with recommendations for corrective actions that involve an upgrade of materials, design features, and installation procedures.

This program has been very successful in that the task objectives have all been met except for Task 5, where efforts to define long-range corrective actions are continuing. A large part of the success can be attributed to the coordination efforts of the AIF/MPC Task Group on Bolting and the aggressive support of industry work by EPRI. The coordination of the B&W Owners' Group activities with those of the rest of the industry resulted in the sharing of Task 1 information on materials data, service experience, closure design, and inspection; the identification of service-sensitive closures through the sharing of information on boric acid wastage and SCC degradation and failure; and the selection of the generalized closure integrity/leak-before-break model as the means for evaluating service-sensitive primary pressure boundary closures. In most cases, the design-specific applications in the B&W Owners' Group program have confirmed the structural integrity of existing closure designs and maintenance procedures. However, some changes -- notably the phased replacement of MoS_2 lubricant and upgraded bolting material specification/sampling requirements -- have been recommended. Future long-term corrective actions may involve alternative materials, changes in closure design, and more controlled installation procedures. Each of the B&W Owners' Group participants will be reviewing these recommendations for plant-specific use, field applicability, and timing of implementation.

WESTINGHOUSE OWNERS' GROUP PRIMARY PRESSURE BOUNDARY BOLTING PROGRAM

An overall program is shown in Table 5-1 for assuring the integrity of primary pressure boundary bolting and closures of LWR power plants. The program was proposed to the Westinghouse Owners' Group (WOG), and the first four tasks were spon-

sored by the WOG. Most of the other tasks were active either under EPRI programs, as efforts within the bolting standards organizations of ASTM, as efforts within the ASME Boiler and Pressure Vessel Code bodies, or as efforts within the MPC. The objectives and a summary of the tasks sponsored by the WOG are described below.

Task I

The objective of Task I was to determine the bolting material, number of bolts, bolt dimensions, and gasket material used for primary boundary closures, i.e., pumps, valves, steam generators and pressurizers. By working toward this objective, engineering data on closures and bolting for Westinghouse plants to be used in determining bases for margin of safety for closures in the primary boundary system were obtained.

A WOG Bolting Data Base User Manual (3) has been prepared for use with a database resident on an IBM PC. This database contains a collection of closure data for reactor coolant pumps, valves, steam generators and pressurizers. The database was prepared from internal Westinghouse information on plant components. The data obtained are available to all WOG members. The valves selected for inclusion in the database were the main loop stop valves and the two valves in series leading off the primary pressure boundary.

This information was used in assessing the integrity of the complete bolted closure rather than the individual fastener, in agreement with the "leak-before-break" criteria and analytical models developed by EPRI for typical primary boundary closures. Analyses were performed to determine the number of bolts which could fail (degrade) before leakage (e.g., one gallon per minute leakage or limits set by Technical Specifications) criteria were violated. The use of "closure integrity" has also been recommended to Section XI of the ASME Boiler and Pressure Code in order to establish nondestructive testing acceptance limits for closures rather than individual bolts.

Task II

The objective of Task II was to provide installation procedures for bolting for primary boundary closures.

An ultrasonic extensometer, the Bolt Gage (Raymond Engineering Inc.), has been applied to the main coolant pumps and steam generator manways at several WPWR plants. The use of the Bolt Gage provides a method of measuring the preload on

bolts and studs that is more precise than turn-of-the-nut or torque measurements. The supporting data, which includes preload measurements comparing torque wrenches, stud heaters and stud tensioners, and the use of the Bolt Gage, were included in the report under Task II (4).

Installation procedures for the steam generator manways (which are applicable to the pressurizer manways, as well) and for the main coolant pump closures were prepared and included in Ref. (4). The following conclusions resulted from the work on the main coolant pump and steam generator manway closures.

Reactor Coolant Pump Main Flange Closure

- The Bolt Gage provided an accurate method for measuring stud elongation (and resultant preload).
- The time to make the RCP closure can be reduced by using the Bolt Gage, as compared to the current method for determining the bolt stretch with a depth micrometer and a gage rod.

Steam Generator Manway Closures

- Bolts without washers had the highest (least efficient) nut factor.
- Use of bolts or studs with washers provided the best configuration (however, studs without washers were only slightly less efficient).
- Use of the four point torquing device was superior to single torque wrenches; also, there was a substantial reduction in time per pass.
- There are significant advantages to using studs and nuts rather than bolts.
- The use of the ultrasonic extensometer improves the ability to establish accurately and uniformly the final bolt or stud preload (including the ability to measure stress relaxation after tensioning).

Task III

The objective of Task III was to catalog service experiences for primary boundary closures and identify service sensitive closures based on utility input.

A review of available data on leakage of the primary boundary closures was made. Most of the data (on 21 Westinghouse plants) were obtained from utility reports that were submitted to the USNRC for their responses to IE Bulletin No. 82-02 (5). The intent of Task III was to list the service-sensitive closures in order to prioritize the effort on closures which should be further evaluated, as well as determining which closures should be identified for testing under the ASME Code, Section XI.

From the available data, the service-sensitive closures and the recorded number of leaks were:

Pressurizer Manways	8
Steam Generator Manways	19
Loop Stop Valves	4
Reactor Coolant System (Motor Operator Valves)	17
RHRS (Valves)	11
SI and SIS (most of these resulted from packing leaks)	80
PORV	3
Pump	14

The following conclusions were established by this task effort, in combination with that of Task I:

1. Limited information has been made available for determining service-sensitive closures.
2. The approach recommended by the AIF/MPC Task Group on Bolting to consider leak-before-break, with the limit for leakage being the plants' allowable leakage within their Technical Specifications, is a sound engineering approach.
3. Changes to Section XI of the ASME Boiler and Pressure Vessel Code should be made to address flaw limits for bolts and studs based on closure integrity and the inherent redundancy of the number of bolts within a closure. New methods for inspection of bolting are being developed under EPRI-sponsored programs (see Section 7).

Task IV

The objective of Task IV was to follow the AIF/MPC Task Group on Bolting action plan, provide liaison to the Task Group for the WOG plants, and ensure that no duplication of effort occurred. The effort on this task accomplished its objective, since a number of the other tasks (Task I, Task III) involved interaction with other parts of the action plan.

Steam Generator Support Bolting

Task 17 of the AIF/MPC Task Group on Bolting action plan involved the development of a field procedure for the ultrasonic inspection of ultra high strength bolts in Westinghouse-designed steam generator lower support feet. The task was assigned to the Westinghouse Owners' Group, and an element of the WOG program was established to develop in situ ultrasonic examination techniques (5). The motivation for in situ inspection derives from field experience that shows that removal of these

bolts in order to perform surface examinations can result in significantly higher costs to the utility. Bolts can become wedged in place and, by attempting removal, potential failures may lead to high costs for bolt remnant removal, bolting replacement, and down time.

The high-strength steam generator support bolting material, in combination with high preloads, is susceptible to stress corrosion cracking because of its relatively low stress corrosion cracking (K_{Iscc}) resistance. The bolts are 1.5 inches in diameter, and are part of the WPWR steam generator supports at the integral support pads -- three per steam generator, with each pad containing six, eight, or ten bolts, depending on the design. The ultrasonic techniques were developed for evaluating head-to-shank and first-thread locations on 1.5-in.-12 UNF-3A by 10-in. (5-in. thread) socket head and 1.5-in.-12 UNF-3A by 10-in. (7-in. thread) heavy hex steam generator support bolts, made of Carpenter 455, Vascomax 250, and Carpenter 455 high-strength material.

For the socket head configuration, the only available contact surface examination of these bolts in place is the bolt head, using either the top of the head, the bottom of the socket, the flats of the socket, or the outside diameter of the head. Based upon results from the WOG program, it was determined that the best surface for the examination of both the head-to-shank and the first-thread regions would be the outside diameter of the head. Electrical discharge machining (EDM) notches were placed at the head-to-shank and first-thread locations, with orientation normal to the shank and depths into the shank ranging from 0.005 to 0.250 inches. Preliminary acoustic studies indicated that a 5.0-MHz frequency would be best suited for the examination of these bolting materials. All of the notches could be detected at the head-to-shank location with a 45° shear, 5.0 MHz transducer. Additionally, a stress corrosion crack implanted at the head-to-shank location was detected. Examination of the first-thread region with a 60° shear, 5.0 MHz transducer was able to detect EDM notches ranging between 0.075 and 0.250 inches in depth.

For the flat-head bolts, the flat itself was selected as the contact area for in situ ultrasonic examination. An identical set of EDM notches were machined into this bolting configuration as were placed in the socket-head bolts. Examination of the flat-head bolt at the head-to-shank location with a 45° shear, 5.0 MHz transducer was found to be capable of detecting the full range of notch depths -- 0.005

to 0.250 inches. Examination of the first-thread region using a 16.5° longitudinal, 5.0 MHz transducer was capable of detecting EDM notches ranging in depth from 0.075 to 0.250 inches.

As a result of this WOG bolting program study, in situ ultrasonic examination techniques were developed for the inspection of WPWR steam generator support bolts. By employing these techniques, utilities will be able to ensure the integrity of in-place bolting without incurring the costs previously experienced during removal for surface examination.

REFERENCES

1. R.A. Davis, et al. "Steam Generator Manway and Reactor Coolant Pump Bolted Closure Evaluation." Report No. BAW-1892P, Babcock & Wilcox Co., Lynchburg, Virginia, May 1986.

2. S. K. Brown, et al. "Task 4: Short Range Corrective Actions -- Primary Pressure Boundary Closure Evaluation." Report No. BAW-1904P, Babcock & Wilcox Co., Lynchburg, Virginia, May 1986.

3. E. I. Landerman, et al. "Assurance of Primary Boundary Bolting and Closure Integrity." WOG Material Subcommittee Program MUHN 1072, December 1985.

4. Op. Cit, "Appendix I: Reactor Coolant Pump Closure Study." J.H. Teller, February 1985. "Appendix II: Assembly Procedure for Steam Generator and Pressurizer Manway." M. E. Looram and J. H. Teller, October 1985.

5. A. A. Jusino. "In Situ Ultrasonic Examination of High-Strength Steam Generator Support Bolts." Transactions of the 12th Biennial Conference on Reactor Operating Experience, Williamsburg, VA, August 4-7, 1985, pp. 14-15.

Table 5-1

SCOPE AND OBJECTIVES OF WESTINGHOUSE OWNERS' GROUP PROGRAM ON BOLTING

I	Determine the bolting material, number of bolts, bolt dimensions, and gasket material used for primary boundary closures, i.e., pumps, valves, steam generators and pressurizers.
II	Provide installation procedures for bolting for primary boundary closures.
III	Catalog service experiences for primary boundary closures and identify service-sensitive closures based on utility input.
IV	Follow the AIF/MPC bolting programs, provide liaison for the WOG plants, and prevent any duplication of effort.
V	Develop nondestructive testing methods for bolting for primary boundary closures.
VI	Prepare specifications for primary boundary bolting including quality assurance requirements for procurement, receipt and preinstallation inspections.
VII	Evaluate and qualify sealants for primary boundary closures.
VIII	Evaluate and qualify lubricants for primary boundary closures.
IX	Establish the number of "failed" bolts in closures resulting in one gallon per minute leakage (or limits set by technical specifications) and determine margins of safety for bolting in primary boundary closures.
X	Establish feasibility of having an inventory of bolting (considering Task III above) for primary boundary closures.

Section 6

ASME & ASTM CODES AND STANDARDS

Tasks 6 and 7 of the AIF/MPC Task Group on Bolting action plan to resolve the issue of bolting degradation and failure in nuclear power plants involved ASTM specification and ASME Code items. Task 6 covered recommendations to various ASTM committees on: (1) a general bolting procurement specification for receipt or pre-installation inspection requirements, in order to insure product acceptability; (2) a revised sampling requirement for structural bolting, in order to provide more consistency with end product expectations; and (3) a specification for the Equotip hardness tester which appears to be a viable tool for in-place hardness measurements of bolting. Task 7 covered the preparation of Task Group comments on the ASME Boiler and Pressure Vessel Code and American Institute of Steel Construction (AISC) rules for bolted joint construction, with an emphasis on bolt preload requirements.

Subtask 6.1, which addressed the general bolting procurement specification, was completed in May 1985 with the preparation of "Utility Recommendations and Guidelines for the Purchase Specification and Receipt/Installation Inspection Requirements for ASME Section III, AISC, ANSI/ASME B31.1, and ANSI B31.5 Bolts and Threaded Fasteners". These guidelines are published in their entirety as Section 1 of Volume 2 of this report.

Subtask 6.2 involved actions by the AIF/MPC Task Group on Bolting to alter the sampling requirements for structural bolting specifications under the jurisdiction of ASTM Subcommittee F16.02. These actions are still pending.

Subtask 6.3 is covered in Section 2 of Volume 2 of this report, which consists of the draft standard, "Standard Test Method for Equotip Hardness Testing of Metallic Materials". The draft standard has been submitted to ASTM Subcommittee E28.06.

The results of Task 7 are given in two parts. First, M. E. Looram and R. W. Schneider collaborated on "Bolting Rules of the ASME Boiler & Pressure Vessel Code, Section VIII, Div. 1; Section III, Div. 1, Subsections NB, NC, ND, NF; and Section

XI". Second, M. E. Looram and J. H. Bickford collaborated on a "Critique of Bolt Preload Aspects of ASME and AISC Codes". Both parts of this study are published in their entirety in Section 9 of Volume 2 of this report.

ASME SECTION XI CODE CASE

One of the most significant outcomes of the AIF/MPC Task Group on Bolting action plan and the EPRI Generic Bolted Joint Integrity Program was the methodology for evaluating the integrity of the complete joint, as opposed to a single fastener. The approach was described by Cowfer (1) and by Nickell, Cipolla and Merrick (2), based on the analogy between a welded joint and a bolted joint, with respect to structural redundancy, load shedding behavior, and early warning detection created by the presence of a leak. Some of the fundamental results for a variety of primary pressure boundary closures were described in Section 3 of this report.

An ASME Section XI Code Case, "Alternate Rules for Volumetric Examination of Pressure Retaining Bolting", has been drafted by R. Cipolla, with initial submittal to Section XI Code bodies in early 1987. The text of the draft follows:

Introduction

This Code Case provides rules for augmented volumetric examinations of bolted closures with observed or detected leakage. These rules shall apply when visual examination for Categories B-G-1 and B-G-2 in Table IWB-2500-1 shows evidence of coolant leakage or when potential degradation of pressure retaining bolting is suspected, and disassembly of the bolted connection is not practical.

The alternate acceptance standards provided herein are based on the overall integrity of the closure instead of current standards of Paragraph IWB-3515 involving individual stud or bolt installation. Ultrasonic (UT) response characteristics inherent in bolting degradation due to coolant leakage and boric acid corrosion (wastage or stress corrosion cracking, etc.) must be considered in the inspection technique. Failure to acceptably demonstrate an in-place UT technique shall require periodic disassembly of affected connections for surface examination.

General Requirements

The rules for acceptance of closure fasteners are subject to the following conditions:

1. Scope of application is primary pressure retaining bolting used in manway cover connections, pump main flanges, and valve-to-bonnet flanges.

2. Bolting materials covered by these rules are all low alloy quenched and tempered steels purchased to approved ASME specifications and meeting the specification requirements, and having a specified minimum yield strength of less than 150 ksi.

3. Nominal bolt size must be greater than or equal to 1 inch.

4. Closure openings must not be less than 6 inches in diameter.

5. The number of pressure retaining fasteners in the connection must not be less than 8 in total.

6. Volumetric methods must be capable of detecting and sizing the reduction in cross-sectional properties, as specified in Tables 6-1 and 6-2.

Acceptance Criteria

The closure will be acceptable for continued service if all of the following conditions are met:

1. The leakage from the closure is corrected.

2. The degradation of any single fastener does not exceed the allowable limits given in Table 6-1.

3. The total number of degraded fasteners does not exceed the allowable numbers given in Table 6-1.

4. The total fastener area loss, as determined by comparing the remaining net-tensile area with the total original net-tensile area of all fasteners in the closure, does not exceed the allowable limits given in Table 6-2.

Preload Requirements

The preload of all fasteners must be checked and verified to ensure a leak-tight connection. When any fastener has been identified to have an area loss in excess of 5%, the following is required:

1. Review the preloading procedure to determine any modifications needed to maintain the design stress in the wasted fateners. If the preload procedure is not modified, the increase in stress in the wasted fasteners shall be calculated and compared to allowable values.

2. Verify or re-establish the preload in all of the fasteners of the joint.

REFERENCES

1. C.D. Cowfer. "Bolting Degradation and NDE-ASME Section XI Code vs. Applied NDE Technique Qualifications." Paper No. D6/10, SMiRT-8, Brussels, August 1985.

2. R.E. Nickell, R.C. Cipolla, and E.A. Merrick. "The Use of Leak-Before-Break Criteria and Assessment of Margins in Addressing Closure Integrity Issues." Paper No. D6/3, SMiRT-8, Brussels, August 1985.

Table 6-1

ACCEPTANCE STANDARDS FOR DEGRADED FASTENERS

Number of Closure Bolts/Studs	Max. Area Loss in Any Single Fastener	Max. Number of Degraded Fasteners
8 to 12	20%	2
14 to 18	20%	3
20 to 24	25%	4
>24	25%	4

Table 6-2

MAXIMUM AREA LOSS FOR CLOSURE-FASTENER SYSTEM

Closure Opening (Diameter)	Maximum Total Fastener Area Loss
≥ 6" to 12"	9%
>12" to 16"	7%
>16" to 24"	5%
>24"	4%

Section 7

NDE OF BOLTING

INTRODUCTION

Task 8 of the AIF/MPC Task Group on Bolting action plan called for EPRI and its contractors to develop field NDE techniques to detect wastage and stress corrosion cracking in pressure boundary and support bolting. In response to the task direction, EPRI funded several research projects aimed at evaluating state-of-the-art technology for bolting inspection. The results of this research are summarized here, as adapted from Ref. (1), by S. C. Liu, and Ref. (2), by G. M. Light, et al.

A major problem in the inspection of bolts is the wide range of sizes: from 10 inches (254 mm) in length and 1-1/2 inches (38 mm) in diameter to well over 7 feet (2 meters) in length and 6 inches (150 mm) in diameter. Many of the larger bolts have a central, axial heater hole over most of the bolt length, which is used for pretensioning control. The heater hole can be used for another purpose -- as a pathway for an ultrasonic transducer. This allows conventional 45° or 60° angle ultrasonic shear-wave beams to be used to detect cracks in the threads with a metal path of only a few inches. However, many of the longer, larger bolts do not have a heater hole, even though the critical crack size in these bolts is just as small as that for bolts with heater holes. In the bolts with no heater holes, cracks must be detected through a metal path approaching twice the total length; i.e., metal paths from 20 inches (510 mm) to over 14 feet (4.3 meters).

CONVENTIONAL ULTRASONIC INSPECTION TECHNIQUES FOR BOLTS

Conventional ultrasonic (UT) bolt inspection techniques are based primarily on the length of the bolt and on whether or not the bolt has a heater hole. It has been reasonably effective to use an angle beam technique for bolts with heater holes. For bolts without heater holes, the only alternative has been the use of 0° longitudinal beam inspection.

Zero-Degree Longitudinal Technique

The 0° longitudinal (0-deg L) technique is based on detection of a 0-deg L beam reflected from a crack. The rest of the beam travels the length of the bolt and is reflected from the end. The threads at the end also reflect ultrasound and become a source of "noise" in trying to find cracks. The longer the bolt, the smaller and less well defined the crack signal. In addition, the critical flaw size (as determined from fracture mechanics consideration) is often so small that its reflected signal amplitude may be lost in the noise. At a 2.25-MHz inspection frequency, the maximum length that can be adequately inspected for cracks is approximately 30 inches (76 cm) (3). As a general guideline, when the product of inspection metal path (in inches) and the frequency (in MHz) approaches a factor of 60 and/or the critical flaw-to-wavelength ratio approaches a factor of 1.5, the 0-deg L technique becomes marginal, in terms of detection.

Angle-Beam Shear-Wave Technique

Many bolts used in the pressure boundary applications are longer than 30 inches (76 cm). Fortunately, a large number of these bolts have a heater hole extending down to within a few inches of the end, with the hole diameter large enough for an ultrasonic shear-wave search unit to be inserted. The shear wave (normally 45° to 60°) can then be used to inspect the thread over a short metal path (usually less than 6 inches (15 cm)), which simplifies small-crack detection.

NEW NDE TECHNIQUES

In an effort to solve the problems associated with the inspection of long bolts that have no heater holes, EPRI funded Randomdec Computers, Sigma Research, and Southwest Research Institute (SwRI) to develop and evaluate new techniques that could be applied in the field and that could detect both Stress-Corrosion Cracking (SCC) and corrosion wastage (CW). Sigma developed the acoustic resonance and reverberation techniques for detection of CW; Randomdec Computers extended the acoustic resonance technique further to detect SCC, and SwRI developed the cylindrically guided wave technique (CGWT) for detection of SCC as well as CW.

Acoustic Resonance Technique

The acoustic resonance technique is based on the natural modes of vibration of the bolt under inspection. It was perceived that any defect in the bolt would alter or modify the natural modes of vibration.

In Sigma's approach, two search units were placed on one end of the bolt: one as a transmitter of "white" excitation, the other as a receiver whose output was analyzed using a Fast-Fourier-Transform spectrum analyzer. The response spectra from suspect bolts were compared with the response spectra from an unflawed bolt. This approach was demonstrated using two 30-inch (76 cm) long x 2.5 inch (6.35 cm) diameter bolt specimens with 25% and 50% reduction in diameter (hourglass-shaped) to simulate corrosion wastage. A typical resonance spectrum is shown in Figure 7-1.

Randomdec Computers evaluated another acoustic resonance technique for the detection of stress corrosion cracking in which longitudinal vibrations were mechanically induced in a bolt, with the lateral resonance modes measured using piezoelectric accelerometers. This technique is based on a theory that assumes that bolts have a low damping coefficient, and that the effect of flaws will be to create a coupling between the longitudinal and lateral modes of vibration. The mechanical excitation is achieved using a shaker bonded to one end of a bolt, and the lateral vibrations at the other end are measured in two perpendicular directions using accelerometers.

Two separate specimens were examined. One was an 88 inch (223.5 cm) long x 2-1/2 inch (6.4 cm) diameter cold-rolled steel bar; the other was a stud of the same dimensions that had been threaded on both ends and contained several intergranular stress corrosion (IGSC) cracks located in a threaded region about 9 inches (22.9 cm) from one end.

These test samples were excited at the first 24 modes of their natural longitudinal frequencies, which ranged from about 1 to 27 kHz. Lateral vibrations were measured using a pair of piezoelectric accelerometers mounted on two sides of a cube attached to the free end of the bolt. The accelerometer outputs were connected to the horizontal and vertical deflection plates of an oscilloscope to produce conventional Lissajou patterns. The angles of the Lissajou patterns were measured and plotted versus frequency to obtain a calibration curve based on the response from the unflawed test bar.

Results for the angles measured from the Lissajou figures are plotted on Figure 7-2. Part (a) is the the standard bar, and part (b) is for the damaged bolt. For the damaged bolt, the angle of lateral oscillation had some significant spectral responses as shown in Figure 7-2. In this case a large shift in the angle of

lateral motion occurred at the frequency corresponding to a wave length of 8 inches (20.3 cm), which indicated the approximate vicinity of the flaw from the end of the bar. A shift in the angle also was seen at a wave length of 4 inches, which confirmed that the effect occurs at multiples of the wave length as well.

A more elaborate approach, called "Randomdec analysis" was also used to analyze the random response time histories of the bolt that were recorded on analog tape during the experiment. This method consisted of obtaining a signature which is the ensemble average of all time segments in a random time history which have the same initial value. These signatures are very repeatable if a structure remains unchanged, but are sensitive to small changes such as introducing a fatigue crack (4).

Reverberation Technique

The reverberation technique utilized a single search unit centered on the bolt end and excited with a conventional "spike" pulser. The reflected echo sequence was then examined in detail using a spectrum analyzer to quantify the frequency content of the pulse-echo envelope and detect characteristic time spacing changes. The approach was based on the concept that an ultrasonic wave propagating back and forth along the length of the bolt will be spectrally affected by the physical characteristics of the bolt. By comparing the reverberation spectrum of a bolt to an unflawed bolt, the condition of the bolt under inspection can be ascertained. A typical reverberation spectrum for a bolt with simulated corrosion wastage is shown in Figure 7-3.

CYLINDRICALLY GUIDED WAVE TECHNIQUE

Theory

The CGWT is based on the fact that an ultrasonic wave traveling in a long cylinder becomes, in effect, guided by the geometry of the cylinder (5,6). That is, instead of a normal beam spread, the ultrasonic beam interacts with the surface of the cylinder and undergoes mode conversion.

In theory, the CGWT can be described by the transmission of the longitudinal beam and the various orders of mode-converted waves that occur when the ultrasonic beam is constrained to propagate down a cylindrical geometry. The mode-converted signals are effective for recording the end of the stud reflection (backwall) as well as reflectors in the stud (such as cracks). In fact, one can positively detect flaws by using the following criteria:

1. Knowing that the backwall reflection from the end of the stud will always be present.

2. Observing the primary longitudinal backwall reflection with its various longitudinal-to-shear-to-longitudinal (LSL) mode-converted components.

3. Looking for any signals that occur prior to the backwall with their associated LSL modes.

4. Observing signals between the L and mode-converted pulses.

The time at which signals occur prior to the backwall reflection arrival also enables the inspector to determine the location of the flaw relative to the end of the stud.

In order to exploit the presence of mode-converted (secondary or trailing) signals, it is necessary that they appear separately from the main reflected pulse or the echo. The extent of this separation depends upon the incident pulse width and the diameter of the cylindrical waveguide under inspection. Several orders of mode conversion occur, as shown in Figure 7-4. The first signal (called the backwall echo) is from the far end (opposite the end on which the transducer was mounted) of the stud. The signals that follow the backwall echo immediately are mode-converted end-of-stud or backwall-trailing pulses, also called the secondary echoes. The time separation between the 0-degree L signal and the first mode-converted signal is directly related to the diameter of the stud (6). The successive mode-converted signals are separated by the same interval of time.

The first backwall echo signal is denoted as the longitudinal (L); the first trailing pulse that follows it is denoted as the longitudinal-to-shear-to-longitudinal (LSL); the second trailing pulse is denoted as the longitudinal-to-shear-to-longitudinal-to-shear-to-longitudinal (LSLSL), etc. The time interval (t) between the L and LSL signals returned from the end of the stud is the time needed to travel the distance S (S-wave path) at shear velocity minus the time needed to travel the distance X at longitudinal velocity (as shown in Figure 7-5). That is, the time difference is:

$$\Delta t = \frac{d\,(V_\ell^2 - V_s^2)^{1/2}}{V_s\, V_\ell}\ , \qquad (7\text{-}1)$$

where d is the diameter of the stud and V_s and V_ℓ are the shear and longitudinal velocities in the steel.

Ordinarily, signals from threads appear like noise, which poses a problem in identifying a weak signal from a shallow notch in a thread. This could be overcome, however, by the proper combination of transducer frequency and diameter in relation to the diameter of the specimen and the position of the transducer at a suitable location, not necessarily at the center, on the end face of the specimen. These conditions, properly addressed, could change thread noise into an identifiable echo from the first thread at the other end followed by its trailing pulses. This transformation would certainly help to locate a weak signal from the shallow notch in threads.

The trailing pulses also are effective for recording the end of the stud reflection (backwall) as well as small reflectors in the stud such as notches or cracks. The time at which signals arrive prior to the backwall reflection also enables the inspector to determine the location of the flaw relative to the end of the stud. The fact that the mode-converted signals are at a constant time spacing that is related to a measurable parameter -- the bolt or stud diameter -- allows use of the technique for signature analysis. This becomes important when inspecting noisy material and when the critical crack size is very small.

Successful ultrasonic inspection depends on the proper selection of transducers for given specimen geometry and material specifications. The selection, in turn, decides detectability, penetration, sensitivity, and resolution. In order to develop a thorough insight into the problem of transducer selection, 0-deg L beam transducers having diameters of 0.25, 0.5, 0.75 and 1 inch (6.3, 12.5, 18.8, and 25.4 mm) and frequencies of 1, 2.25, 5, and 10 MHz were used. The search units consisted of lead metaniobate piezoceramic crystals with quarter-wave matching plate.

Before testing the various search units on the specimens of various lengths and diameters, five tables were constructed showing the beam spread and the point of contact values where the ultrasonic beam first touched the outer edge of the cylindrical stud or bolt generating the mode-converted signals. These values were calculated using the longitudinal ultrasonic velocity of 2.3×10^5 in/s (5,840 m/s) in steel and the formulas:

$$C = \lambda f \quad , \tag{7-2}$$

$$N = a^2/\lambda \quad , \tag{7-3}$$

$$\sin\theta = \frac{0.61\lambda}{a} \quad , \tag{7-4}$$

where

C = velocity of longitudinal ultrasonic waves in steel, in/s (m/s);

λ = wavelength in steel, in (m);

f = transducer frequency, Hz;

N = near field in steel, in (m);

a = transducer radius, in (m), and;

θ = half angle of the main lobe to the point of zero energy, degrees.

Table 7-1 gives the calculated values of ultrasonic wavelengths in steel, the near-field values, and the values of the half angle of the main lobe to the point of zero energy for four different diameters and four different transducer frequencies. The transducer was assumed to be mounted at the center of one of the end faces of an anchor stud.

Table 7-2 shows, for various bolt or stud diameters, the calculated values of the first point of contact between the central ray of the ultrasonic beam and the sidewalls of the cylindrical specimen when the 0.25-inch (6.3 mm) diameter transducer was located centrally on one of the end faces of a bolt. Tables 7-3 through 7-5 show the similar calculated values for transducers of diameters 0.5, 0.75, and 1 inch (12.5, 19, and 25.4 mm), respectively. The distance between the transducer and the point of contact was given by (d/2) tan θ (Figure 7-6), where d is the diameter of the bolt and θ is the half angle.

Table 7-6 shows the length, diameter, and thread distribution of mock anchor studs prepared for tests. Five different diameters were used. The testing ranges (X) varied from 16 to 112 inches (406 to 2,844 mm), and the operating times (t_a = 2X/C) varied from 139 μsec to 974 μsec.

EXPERIMENTAL TESTS AND EQUIPMENT

The experimental apparatus is shown in Figure 7-7. A Metrotek MP215 pulser was chosen to excite the piezoelectric transducers in all tests performed using the pulse-echo technique. The choice of pulse repetition rate depended upon the operating time (t_a). The repetition rate of the pulser should be low enough so that the backwall echo train becomes attenuated before the pulser is pulsed again. It should be high enough to intensify the image on the CRT screen without causing overlap among echo trains, creating artificial echoes. The time interval between successive pulses must, therefore, be at least six times as long as the operating time t_a.

In the present testing program, the minimum pulse spacing varied from 0.8 milliseconds to 5.8 milliseconds and the maximum repetition rate (or frequency) from 1.2 kHz to 172 Hz. The Metrotek pulser allowed the choice of either LO or HI pulse width. In the LO pulse width range, the repetition rate was adjustable from 100 Hz to 10 kHz; while in the HI pulse width range, the repetition rate was adjustable from 100 Hz to 5 kHz. Since the testing range varied from 16 to 112 inches (406 to 2,844 mm), the pulse width choice, especially in the HI range, was useful in the hard-to-penetrate testing range. The feature, when used in conjunction with the damping control, provided a wide range of output pulse widths useful in separating trailing pulses from each other and from the echo. The pulse width thus could be varied from 0.1 to 1 microsec. The amplitude of the output pulse also could be varied up to the absolute value maximum of 360 volts. With high pulse width and minimum damping, the amplitude of the main incident pulse, as seen on the oscilloscope, was 16 volts.

The ultrasonic power generated by the application of high electrical pulses to the moderately damped transducer was enough to penetrate the longest stud (112 inches (2,844 mm)) in the test program, which could show three successive backwall echoes with many trailing pulses following each of them. In all tests, the pulse width knob was set on HI with the damping knob on the minimum setting.

The Metrotek MR101 receiver used was a wideband (0.5 to 20 MHz) ultrasonic receiver with overall gain of 100 dB. The receiver features low equivalent input noise, calibrated 40-dB gain, a large output voltage swing, and wide bandwidth. Signal gain was adjusted by means of a push-button attenuator which provides 62 dB of attenuation in 1-dB steps. The noise of the system electronics with all available gain was around 20 mV.

The Tektronix oscilloscope had a 100-MHz bandwidth with one beam, two traces, and two sweeps. The feature of the delayed sweep was useful in measuring microsecond intervals. The maximum vertical sensitivity setting was 5 mV/div, but that value was rarely used. Since the noise level was around 20 mV, the vertical sensitivity chosen in almost all tests at the time of detecting the shallowest notch in the calibration sample -- 0.048 in (1.2 mm) -- was 20 mV/div. The horizontal time scale can be expanded down to 0.02 microsec/div, but that value was rarely used. In the delayed sweep, the delayed time scale of 1 microsec/div was sufficient to identify all signals and to measure time intervals between them.

The spacings of trailing pulses (TP), the operating times or times for the first backwall echoes, and times for echoes from the first thread at the far end were calculated for each bolt specimen and are given in Table 7-7. In all tests, the couplant used between the search unit and the end face of a bolt was Ultragel II (Echo Laboratories). It became apparent quite early, while trying to detect the minimum detectable flaw in threads at the far end, that many signals were present just before the backwall echo signal. In order to identify the signal from the minimum detectable flaw, it was necessary to move the transducer all over the end face, especially around the periphery of the face, to maximize amplitudes of signals appearing prior to the backwall echo.

For the results discussed below, the transducer was placed at the center of the top of the bolt and moved on that surface until a maximum signal was detected. Figure 7-8 shows a typical oscilloscope trace for a bolt with no defects. Figure 7-9 shows an expanded view of a similar trace. In both figures the peaks are periodically spaced, in accordance with the theory. No signals are present before the first pulse, which is the backwall echo. For a bolt with a defect, the signals would appear before the backwall echo.

RESULTS

Initially, all bolts (in the nondefective condition) were inspected using the CGWT. These data clearly showed the backwall echo and its trailing pulses. In addition, data were collected at very high gain in these good bolts to observe any signals generated by the threaded region of the bolt (see Figure 7-10). These signals appear before the backwall signal from the end of the bolt. The first thread provided the same type of signals observed for the end of the bolt (i.e., the first reflection and trailing pulses separated by the proper time). These

signals, however, were very low in amplitude compared to the backwall echo (see Figure 7-11). With an understanding of the signals coming from the threads, the time region in front of the backwall signal from the end of the bolt could be evaluated at high gain; any signals appearing in this time zone that did not coincide with the thread signals could be clearly identified as defect signals. This allowed a high detection sensitivity to be established.

Using this concept for testing, saw cuts were placed in the threaded regions of all stud bolts. The bolts were then inspected using the CGWT, and the detection sensitivity was determined. The minimum detected notch experimentally determined for each bolt size is shown in Table 7-8. Straight cuts across a portion of the bolt diameter produced penny-shaped notches. The areas of these notches were calculated and are shown in Table 7-8.

After a notch had been detected, the next step was to determine possible size information from the technique. In order to determine the relationship between notch size and CGWT signal, the signal from the notch was monitored as the depth (and area) were increased. The results of these data are plotted in Figure 7-12.

Figure 7-12 clearly shows that the amplitude of the L wave increases as that area increases in a somewhat linear fashion for each of the stud bolts tested. Similar plots have been obtained for the LSL and LSLSL mode-converted signals. Also, the data have similar characteristics when the amplitude is plotted as a function of depth, although the larger diameter bolts tend to produce nonlinear plots. An interesting comparison of data can be seen from the 2.25-inch (57-mm) diameter stud bolts with different lengths. The data show that all three yield linear plots and that the amplitudes decrease as the length increases.

Data were also collected on bolts that had simulated corrosion wastage. Previous work had shown that corrosion wastage simulated by an hourglass-shaped 25% reduction of bolt diameter could easily be detected using the CGWT. However, the symmetrical shape could have made detection of the corrosion wastage too easy. Therefore, another model was adopted; this model produced a reduction in diameter from one side only as shown in Figure 7-13.

On the previous model, the symmetrical shape yielded an easily identifiable peak between the normal L to LSL and other mode conversion peaks (as shown in Figure

7-14). This peak was due to a reduced diameter. Based upon the reduced diameter observed from the signals, the amount of corrosion wastage could be predicted. However, the corrosion wastage simulated by the one-sided diameter reduction produced data that appeared to be more like the crack data as shown in Figure 7-15 for a 25% reduction in diameter from one side. The reduction occurred over a 1-inch (25.4 mm) length. This reduced section over a long portion of the length simply tends to reduce the amplitude of the backwall echo a significant amount. With both models, a 25% reduction in diameter can easily be determined.

CONCLUSIONS

The cylindrically guided wave technique provided an inspection method applicable to most studs or bolts over a range of 16 to 112 inches (406 to 2,844 mm) in length and 1 to 4.5 inches (25.4 to 114 mm) in diameter. The technique can be used to detect cracklike defects as small as 0.05 inch (1.27 mm) deep in the threaded region of the bolt. In addition, the CGWT can be used to detect corrosion wastage greater than 25% of the bolt diameter.

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3. W.T. Flach. Memorandum to J. E. Doherty on Stud and Bolting Inspection. Southwest Research Institute, December 14, 1981.

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Table 7-1

CALCULATED VALUES OF NEAR FIELD AND HALF ANGLE OF THE MAIN LOBE TO THE POINT OF ZERO ENERGY

Transducer Mounted at the Center of the End Face

Transducer Diameter (inch)	Frequency (MHz)	Wavelength (inch)	Near Field (inch)	Half Angle (degree)
0.25	1.0	0.230	0.068	-*
	2.25	0.102	0.153	29.3
	5.0	0.046	0.34	12.71
	10.0	0.023	0.68	6.3
0.5	1.0	0.230	0.272	34.0
	2.25	0.102	0.61	14.4
	5.0	0.046	1.36	6.4
	10.0	0.023	2.7	3.2
0.75	1.0	0.230	0.61	21.9
	2.25	0.102	1.38	9.5
	5.0	0.046	3.06	4.3
	10.0	0.023	6.1	2.1
1.0	1.0	0.230	1.09	16.3
	2.25	0.102	2.45	7.1
	5.0	0.046	5.4	3.2
	10.0	0.023	11.0	1.6

*The half angle corresponds to an angle greater than 90°, so the data point is not physically meaningful.

Table 7-2

CALCULATED VALUES OF THE FIRST POINT OF CONTACT BETWEEN THE ULTRASONIC BEAM AND CYLINDRICAL SPECIMEN SIDEWALL

Transducer Diameter = 0.25 Inch Mounted at Center of the End Face

Frequency (MHz)	Near Field (inch)	Half Angle (degree)	Bolt Diameter (inch)	Point of Contact (inch)
1.0	0.068	-*	1.0	-*
		-*	1.5	-*
		-*	2.25	-*
		-*	3.5	-*
		-*	4.5	-*
2.25	0.153	29.3	1.0	0.89
			1.5	1.34
			2.25	2.0
			3.5	3.1
			4.5	4.0
5.0	0.34	12.71	1.0	2.22
			1.5	3.32
			2.25	5.0
			3.5	7.76
			4.5	10.0
10.0	0.68	6.3	1.0	4.53
			1.5	6.8
			2.25	10.2
			3.5	15.8
			4.5	20.4

*The data points correspond to angles greater than 90°, and are not physically meaningful.

Table 7-3

CALCULATED VALUES OF THE FIRST POINT OF CONTACT BETWEEN THE ULTRASONIC BEAM AND CYLINDRICAL SPECIMEN SIDEWALL

Transducer Diameter = 0.5 Inch Mounted at Center of the End Face

Frequency (MHz)	Near Field (inch)	Half Angle (degree)	Bolt Diameter (inch)	Point of Contact (inch)
1.0	0.272	34	1.0	0.74
			1.5	1.1
			2.25	1.9
			3.5	2.6
			4.5	3.3
2.25	0.61	14.4	1.0	1.9
			1.5	3.9
			2.25	4.3
			3.5	6.8
			4.5	8.8
5.0	1.36	6.4	1.0	4.5
			1.5	6.8
			2.25	10.0
			3.5	15.6
			4.5	20.0
10.0	2.7	3.2	1.0	8.9
			1.5	13.4
			2.25	18.75
			3.5	31.3
			4.5	40.2

Table 7-4

CALCULATED VALUES OF THE FIRST POINT OF CONTACT BETWEEN
THE ULTRASONIC BEAM AND CYLINDRICAL SPECIMEN SIDEWALL

Transducer Diameter = 0.75 Inch Mounted at Center of the End Face

Frequency (MHz)	Near Field (inch)	Half Angle (degree)	Bolt Diameter (inch)	Point of Contact (inch)
1.0	0.61	21.9	1.0	1.2
			1.5	1.8
			2.25	2.8
			3.5	4.8
			4.5	5.6
2.25	1.38	9.5	1.0	2.9
			1.5	4.4
			2.25	6.6
			3.5	10.3
			4.5	26.5
5.0	3.06	4.3	1.0	6.67
			1.5	10.0
			2.25	15.0
			3.5	23.3
			4.5	30.0
10.0	6.1	2.1	1.0	12.5
			1.5	18.7
			2.25	28.0
			3.5	43.7
			4.5	56.0

Table 7-5

CALCULATED VALUES OF THE FIRST POINT OF CONTACT BETWEEN
THE ULTRASONIC BEAM AND CYLINDRICAL SPECIMEN SIDEWALL

Transducer Diameter = 1 Inch Mounted at Center of the End Face

Frequency (MHz)	Near Field (inch)	Half Angle (degree)	Bolt Diameter (inch)	Point of Contact (inch)
1.0	1.09	16.3	1.0	1.7
			1.5	2.5
			2.25	3.75
			3.5	5.8
			4.5	7.5
2.25	2.45	7.1	1.0	4.1
			1.5	6.2
			2.25	9.4
			3.5	14.6
			4.5	18.7
5.0	5.4	3.2	1.0	8.3
			1.5	12.5
			2.25	18.75
			3.5	29.1
			4.5	37.5
10.0	11.0	1.6	1.0	16.7
			1.5	25.0
			2.25	37.5
			3.5	58.3
			4.5	75.0

Table 7-6

LENGTH, DIAMETER, AND THREAD DISTRIBUTION OF MOCK ANCHOR STUDS

Serial No.	Diameter (inch)	Length (inch)	Thread (inch)	Thread Size (turns/inch)
1	1.0	16.0	4.0	1-8N
2	1.5	84.0	12.0	1.5-8N
3	2.25	60.0	10.0	2.25-8N
4	2.25	37.5	6.0	2.25-8N
5	2.25	112.0	14.0	2.25-8N
6	3.5	60.0	10.0	3.5-8N
7	4.5	30.0	6.0	4.5-8N

Table 7-7

SPACING OF TRAILING PULSES, OPERATING TIMES (TIMES FOR BACKWALL ECHO), AND TIMES FOR ECHOES FROM THE FIRST THREAD AT THE FAR END

Longitudinal Wave Velocity in 4340 Steel = 2.30×10^5 in/s

Serial No.	Diameter (inch)	Testing Range (Length) (inch)	Thread (inch)	Trailing Pulse Spacing (microsec)	Operating Time (microsec)	Time for Thread Echo (microsec)
1	1.0	16.0	4.0	6.64	139.0	104.0
2	1.5	84.0	12.0	10.0	730.0	626.0
3	2.25	37.5	6.0	15.0	326.0	274.0
4	2.25	60.0	10.0	15.0	522.0	435.0
5	2.25	112.0	14.0	15.0	974.0	852.0
6	3.5	60.0	10.0	23.0	522.0	435.0
7	4.5	30.0	6.0	30.0	261.0	209.0

Table 7-8

MINIMUM DETECTED NOTCH DEPTHS IN ANCHOR STUDS
OF VARIOUS LENGTHS AND DIAMETERS

Diameter (inch)	Length (inch)	Distance to Notch (inch)	Depth of Notch (inch)	Notch Area (sq. inch)
1.0	16.0	13.0	0.110*	0.065
1.5	84.0	80.0	0.079	0.051
2.25	37.5	37.0	0.048	0.028
2.25	60.0	50.0	0.048	0.028
2.25	112.0	105.0	0.048	0.028
3.5	60.0	55.0	0.048	0.023
4.5	30.0	26.8	0.079	0.042

*The signal from the notch coincided with the signals from the threads; therefore, the notch had to be made deeper to become clearly discernible.

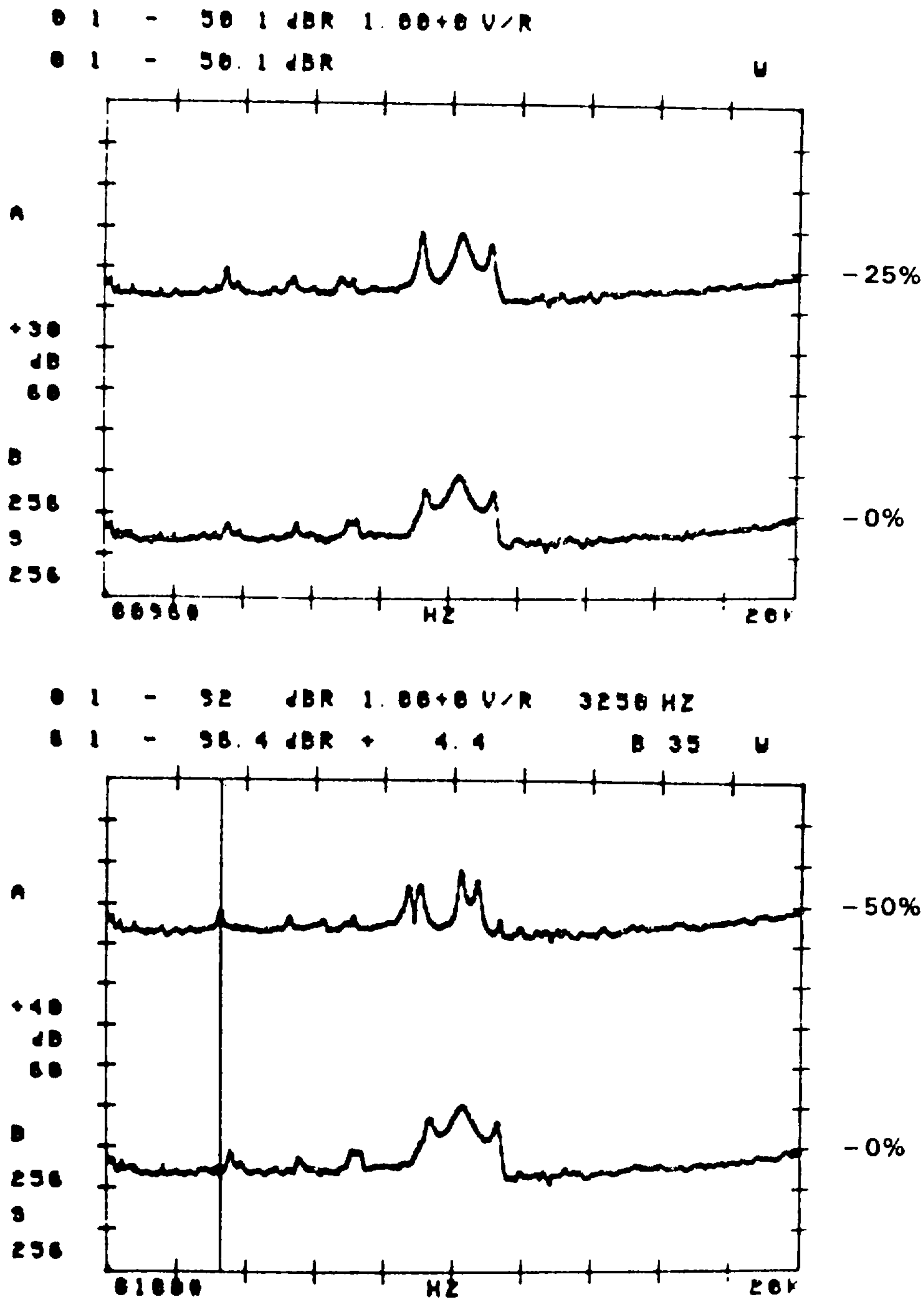
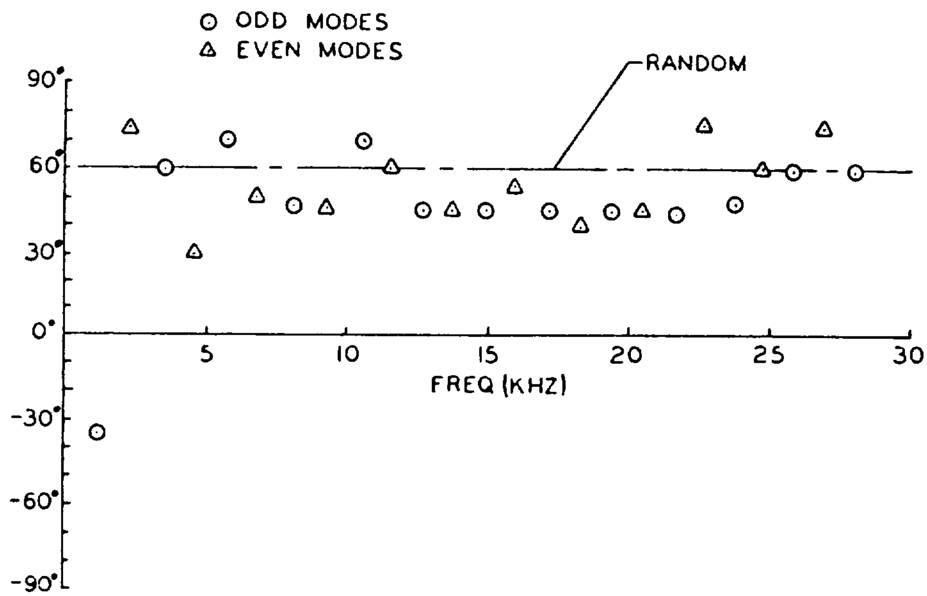
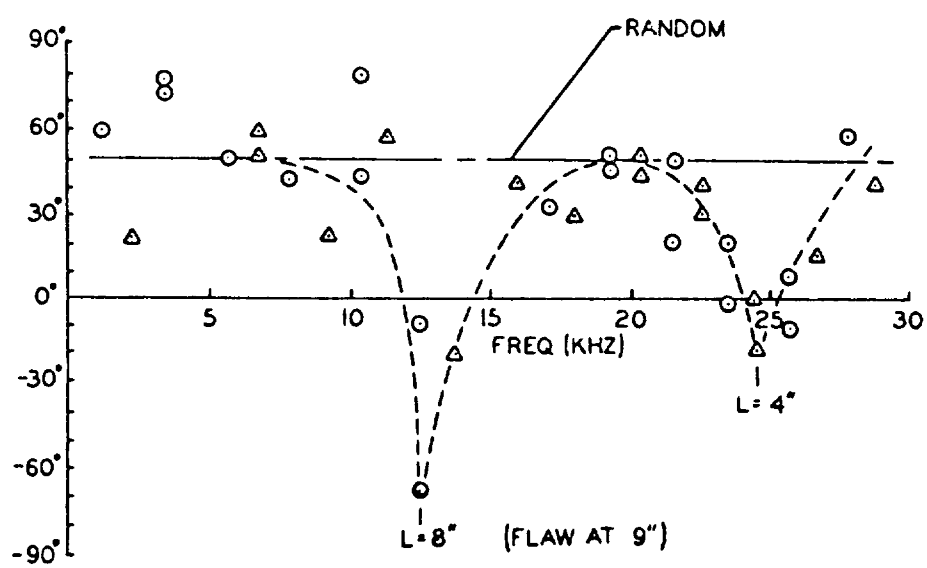


Figure 7-1. Effect of Simulated Corrosion Wastage on Resonance Spectrum (0-20 kHz)



(a) Standard Bar



(b) Damaged Bolt

Figure 7-2. Measured Angles of Lateral Motion from the Lissajou's Figures During Excitation of Longitudinal Natural Modes of Vibration

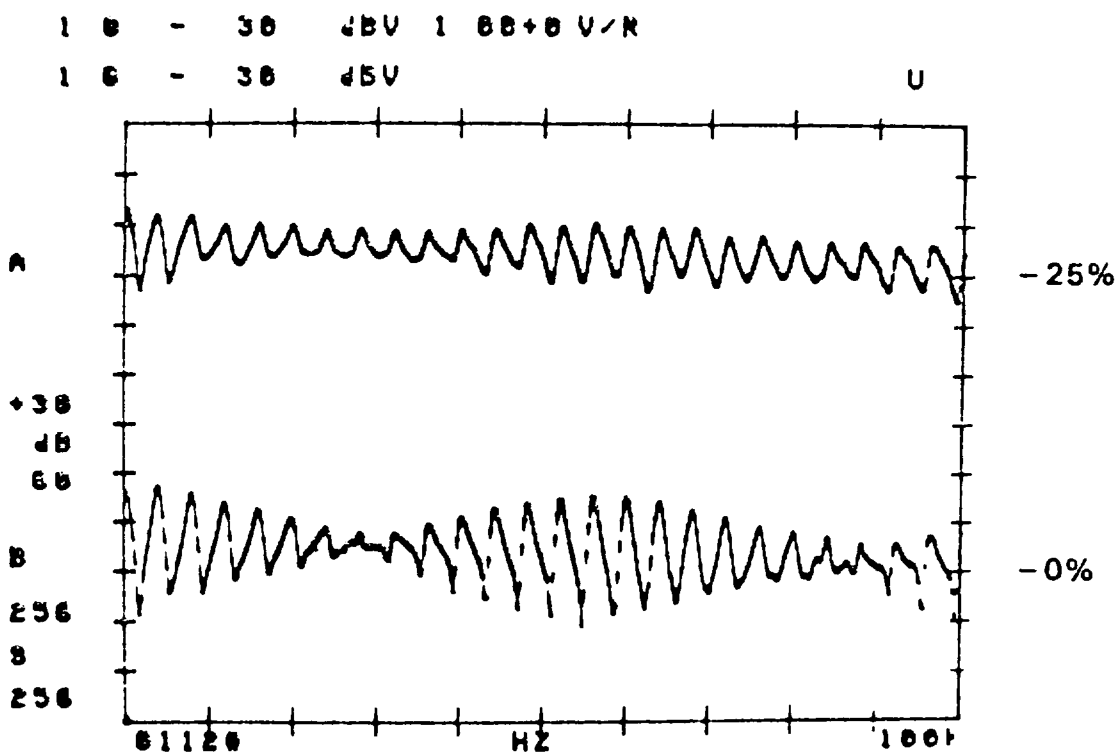


Figure 7-3. Effect of Simulated Corrosion Wastage on the Reverberation Spectrum for Bolts Encased in Concrete (0-100 kHz)

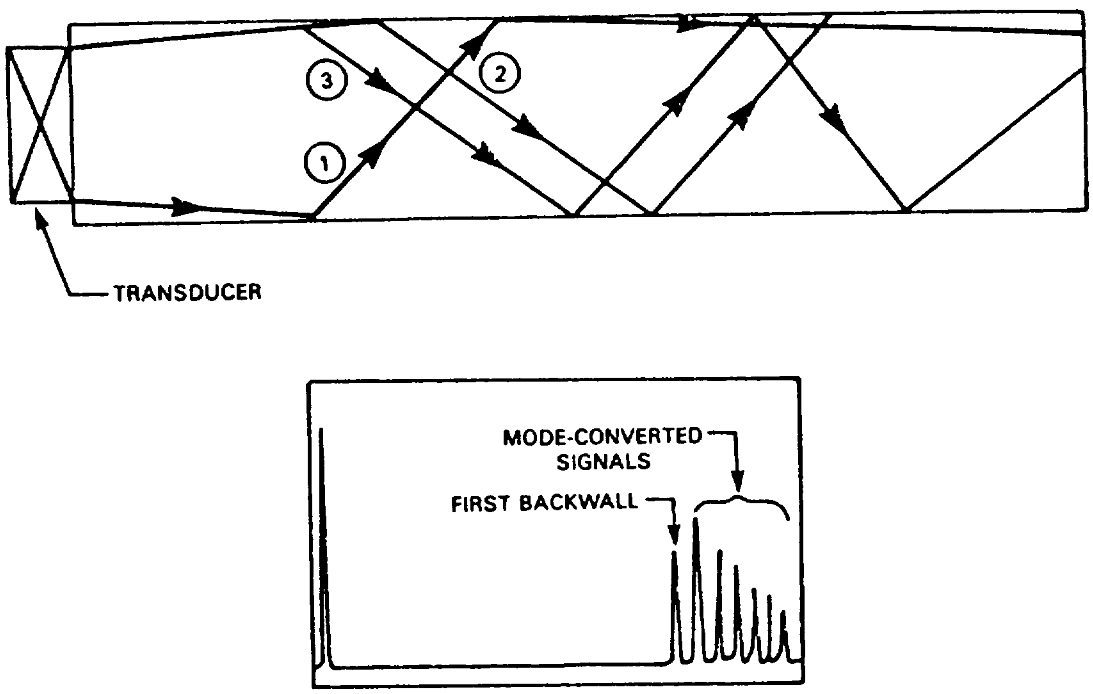


Figure 7-4. Schematic View Illustrating How the Cylindrically Guided Wave Technique Works - The First Signal to Return Is from the Edge of the Bolt (Backwall) - The Following Signals are Due to Backwall Reflections That Have Undergone Mode Conversion

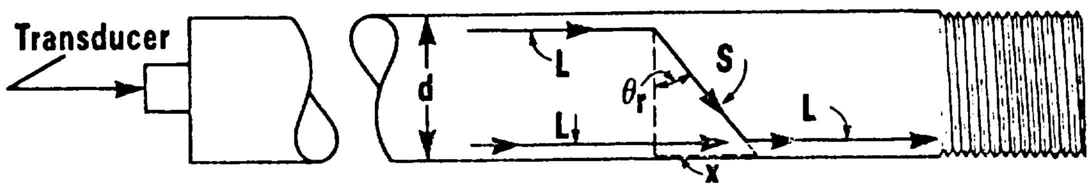


Figure 7-5. Schematic View Illustrating the Path-Length Difference between the 0° Longitudinal Wave and a Similar Wave That Undergoes Mode Conversion - The Path Difference Is the Tangential Component X of the Shear Wave, S, Going Across the Bolt Diameter

$$DC = AB = \frac{BC}{TAN\ \theta} = \frac{d/2}{TAN\ \theta} \text{ WHERE}$$

d = DIAMETER OF THE SPECIMEN
θ = HALF ANGLE

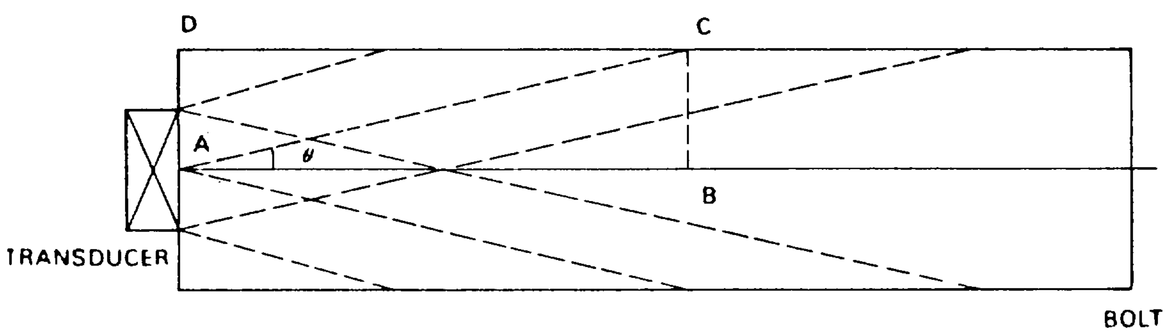


Figure 7-6. Geometry for Calculation of DC - The Distance from the Transducer to the Point of Contact of the Ultrasonic Beam with the Sidewalls of the Cylindrical Specimen

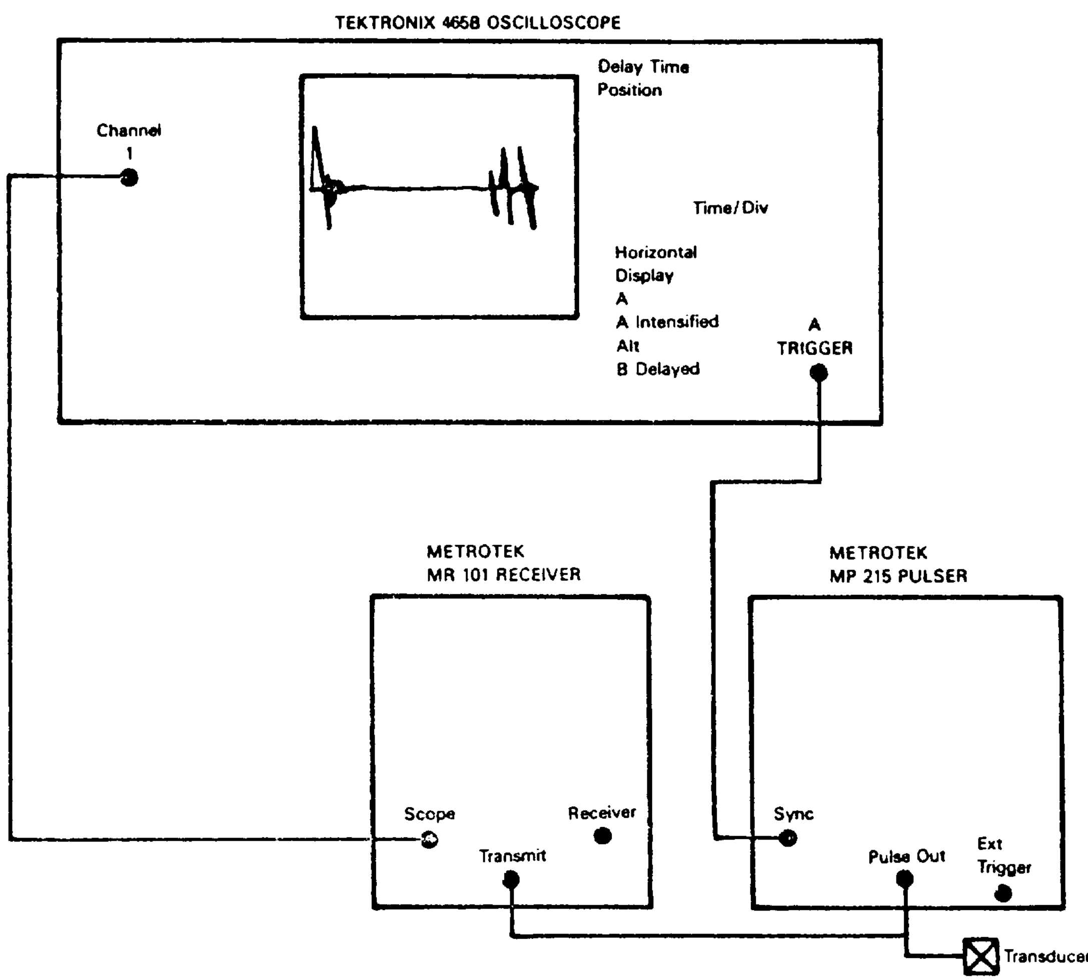


Figure 7-7. Schematic View of Equipment Setup for the Cylindrically Guided Wave Technique

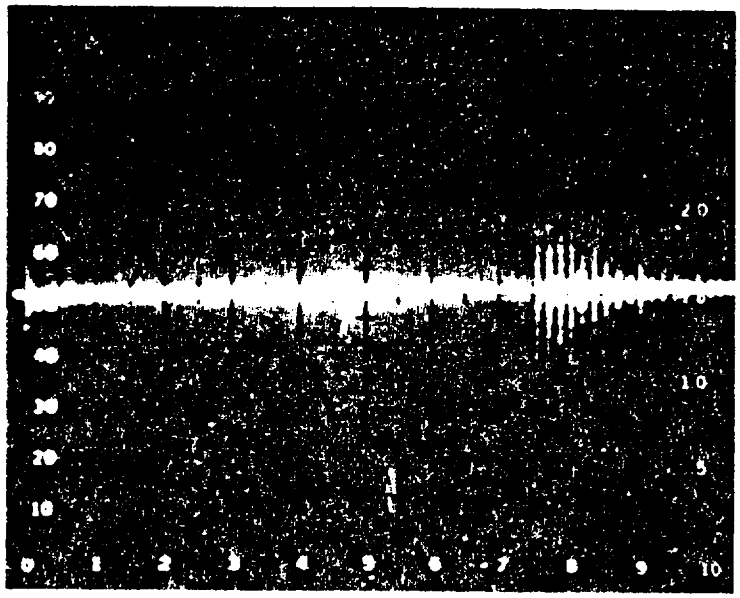


Figure 7-8. A Typical Oscilloscope Trace for a Stud Bolt Without Defects

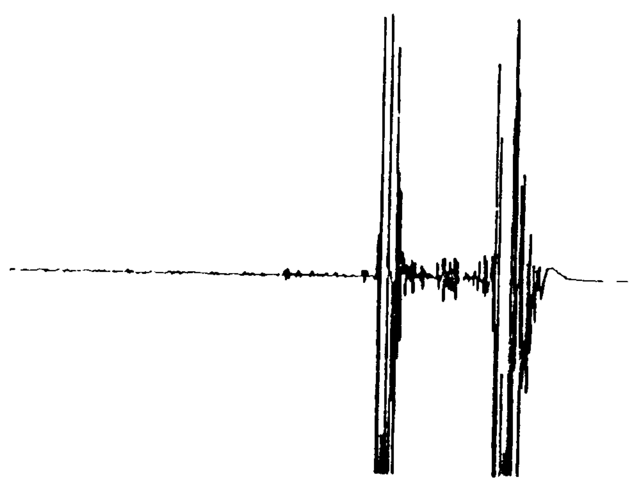


Figure 7-9. An Expanded View of the Trace in Figure 7-8.

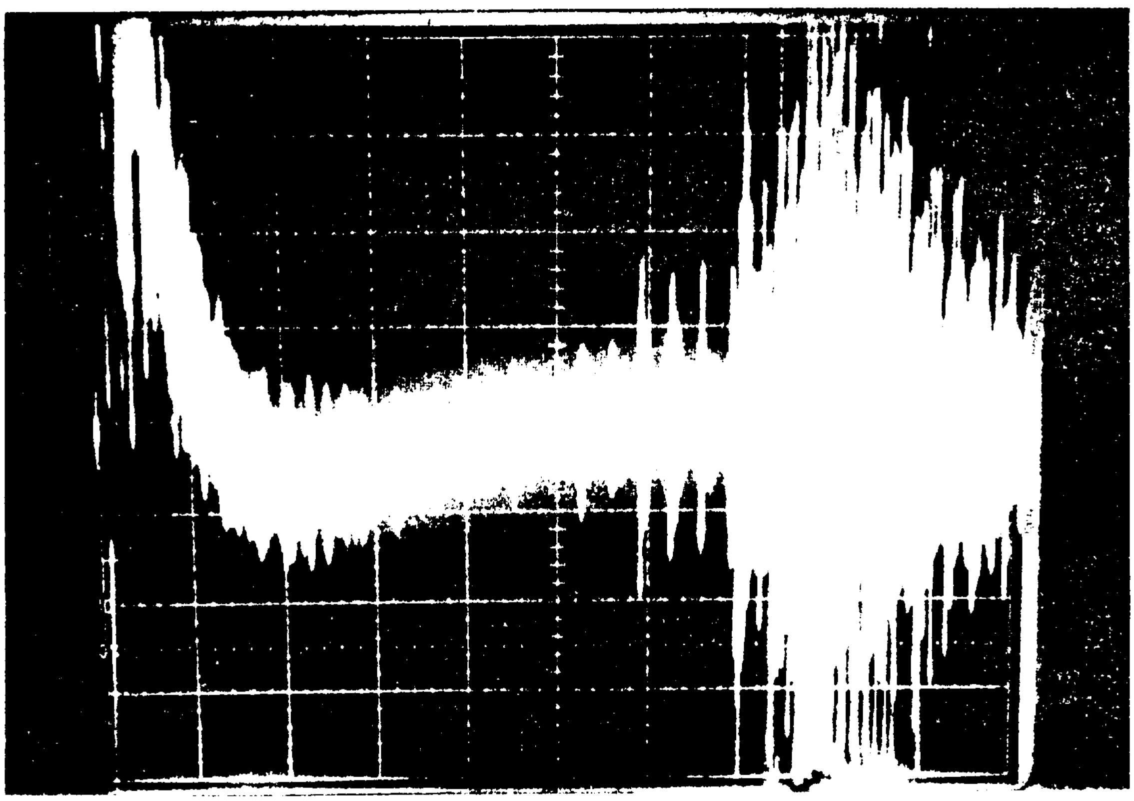


Figure 7-10. A Typical Oscilloscope Trace with a High Gain Showing Thread Signals Before the Backwall Echo on the Seventh Division

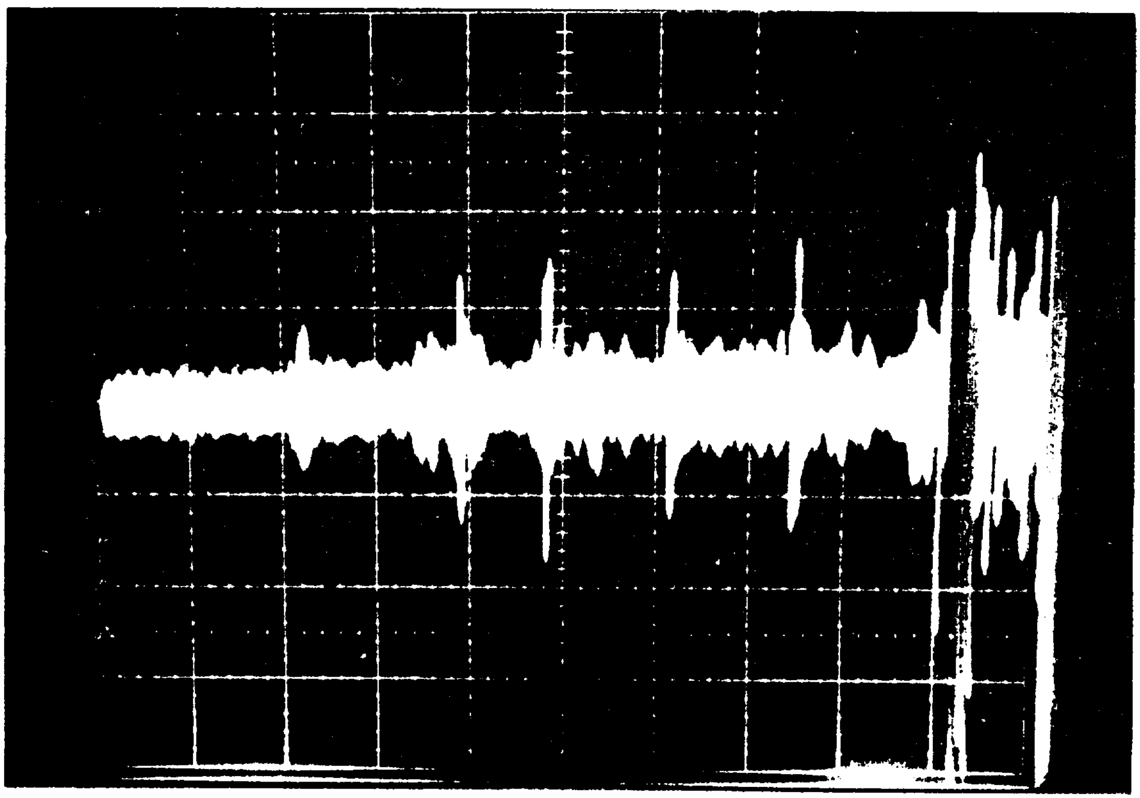


Figure 7-11. The Oscilloscope Trace from Figure 7-10 with Delayed Time Base - The Trace Shows the Echo from the First Thread Between the Second and Third Divisions, Five Trailing Pulses of the Thread Echo, and the Backwall Echo on the Ninth Division

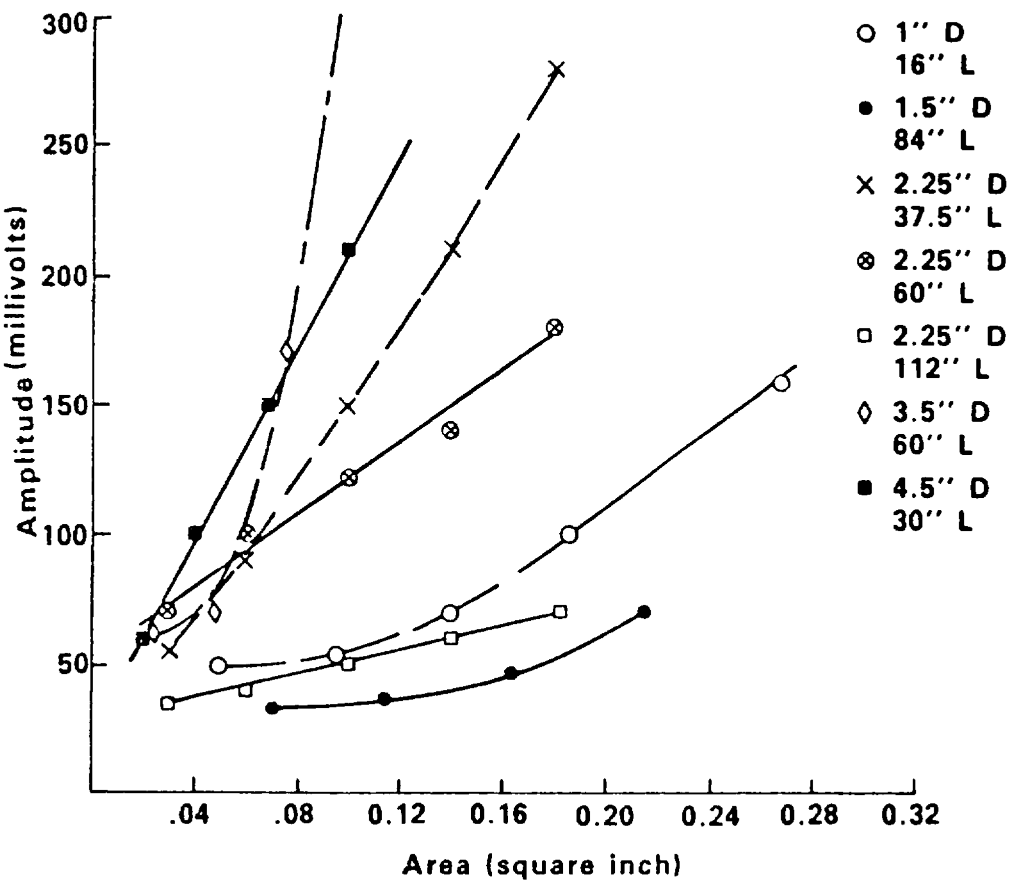


Figure 7-12. L Amplitude Versus Notch Area

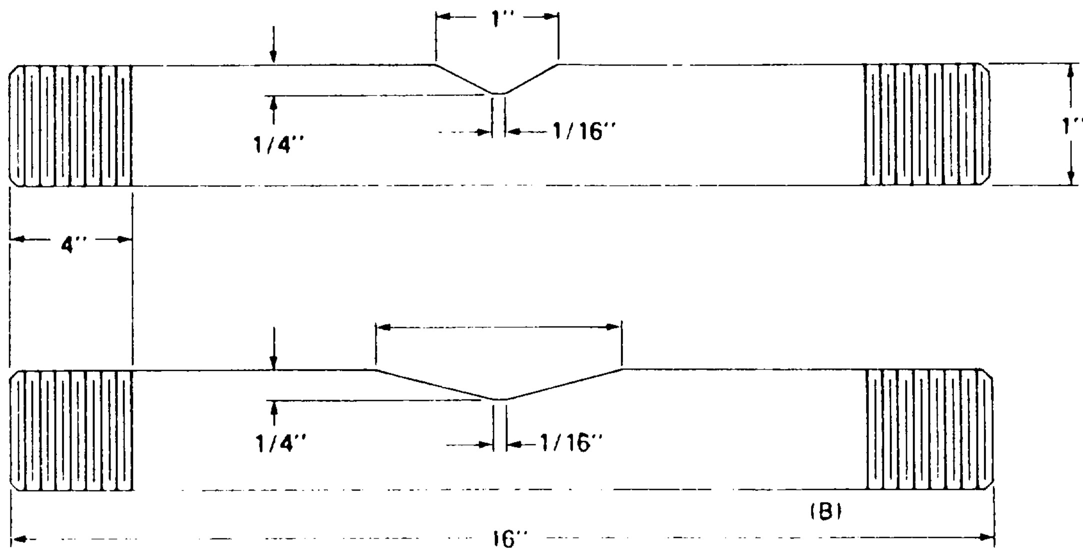


Figure 7-13. Specimens Simulating One-Sided Corrosion Wastage

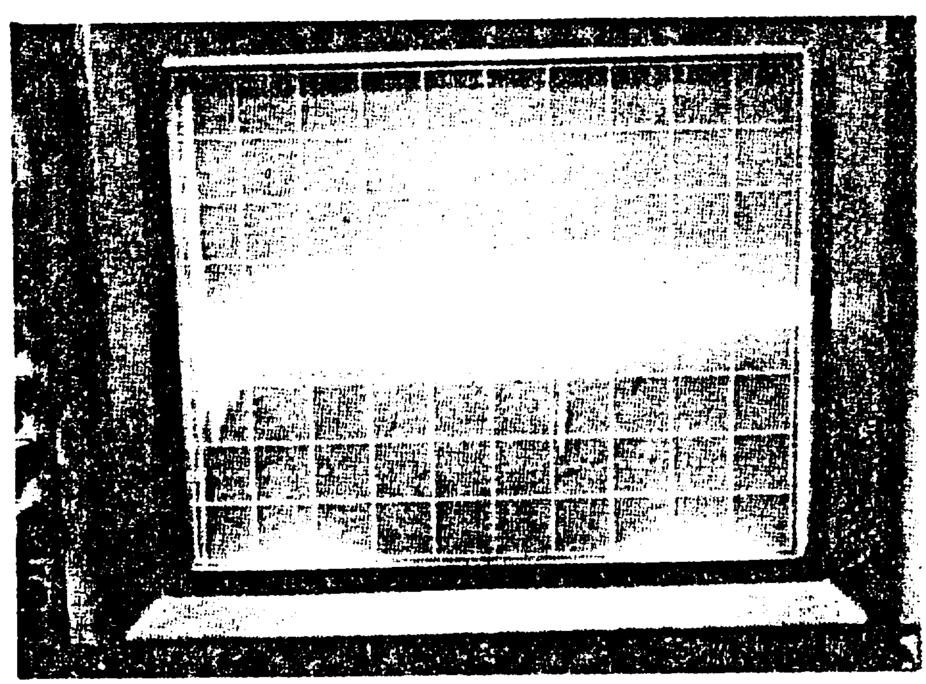


Figure 7-14. Signals from Specimen with an Hourglass Contour Along a Portion of Its Length

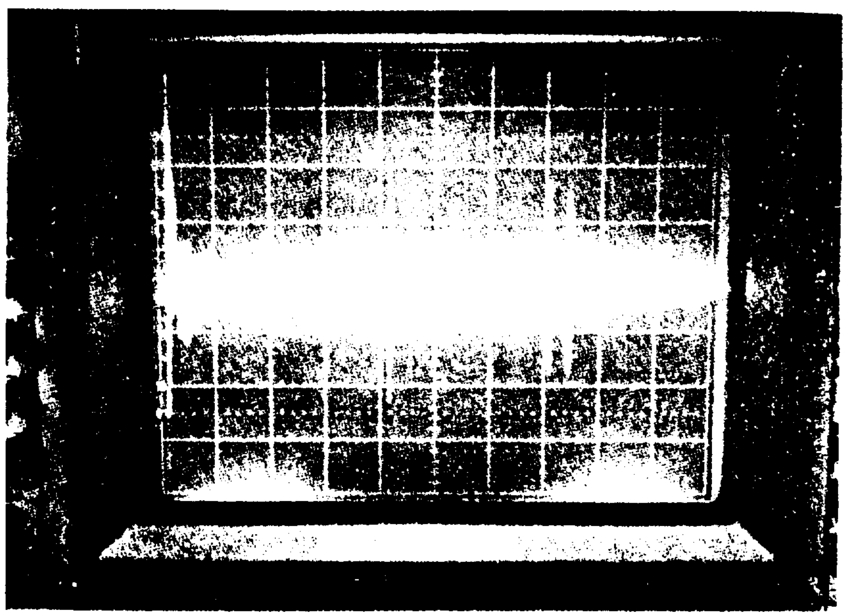


Figure 7-15. Signals from Specimen with a 25% Reduction in Diameter from One Side Over a 1-Inch Length

Section 8

LUBRICANTS AND SEALANTS

INTRODUCTION

Task 12 of the AIF/MPC Task Group on Bolting action plan for resolving the issue of bolting degradation and failure in nuclear power plants was related to the study of: (1) accelerated boric acid attack and wastage of carbon and low-alloy steel fasteners, (2) the possible effect of molybdenum disulfide (MoS_2) lubricant on stress-corrosion cracking (SCC) of high-strength fasteners, and (3) sealants for PWR primary system components. Boric acid wastage has been attributed to leakage of primary system coolant, and stress-corrosion cracking has been attributed to the presence of hydrogen sulfide, possibly derived through decomposition of MoS_2 lubricant. Also, Task 3 of the action plan was concerned with SCC of low-alloy, quenched and tempered (LAQT) bolting materials in water environments. Elements of Task 3 have been combined with Task 12, and the results are reported in this section.

These concerns were addressed through a variety of projects and studies. A considerable body of experimental data were accumulated at Combustion Engineering (1) and at Brookhaven National Laboratory (2,3) on boric acid corrosion in the presence of lubricants. Engineering data in this regard were derived from a steam generator manway assembly project at the TVA (4). Stress-corrosion cracking in the presence of lubricants was also studied at Combustion Engineering (1), Brookhaven National Laboratory (3) and at the TVA (4). In addition, a workshop on lubricants and their possible role in stress-corrosion cracking of bolting was conducted by MPC. This workshop led to some fundamental work on the corrosivity of manufacturing chemicals by General Electric R&D personnel (5). These efforts are summarized below, as adapted from Ref. (6).

MOLYBDENUM DISULFIDE DECOMPOSITION

The lubricating behavior of MoS_2 is well documented (7,8,9,10), and its application as a thread lubricant is widespread in the nuclear industry. However, very little

information is available on the conditions that lead to MoS_2 decomposition, except that the presence of moisture influences its chemical behavior. For example, Lansdown (11) summarized the effect of moisture on MoS_2, as follows:

- In the presence of water or in an oxidizing environment, MoS_2 reacts to form an oxide layer and H_2S.
- Following chemisorption of water, H_2SO_4 can evolve in ad adsorbed form.

Johnston et al. (12) found that MoS_2 which had been exposed to damp air contained sulfuric acid, molybdenum trioxide, and both chemisorbed and physically adsorbed water. Sulfuric acid contamination promotes physical adsorption of water, whereas MoO_3 promotes chemisorption of water. Both influence the coefficient of friction of the lubricant which, in turn, affects the torquing characteristics of the lubricated fastener.

In terms of H_2S formation under typical nuclear power plant conditions, Czajkowski (3) conducted steaming experiments on chemically-pure molybdenum disulfide which had been placed in a glass dish and suspended over water in a stainless steel autoclave at 100°C. The autoclave head was vented into a plastic tube with a metering valve into a test tube of water, followed by venting into a test tube of cadmium acetate. H_2S formation was detected through reaction with the cadmium acetate to form cadmium sulfide. The experiments were carried out for five-hour periods, with the MoS_2 surface area varied for each experiment. H_2S formation was detected in all of the experiments.

Hall (1) conducted experiments on SA-540, Grade B24, Class 3 steel coated with MoS_2 lubricant and immersed in 1000 ppm boron solution at 66°C for 1200 hours. The solution simulated boric acid concentrations of interest. The specimen was loaded to a stress level of 338 MPa (49 ksi), and no H_2S evolution was detected. A second test involved 500 hours of exposure at 66°C, followed by 170 hours at 310°C. After an examination of the specimen, the experiment was continued for 290 additional hours at 66°C, followed by an additional 190 hours at 310°C. At the end of the test, the H_2S in the solution was measured at 1700 ppm. The production of H_2S was attributed to the higher temperature in the second test.

Experiments at the TVA involved coarse MoS_2 powder in a saturated boric acid solution ($pH < 2$) at 100°C. Significant amounts of H_2S were produced in these

experiments. It was noted that aeration and deaeration had no influence on the H_2S evolution, and that H_2S did not form at room temperature.

From these limited results, we can conclude that H_2S can be evolved under typical nuclear power plant bolting applications, if the boric acid concentrations and the temperature are in the appropriate range. Temperatures lower than 66°C do not promote the reactions, while temperatures above 100°C promote H_2S evolution.

It is worth pointing out that the removal of the MoS_2 lubricant from fastener threads is somewhat controversial. Czajkowski (3) reported good success using carbon disulfide (CS_2) as a cleaning agent. On the other hand, Bertrand et al. (13) have noted that a burnishing film of highly-micronized MoS_2 and an air cured, MoS_2-containing, resin-bonded coating on smooth pin surfaces were very difficult to clean. Obviously, removing the film from a threaded surface, especially an internal thread surface, would be even more difficult. Another factor is the chemistry of the cleaning solvents themselves, most of which are either alkaline or acidic in nature. Proper flushing of these solvents would be necessary to avoid potential stress-corrosion cracking problems.

BORIC ACID CORROSION IN THE PRESENCE OF LUBRICANTS

With this basic information on MoS_2 decomposition in hand, the available data on the corrosion behavior of lubricated low-alloy steels in reactor coolant environments can be assessed. Hall (1) has reported results of experiments on SA-193, Grade B7; SA-540, Grade B23, Class 4; and SA-540, Grade B24, Class 3 steels exposed to steam impingement from borated water. The small-diameter stud specimens were loaded to 1/2 to 2/3 of their yield strength in either austenitic stainless steel or low-alloy steel fixtures. The temperature of each stud was carefully controlled. The specimens were coated with one of two lubricants -- Moly G or PNS-506. The steam was maintained at 316°C, and contained 1000 ppm boron to represent boric acid solution. The experimental results are shown in Figures 8-1 and 8-2.

Figure 8-1 provides a comparison of the corrosion rates of SA-540, Grade B24, Class 3 steel as a function of metal temperature, lubricant, and galvanic couple (stainless or low-alloy steel). The latter seems to have little or no influence on corrosion behavior of this particular steel. Note that the corrosion rates increase with temperature. Figure 8-2 provides a composite picture of corrosion rates for all three materials and compares these rates with the rates measured by

Czajkowski (2) on bare specimens, as shown by the dashed line. The higher rates could be due to a number of factors -- the steam impingement, galvanic action, or other effects.

Czajkowski (3) conducted weight-loss experiments on SA-193, Grade B7 and SA-540, Grade B24 materials, using a variety of lubricants. He evaluated chemically pure molybdenum disulfide and various commercial grades from a number of suppliers, graphite in isopropanol, nickel-plus-graphite lubricant, copper-plus-graphite lubricant, anti-seizing lubricant, never-seizing lubricant, and bonded-solid-film lubricant. The latter lubricant had a manufacturer-supplied chemical analysis showing 29 ppm fluorine, 200 ppm chlorine, 98 ppm sulfur, 2 ppm lead, 1 ppm mercury, 0.05 ppm arsenic, and 1 ppm zinc. Corrosion rates for test coupons with this bonded-solid-film lubricant are shown in Figure 8-3 and can be compared to unlubricated test coupon data. The corrosion rates are seen to be about an order of magnitude lower at 100°C and 178°C for the lubricated specimens, but the lubricant protection appears to be lost at 315°C.

Also shown in Figure 8-3 is a single data point from work done at the TVA (4), using Fel-Pro N-5000 lubricant on the surface of SA-193, Grade B7 bolts prestressed to 550 MPa (80 ksi) in a saturated solution of boric acid containing 200 ppm chlorine at 288°C. This test condition produced corrosion rates an order of magnitude higher than those reported by Czajkowski. The higher corrosion rate is attributable to the high boric acid concentration, the complete immersion of the specimens, and the presence of chloride ions in the solution.

STRESS CORROSION CRACKING IN THE PRESENCE OF LUBRICANTS

During a maintenance outage in 1982, several steam generator manway cover studs at Maine Yankee fractured during their removal from the manway flanges. The cause of the fractures was stress corrosion cracking, and examination of the crack surfaces showed weak indications of Mo and/or S. The studs had been exposed to leakage caused by interference contact between the gasket retainer plate and the steam generator vessel cladding, which prevented proper compression of the gasket. Qualitative analysis of lubricant samples removed from the studs indicated the presence of Ni, Cu, Mo and S. Ni was a constituent in the lubricant in use at the time for the manway cover studs at Maine Yankee, while Cu, Mo and S were constituents in previously-used lubricants.

Similar failures had been observed at Unit 2 of the D.C. Cook plant in 1981. Several of the internal studs joining the disc guide and baffle plates in the main steam isolation valves had fractured during service, and many more fractured while being removed for replacement. Failure analysis indicated the presence of S and Cl on the fracture surface, with large amounts of Mo and S on the thread flank. These and other failure observations suggest a role for lubricants as an enhancement to stress corrosion cracking.

Since the decomposition of molybdenum disulfide to form H_2S has been demonstrated for ranges of boric acid concentration and temperature, some care should be exercised in the selection and use of lubricants and sealants on fasteners which may be exposed to primary coolant at elevated temperatures. However, stress-corrosion cracking is caused by a combination of: (1) material, (2) stress, and (3) environmental factors. With given bolting materials, such as SA-193 or SA-540 grades, stress-corrosion cracking can be avoided through control of stress and environment. For example, good housekeeping practices that control boric acid attack should reduce the potential for stress-corrosion cracking. Leaks from flanged joints should be eliminated or minimized. Any spillage of primary coolant during maintenance operations should be removed promptly to avoid contamination. Actions such as these will reduce the possibility that a hostile environment will initiate stress-corrosion cracking. Stress levels should be controlled whenever possible, since the susceptibility to stress-corrosion cracking decreases when stresses are reduced.

The choice of lubricant, when considered statistically in relation to fastener material, applied stress, and environmental factors, has a much less significant effect.

LEAK SEALANTS

A number of potential concerns have been identified with respect to sealing leaks in nuclear power plants, including increased loads on components and added weight to piping systems, sealant intrusion into the process line, and increased corrosion potential. These concerns can be combined into two parts: (1) maintenance of pressure boundary integrity during and subsequent to sealant injection, and (2) the effect on system/component function and operability from sealant injection. Each of these imposes criteria to be satisfied by proposed leak sealing operations.

The AIF/MPC Task Group on Bolting has recommended that the responsible design organization evaluate and concur with the effect of proposed leak sealing operations on the reactor coolant pressure boundary (ASME Section III, Class 1 or equivalent component classification), on active components of all ASME Code classes, and on the packing of active or nonactive dynamic valves. The Task Group also recommended that applications of leak sealants be considered temporary solutions, with leaking components repaired or replaced at the next available opportunity. Repair should involve the removal of all sealant and restoration of the component to its original configuration or to an approved alternate configuration. A controlled standard practices document, or comparable specification, should be readily available at the plant site to guide and insure the adequacy of leak sealing operations. Some of the items to be covered by this document are:

- Sealant contaminants. The sealant chemistry should be prescribed and verified to be within acceptable limits. Each sealant lot or batch should be tested, and its compliance with the chemistry requirements established and documented.

- Sealant cavity pressure should be closely monitored during the injection operation, using sealant injection pressure as a conservative measure, if appropriate. Overpressure check points should be established prior to injection.

- Prior to injection, the anticipated volume of sealant needed to fill the volume of the sealant cavity or enclosure should be determined. A check point to limit the volume of injected sealant should be established. This will provide reasonable assurance that excess sealant will not be forced into the process fluid.

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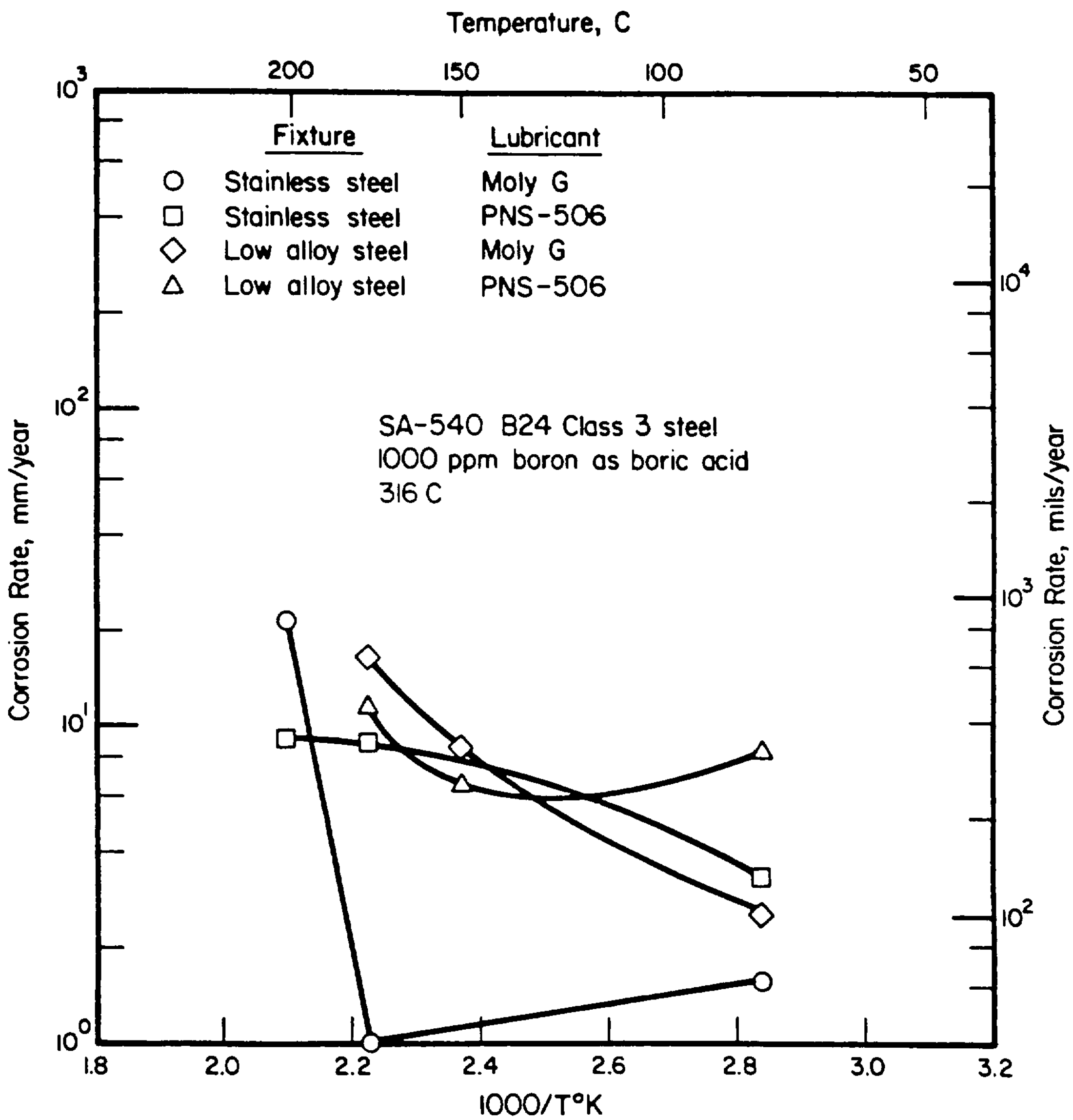

Figure 8-1. Corrosion Rates of SA-540 B24 Class 3 Material Under Coated Conditions (1)

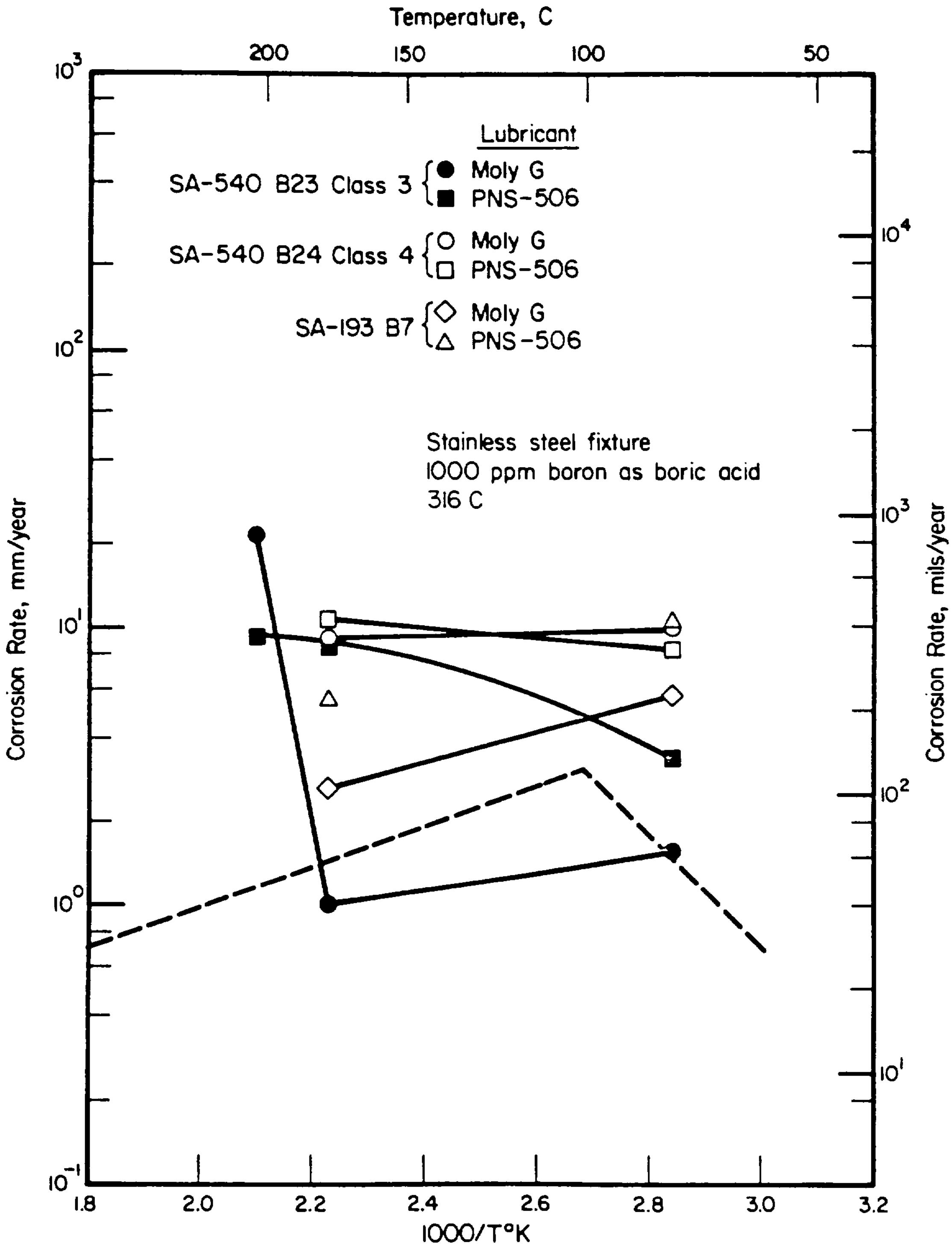

Figure 8-2. Corrosion Rates of Various Low-Alloy Steels Under Coated Conditions - The Dashed Line Corresponds to Rates for Bare Specimens (2)

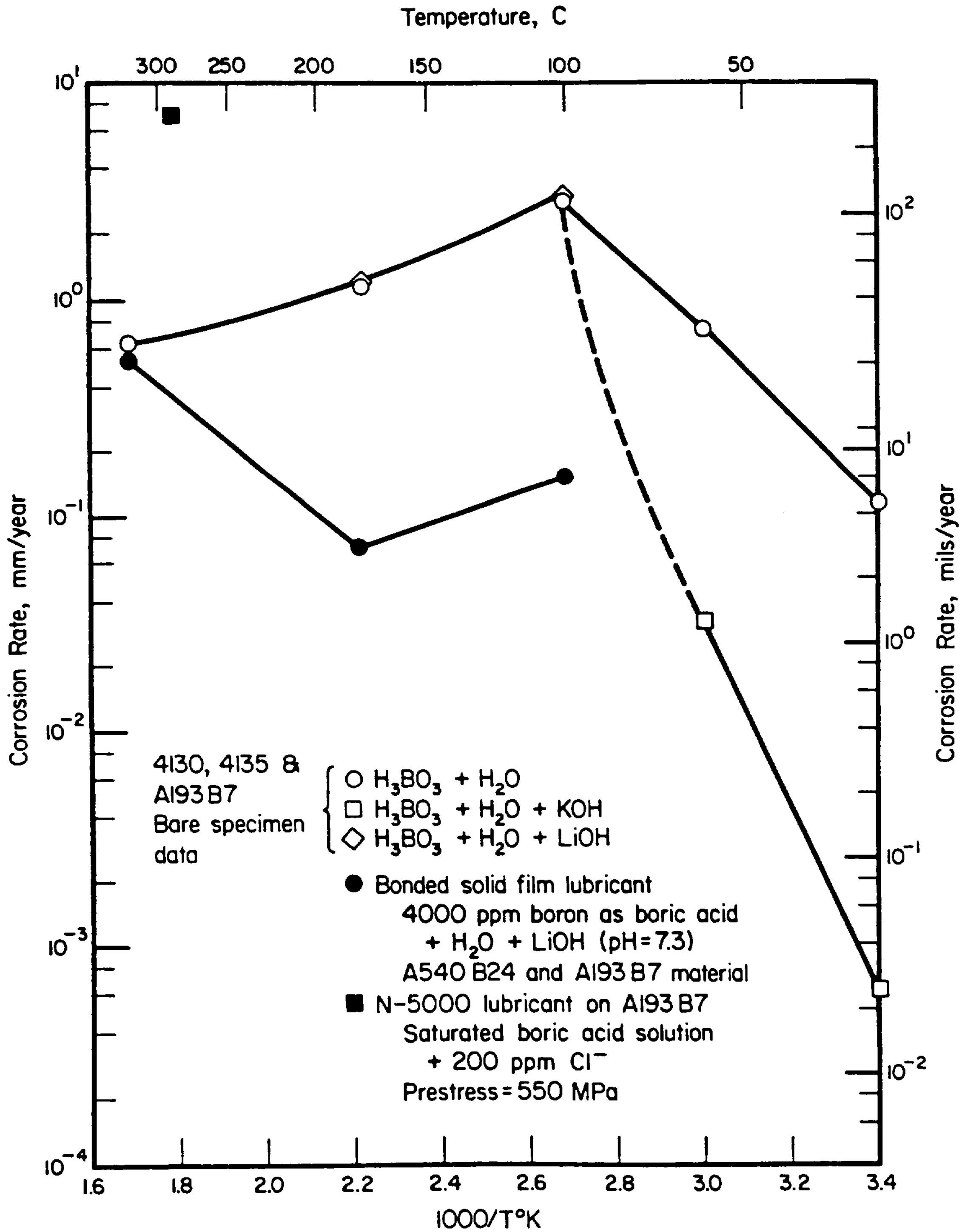

Figure 8-3. Comparison of Bare Metal Corrosion Results With Coated Metal Corrosion Results

Section 9

ALTERNATIVE MATERIALS

INTRODUCTION

Task 13 of the AIF/MPC Task Group on Bolting action plan had as its objective to provide recommendations with respect to alternative materials and coatings, and to provide guidance regarding their application. Under contract to EPRI, Battelle-Columbus Laboratories reviewed the data for six bolting material alloys with respect to corrosion and stress-corrosion cracking (SCC) resistance in nuclear power plant applications (1). This work was also related to that of Task 3 of the action plan. The following alloys were evaluated: A-286, an austenitic, precipitation-hardened, iron-based alloy; Inconel 625, an austenitic, nickel-based alloy; Inconel X-750, an austenitic, precipitation-hardened, nickel-based alloy; Inconel 718, another austenitic, precipitation-hardened, nickel-based alloy; AISI 410, a martensitic stainless steel; and 17-4 pH, a martensitic, precipitation-hardened stainless steel. As a baseline for this evaluation, data for standard low-alloy steels that constitute the bulk of nuclear bolting applications were also reviewed.

The evaluation criteria were: (1) boric acid corrosion rates and conditions promoting boric acid corrosion, such as the formation of galvanic cells with a low alloy steel structure; (2) stress-corrosion cracking performance, including the role of contaminants and lubricants; (3) the determination of threshold K_{ISCC} values for establishing safe preloads; and (4) thermal expansion coefficient mismatches. Other important metallurgical issues, such as control of composition, microstructure, and heat treatment, that can influence the service performance, are not covered in this discussion.

A more complete discussion of bolting failure experience is covered in Section 3, Volume 2; however, it is important to recognize that bolts have failed prior to service, as well as during service, and that the failures are especially prevalent in PWRs.

The pressure boundary components affected by such failures include reactor coolant pumps, steam generator and pressurizer manway closures, and reactor vessel closures. The majority of corrosion damage and stress-corrosion failures can be subdivided into three broad categories. Failure of A-286 stainless steel fasteners in reactor internals constitute more than half of SCC failures (nearly 155 failures). Such failures have been attributed to presence of chloride ions, traces of sulfide, as well as to borated water. Corrective action has involved replacing the fasteners by X750 bolts. Failure of high-strength maraging steel bolts in steam generator column supports constitute the second largest category of SCC failures (approximately 54). These failures were attributed to excessive preload of such high-strength materials. Corrective actions have involved better bolted joint design for the same material and application of lower preload. The third major category of corrosion damage and SCC failures was associated with low-alloy steels, mainly in external applications such as steam generator holddown supports, steam generator manway closures, and valves (approximately 75 instances). The failures had been attributed either to leaking borated water or to the presence of hydrogen sulfide. Hydrogen sulfide is suspected to have formed by the decomposition of molybdenum disulfide lubricant on the bolts. Generally, such failed studs and bolts have been replaced by similar low-alloy steel material, but with lower preloads. In addition to SCC failures in low-alloy steels, there have been over 200 instances of bolting degradation and failure of low alloy steels due to simple corrosion from borated water leakage.

BORIC ACID CORROSION

A recent review by Hall (2) described the inservice boric acid problem as an accelerated general corrosion process, in localized areas of the fastener, which results in a major reduction in the diameter of fasteners fabricated from carbon steels and alloy steels. The most widely affected components have been various valves and reactor coolant pumps. The occurrences have been isolated for the most part and have occurred only in borated water systems when leaks were present.

In this section, the boric acid corrosion behavior of low-alloy steels, as well as of the alternative alloys is reviewed, although very little data could be found for the alternative alloys.

Results of a detailed study conducted by Westinghouse on A302B low-alloy steel in aerated and deaerated boric acid solution are presented in Figures 9-1 and 9-2, respectively (3). These experiments were conducted on electrically-isolated

coupons, as well as on coupons coupled to 304 stainless steel. The results suggested that the corrosion rate is much higher under aerated conditions than under deaerated conditions. Corrosion rates increased with temperature under aerated conditions. Within the limited temperature range investigated, coupling with 304 stainless steel did not influence the corrosion rate under aerated conditions. One influence of such a coupling was noted under deaerated conditions; the coupled coupons corroded faster than the isolated coupons at 21°C and 60°C. These results also suggest that short-term exposure tests may produce non-steady-state corrosion rates which are higher than the steady-state corrosion rates. It should be mentioned that the leakage conditions under which existing fasteners have failed in service correspond essentially to aerated conditions. Therefore, in any further evaluation, aerated conditions might represent more appropriate experimental conditions.

Although A302B steel differs significantly in chemical composition and mechanical properties compared to the ferritic steels used as fasteners in nuclear power plants, recent work has shown (2,4) that corrosion rates may not depend significantly on composition of the steel around room temperature. This may be observed from Figure 9-3, which shows that corrosion rates ranged between 0.1 to 0.5 mm/year (3.9 mils/year to 19.7 mils/year) for the various materials at room temperature. The Soviet alloys were pearlitic materials. Except for the A302B steel, all experiments have been conducted with the solution exposed to air. Also shown on Figure 9-3 are some data from the work of Czajkowski (4) on boric acid corrosion of low-alloy steels. Czajkowski concluded that, up to the boiling point of water, the corrosion rate did not depend sensitively on the concentration of boric acid in solution. The corrosion rates dropped for temperatures above 100°C because of the boiling away of water. Czajkowski also concluded that additions of potassium hydroxide and lithium hydroxide reduced boric acid corrosion rates up to 100°C. However, data do not exist below 100°C for boric acid corrosion in the presence of lithium hydroxide. Therefore, additional tests may be needed to verify that lithium hydroxide addition indeed reduces boric acid corrosion rates below 100°C.

The data indicate that the low-alloy fastener materials are prone to boric acid corrosion. The maximum corrosion rates, ranging between 2 and 5 mm/year (79 mils/year to 197 mils/year), occur under borated conditions either in boiling water or with steam impingement. Such rates can cause significant wastage and the integrity of a fastener.

On the other hand, limited results from Hall (2) on 410 stainless steel, 17-4 pH stainless steel, and Inconel 718 have shown that these materials are highly resistant to boric acid corrosion. In Hall's study, AISI 410 specimens were stressed up to their yield point and partially submerged in an 88°C solution of boric acid (2,000 to 5,000 ppm boron). Also, a 21°C solution of boric acid (950 to 2,100 ppm boron) was dripped on to the exposed part of the specimens. After 1,785 hours of exposure, there was only slight loss of luster and instances of minor pitting. Specimens of 17-4 pH stainless steel, aged at 593°C, were subjected to steam impingement at 316°C. The source of steam was borated water containing approximately 1,000 ppm boron as boric acid. After 2,500 hours of exposure, the specimens maintained their original luster. Inconel 718 specimens stressed from 1/2 to 2/3 of yield strength and exposed to similar steam impingement conditions as the 17-4 pH material also did not show any loss of luster after 2,500 hours of exposure. No data on boric acid corrosion of alloys A-286, Inconel 625, and Inconel X-750 were found in the literature.

Galvanic Corrosion in Reactor Coolant

Except for the data presented earlier on A302B steel, no data could be found for the galvanic corrosion behavior of low-alloy steels in borated water. However, some data, reported by Sammarone (5), on galvanic behavior of 4340 steel in demineralized water containing various additions, are considered relevant and are discussed here. Galvanic corrosion behavior of 4340 steel seems to agree with the data shown in Figures 9-1 and 9-2 for A302B steel. These results, given in Table 9-1, suggest that a galvanic couple between 4340 and 304 stainless steel will occur only under low-oxygen conditions. Lithium hydroxide addition to water at 60°C reduced the corrosion rate under low-oxygen conditions. This combination produced a corrosion rate of 0.0007 mm/year (0.03 mil/year), when coupled to 304 stainless steel. On the other hand, coupling 4340 with Inconel, under otherwise identical conditions (6.9 ppm LiOH and 0.5 ppm oxygen), produced corrosion rates that were faster by a factor of about 25. These results suggest that the type of austenitic material used in the couple may strongly influence the galvanic corrosion rates of a low alloy steel. As with isolated-coupon results of Czajkowski (4), presented earlier, these galvanic-corrosion results suggest that addition of lithium hydroxide will reduce corrosion rates, especially under conditions of low oxygen.

Preload Versus K_{ISCC}

Considerable effort has been expended in gathering K_{ISCC} data for low-alloy and other steels used in bolting applications in the nuclear industry (6). One purpose of such an exercise is to develop the preload that can be applied to fasteners in service in order to avoid SCC. The link between bolt preload and K_{ISCC} can be established using linear elastic fracture mechanics (LEFM) methodology.

LEFM defines a parameter known as the stress intensity factor (denoted as K_I for the opening mode of loading), which is the driving force for a crack to progress in a given geometry. This driving force K_I is related to the size of the crack, the applied load, and the geometry of the component:

$$K_I = Y \sigma \sqrt{a} ,$$

where σ is the net applied tensile stress, a is the length of the crack, and Y is a geometry factor.

Mechanical failure of the component, at a given temperature, occurs when applied K_I reaches a critical point, known as the fracture toughness of the material at that temperature. Under plane strain conditions, this is known as the plane strain fracture toughness, K_{IC}. To avoid mechanical failure, the applied K_I should be less than K_{IC}. Similarly, to avoid SCC, the applied K_I should be less than K_{ISCC}. It may be noted that K_{ISCC} is generally far lower than K_{IC} for a material that is susceptible to SCC.

To be able to use this methodology, one has to develop the stress intensity solution for the bolt geometry and a reference flaw size to calculate K_I (or K_{ISCC} or K_{IC}). Development of the stress intensity solution was the object of the work of Cipolla et al. (7,8). Using this methodology and a representative flaw geometry, semi-elliptical in shape, with a depth a = 0.02 inch (0.508 mm) and surface length, 2c = 0.08 inch (2.032 mm) (aspect ratio a/2c = 1/4), Czajkowski (9) developed a relationship between yield strength and bolt preload to avoid SCC. A typical example, for a 4 inch (101.6 mm) nominal diameter bolt with 8 threads per 1 inch (25.4 mm), is presented in Figure 9-4. There are several notes of caution that should be kept in mind when using a plot such as this:

- The representative flaw size used in developing these data is rather arbitrarily defined. An appropriate representative flaw size should

be established before this method is employed. It seems reasonable to establish this size based on the limits of nondestructive inspection techniques used in the industry. The Cylindrically Guided Wave Technique (CGWT), that detects a minimum flaw size of 1 mm (40 mil) depth, is discussed in Section 7 of this volume. Other techniques are being developed by EPRI that could improve the detection limit. Another approach that one could look at is the consideration of design based on notch (thread) stress concentration factor. Data should be developed as preload versus time-to-failure for various stress concentration factors.

The data trend indicated in Figure 9-4 suggests that, as the yield strength of the bolt material decreases, the preload on the bolt can be increased without causing stress-corrosion cracking. Below about 896 MPa (130 ksi) yield strength, the preload on the bolt is indicated to be equivalent to or in excess of the yield strength. Such a condition will produce mechanical yielding of the bolt. Clearly, a cut-off needs to be defined in the plot. A line drawn such that preload is equal to the yield strength can serve as a cut-off limit. As indicated in Figure 9-4, the hatched region represents the preload condition that would theoretically avoid SCC or mechanical failure. Such data will have to be developed for the alternative alloys being considered.

- Finally, it should be appreciated that yield strength does not, by itself, completely define SCC susceptibility. The SCC resistance of the material will depend upon other variables such as heat treatment, microstructure and composition of the material. It is, therefore, best to develop SCC data (K_{ISCC} in particular) for the actual material condition that is going to be used in service. The argument is valid for the environment as well. The K_{ISCC} of the material changes with environmental composition and temperature, and it is best to develop such data in the anticipated service environment. Once such data have been developed, the LEFM methodology can then be more reliably employed to establish the preload on a fastener made from the tested material.

THERMAL EXPANSION OF ALTERNATIVE ALLOYS VERSUS LOW-ALLOY STEELS

It was noted earlier that steam generator manway closures were made of low-alloy steel, and that the use of austenitic or martensitic material for fasteners will set up a galvanic couple between the two materials. Another consideration is the difference in coefficient of thermal expansion between the low-alloy steels and the alternative materials. A significant difference can influence the clamping force or the initial room temperature preload on the fastener. In the joint, both the structure and the fastener will expand with increasing temperature. The amount of expansion will depend on the coefficient of thermal expansion of each material. When the coefficient of thermal expansion of the fastener is greater than that of the structure, clamping force will be lost with increasing temperature. On the

other hand, when the coefficient of thermal expansion of the structure is greater, the load on the fastener will increase with increasing temperature. In the case of the steam generator manway closure, the structure (made of low-alloy steel) has a lower coefficient of thermal expansion compared to, for example, the austenitic fasteners. Therefore, the clamping force may be lost with increasing temperature. The loss of clamping force is not a desirable situation, since leakage of water from the system could result. This factor will have to be considered in establishing the preload on the fastener during initial assembly at room temperature. The extra preload required on the bolt at room temperature to avoid loss of clamping force at higher temperature means that the K_{ISCC} of the material may be exceeded at room temperature. The significance of the problem can be answered with some calculations for a given joint configuration and its load requirements. Although analytical tools are available to determine the loss of preload under differential coefficient of thermal expansion, it is recommended that experimental methods be employed to confirm the analytical predictions because of the complex geometry and bolting pattern involved.

DISCUSSION AND RECOMMENDATIONS

As noted earlier in this section, a more complete discussion of the specific aspects of corrosion and SCC behavior of both the low-alloy steels and the alternate materials is available in Ref. (1). It should be mentioned here, however, that data are lacking for service-typical environments of interest. Even when some data are available, the stress corrosion resistance of the various alloys is not expressed by a unique set of parameters, which makes comparison of various alloys rather difficult. From the damage-tolerant design standpoint, K_{ISCC} data should be developed for the alloys in specific environments. In addition, crack initiation data may have to be generated from time-to-failure studies of smooth and notched specimens. Such notched specimens are more representative of constrained yielding conditions at the roots of threaded fasteners. The experimental efforts would have to take into account the influence of heat treatment, microstructure, composition and chemical homogeneity on SCC susceptibility. Based on the data reviewed in the paper, the following conclusions may be drawn:

1. Low alloy steels are prone to boric acid corrosion with corrosion rates varying from 0.1 mm/year to 7 mm/year depending on the test conditions. By comparison, there is little attack on 410 stainless steel, 17-4 pH stainless steel, and Inconel 718.

2. Limited data indicate that the galvanic corrosion behavior is dependent not only upon the materials in the couple, but also on the presence of such constituents as oxygen or LiOH in water. Galvanic corrosion data should be developed for each of the alternative alloys with a low-alloy steel couple.

3. Laboratory tests indicate that under certain conditions hydrogen sulfide can indeed be liberated from molybdenum disulfide lubricant. The conditions for such reaction to occur need to be better defined and compared with existing service conditions.

4. In order to incorporate a damage-tolerant design methodology, efforts should be made to generate K_{ISCC} and crack initiation data for the important alloys in typical service environments.

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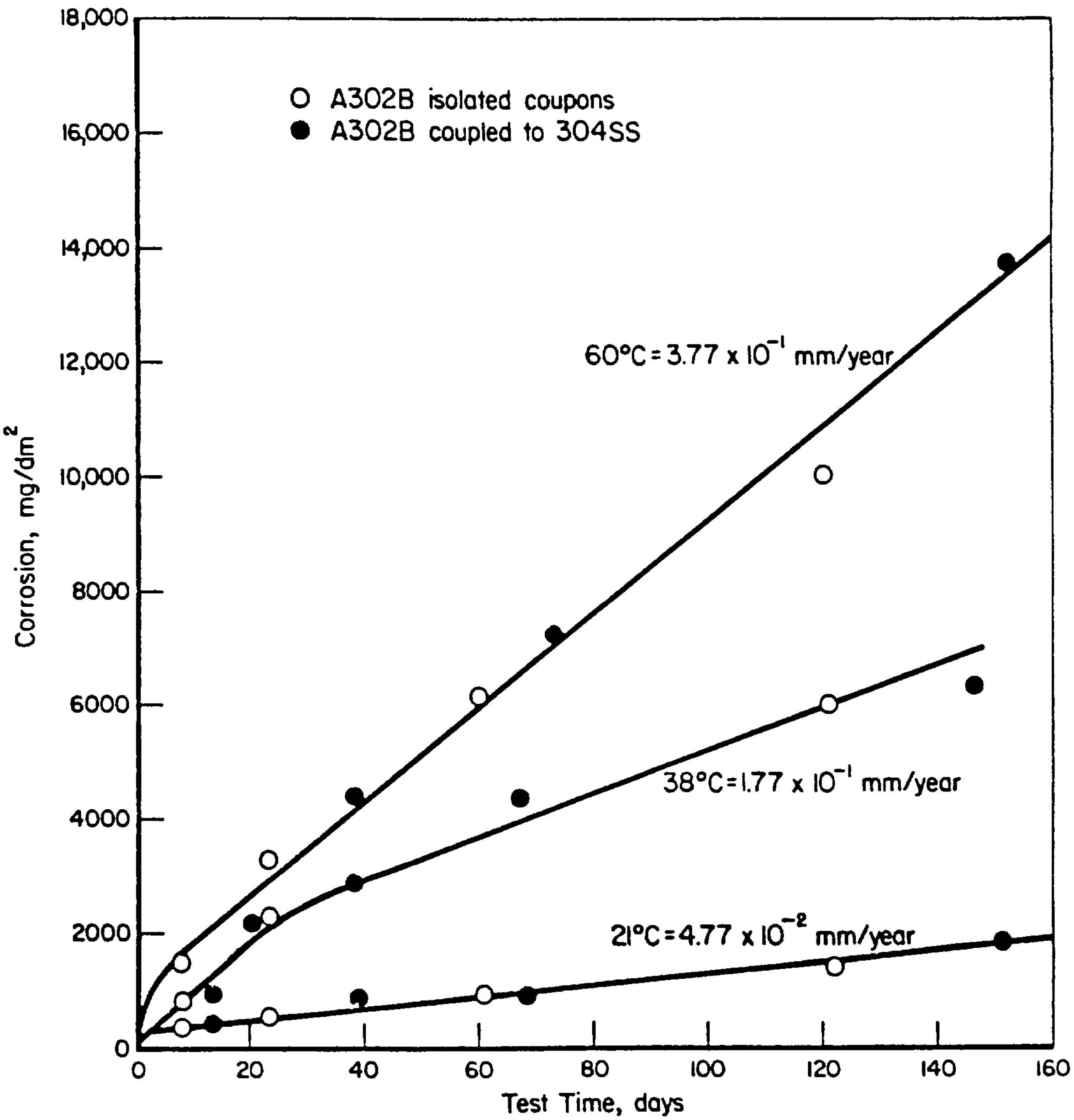

Figure 9-1. Corrosion As Measured in Weight Loss of A302B in Air Saturated Boric Acid Solution Containing 2500 ppm Boron (3)

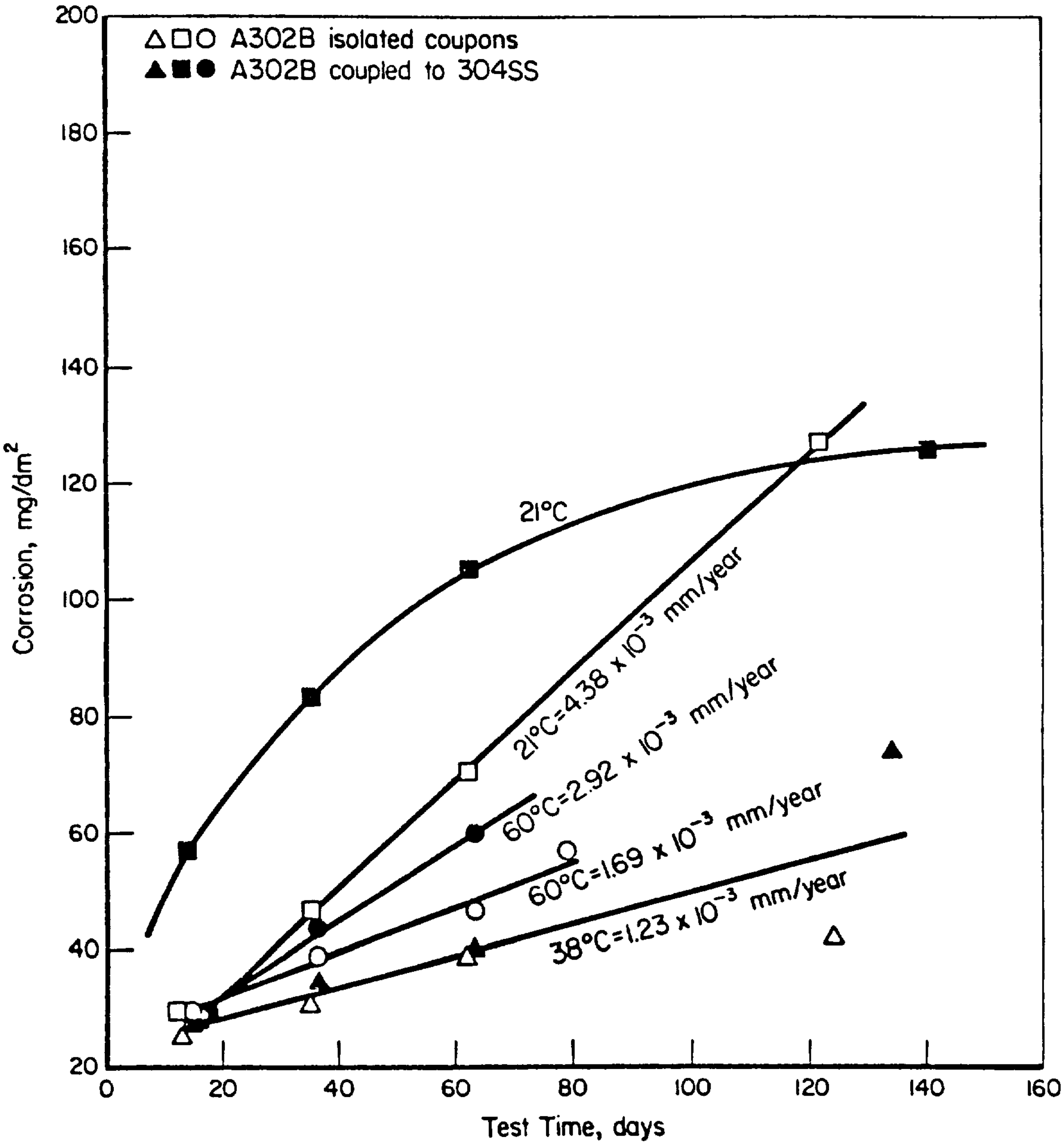

Figure 9-2. Corrosion of A302B in Deaerated Boric Acid Solution Containing 2500 ppm Boron (3)

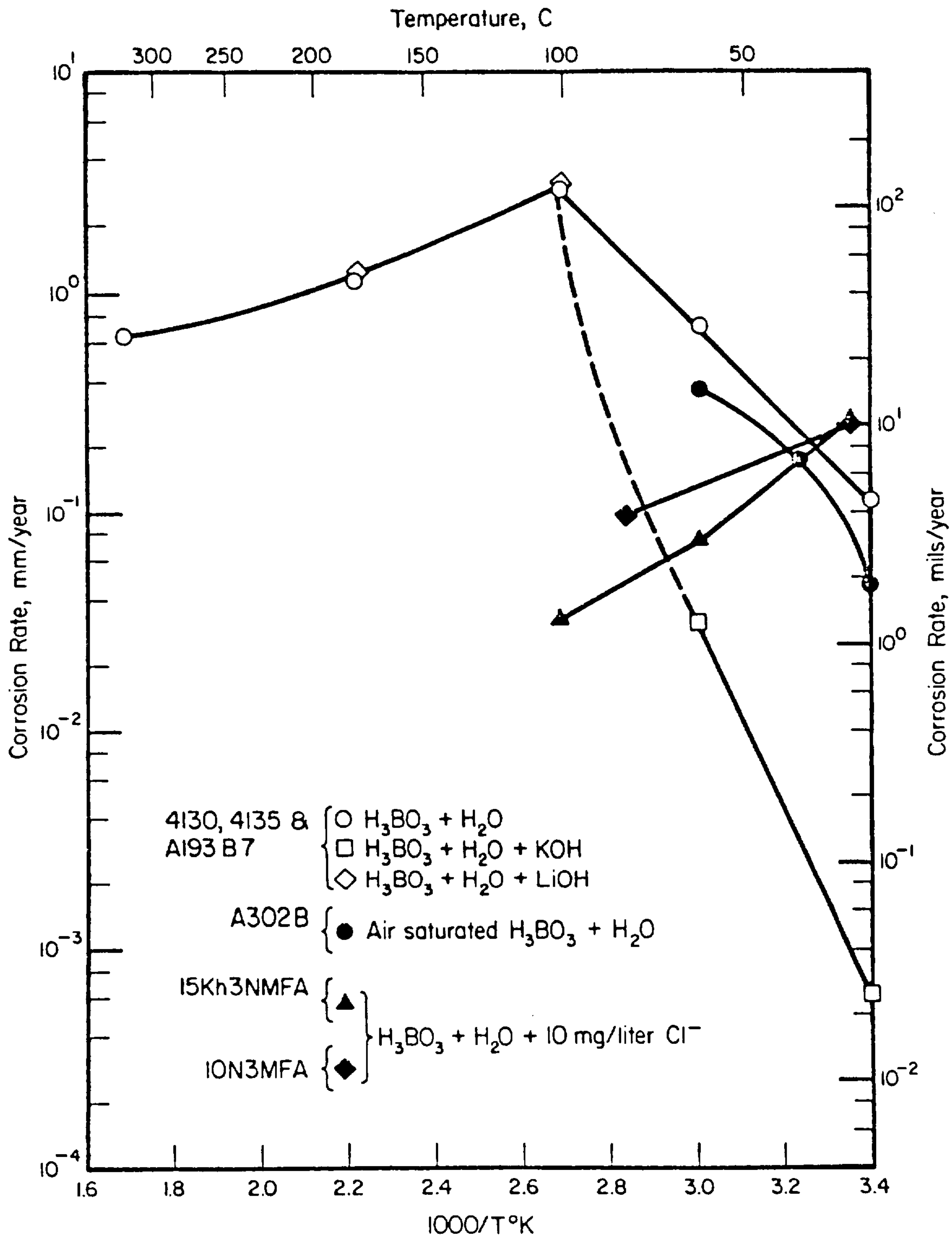

Figure 9-3. Corrosion Rates As a Function of Temperature for Several Low Alloy Steels

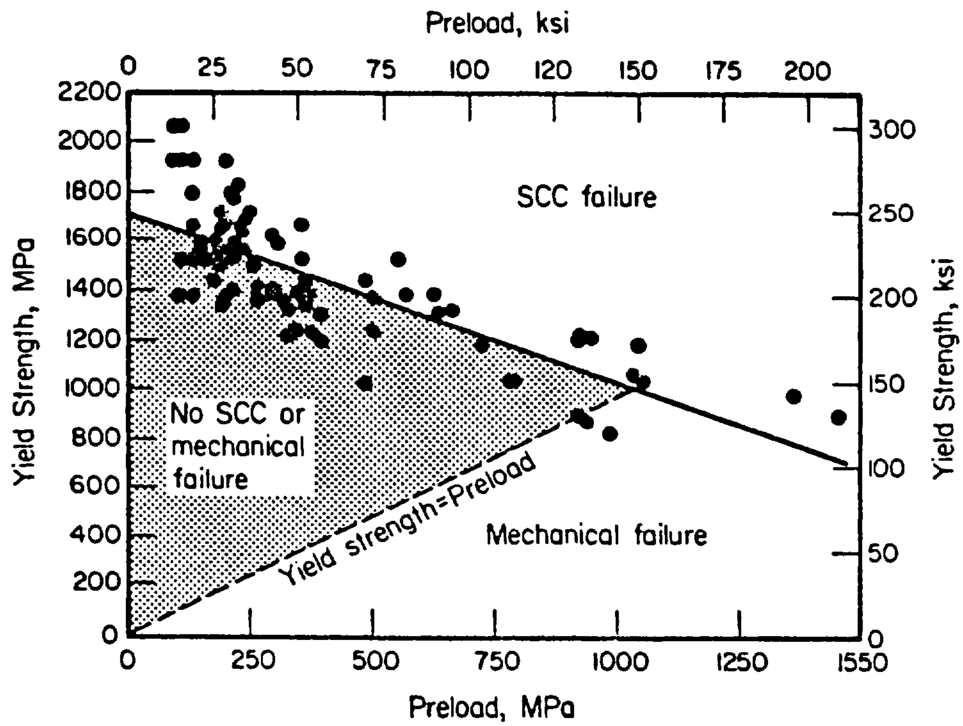

Figure 9-4. Yield Strength Versus Preload for a 101.6 mm (4 inches) Nominal Diameter Bolt with 8 Threads per 25.4 mm (1 inch, Made of 4340 Steel

Table 9-1

GALVANIC CORROSION BEHAVIOR OF 4340 STEEL IN REACTOR COOLANT ENVIRONMENT (5)

Couple	Environment	Temperature °C	(°F)	Test Duration (Days)	Measured Corrosion mg/cm^2	Approximate Corrosion Rate mm/year
4340 Carbon Steel vs. 304 Stainless Steel Containing 1.5 w/o Boron	Demineralized Water Containing 2 ppm Oxygen at 8 psia	82	(180)	13.8	1,206	4.032×10^{-1}
4340 Carbon Steel vs. 304 Stainless Steel	Demineralized Water + 6.9 ppm LiOH + 3 to 5 ppm Oxygen at Atm. Pressure	60	(140)	9.9	1,590	7.41×10^{-1}
	Demineralized Water + 6.9 ppm LiOH + 0.5 ppm Oxygen at 3 psia	60	(140)	82	12.1	6.81×10^{-4}
	Demineralized Water + Less Than 0.5 ppm Oxygen at 3 psia	60	(140)	90	627	3.21×10^{-2}
	Demineralized Water + 2 ppm Oxygen at 8 psia	82	(180)	14	645	2.12×10^{-1}
4340 Carbon Steel vs. Inconel (Unspecified)	Demineralized Water + 6.9 ppm LiOH + 3 to 5 ppm Oxygen at Atm. Pressure	60	(140)	9.8	963	4.53×10^{-1}
	Demineralized Water + 0.05 ppm Oxygen at 7.5 psia	82	(180)	35	1,790 1,620	2.3×10^{-1} 2.13×10^{-1}
	Demineralized Water + 2 ppm Oxygen at 8 psia	82	(180)	14	738	2.43×10^{-1}
	Demineralized Water + 6.9 ppm LiOH + 0.5 ppm Oxygen at 8 psia	60	(140)	82	332	1.87×10^{-2}
4340 Carbon Steel vs. Nickel	Demineralized Water + 2 ppm Oxygen at 8 psia	82	(180)	14.1	532	1.74×10^{-1}

Section 10

TRAINING PACKAGE

Task 9 of the AIF/MPC Task Group on Bolting action plan addressed the exchange of information between EPRI and its contractors, on the one hand, and utility engineering/maintenance organization, on the other hand. Three subtasks were identified, beginning with an initial workshop in the Fall of 1983 to exchange information on industry/EPRI efforts on bolting integrity to that date, followed by the production of videotapes on pressure boundary and structural bolting.

EPRI contracted with Raymond Engineering, Inc. to produce a set of three videotapes on "Pressure Boundary Bolting Problems", which constituted the satisfaction of the second subtask -- the production and distribution to utilities of a videotape on the behavior and maintenance of flanged pressure boundary connections, as an aid to improving bolting design, installation, and maintenance techniques. The tapes illustrate the basics of bolted connections, engineering and design considerations, and mechanic and tooling aspects. It was felt that the tapes would improve personnel training, thereby contributing to more efficient and safer plant operation, with a reduced probability of losing pressure boundary integrity. Although the videotapes formally deal with pressure boundary bolting only, Part II was modified to deal with preload control and its effect on stress-corrosion cracking (SCC). In this way, much of the material is applicable to structural bolting, as well.

Distribution of the videotapes is handled by the Maintenance Equipment Application Center at the EPRI NDE Center, Charlotte, North Carolina. A description of the videotape contents is provided below.

"PRESSURE BOUNDARY BOLTING PROBLEMS"

In an effort to achieve cleaner, more reliable plants with reduced radiation and operating costs, EPRI contracted with Raymond Engineering, Inc. to produce a three-part training videotape on achieving leak-free pressure boundary joints.

Part I The Basics (30 Minutes): discusses basic principles of bolting, including elastic behavior, load tightening, and preload. Three factors

working against bolted joints are friction, flange rotation, and cycling. Factors affecting bolt integrity include chemical attack, borated water, dissimilar metals, and fatigue. Manual wrenches, hydraulic torque wrenches, and hydraulic tensioners are the tools recommended for producing leak-free joints.

Part II Engineering Considerations (47 Minutes): addresses proper planning and implementing control strategies to produce more reliable bolted joints. Three factors contribute to stress-corrosion cracking (SCC): susceptible materials, stresses above threshold level, and undesirable environments. To control maximum stress, the preload must be controlled, thus minimizing high stress considerations. To achieve leak-free joints, engineers should: (1) develop specific and detailed procedures according to plant needs, (2) train personnel, and (3) implement stretch control.

Part III The Mechanic and Bolting (24 Minutes): provides guidance to the mechanic assembling flanged joints. A checklist for the mechanic to use while performing the work is presented, including: use calibrated tools as designed; use hardened washers and lubricants; tighten bolts according to a cross bolting pattern; check the gasket for distortion. Three ways to measure bolt preload involve ultrasonic extensometers, micrometers, and datum rod-depth gauges. Lastly, the mechanic should maintain a data log which can be used for future designs.

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Section 11

CONCLUSIONS AND RECOMMENDATIONS

The AIF/MPC Task Group on Bolting has now completed its nineteen-point program on degradation and failure of bolting in commercial nuclear power plants, using the EPRI Generic Bolted Joint Integrity research project as its cornerstone. The Task Group and EPRI efforts are described in these two volumes, with Volume 1 devoted to the overall description and highlights of the research and Volume 2 covering the detailed results of each task. This section will summarize the conclusions reached and the recommended resolution of the bolting issue.

The EPRI Generic Bolted Joint Integrity project was put together in such a way as to integrate the many technical disciplines (e.g., metallurgy, non-destructive examination, corrosion engineering, fracture mechanics, and others) and activities (e.g., bolt tensioning control, specifications and standards, material selection, quality assurance, and others) involved, with an ultimate goal of providing the tools and procedures for demonstrating safety margins in both pressure boundary and structural joints, and recommending realistic inspection and maintenance programs for utilities. The approach taken to meet this goal is based upon the inherent structural redundancy of a bolted connection, so that safety and reliability criteria can be met even with some degraded or failed fasteners. The EPRI project results were to be implemented through technology transfer mechanisms, such as this two-volume report, workshops, and videotape instruction.

The AIF/MPC action plan also included interactions with relevant American Society for Testing and Materials (ASTM) and American Society of Mechanical Engineers (ASME) standards bodies, the Institute of Nuclear Power Operations (INPO) and the U.S. Nuclear Regulatory Commission (USNRC). These interactions are summarized here, as well.

CODES AND STANDARDS

The ASTM committees with jurisdiction over bolting material and testing specifications have been evaluating the need for modifications to these specifications,

based on commercial nuclear power plant experience and recommendations from the AIF/MPC Task Group. Several specifications have already been modified.

The ASME Nuclear Operations and Maintenance Committee has formed a Working Group on Bolting, whose purpose is to evaluate the need for a new American National Standards Institute (ANSI) standard for bolted joints, based upon guidelines from the EPRI Generic Bolted Joint Integrity project, that would provide a similar level of attention as that provided for welded joints by the ASME Boiler and Pressure Vessel Code. The relevant paragraphs of Section III, Division 1, of the Code have been reviewed, and some clarification and amplification of existing design requirements has been recommended. A formal Code Case is being sought within Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components, so that bolted joint inspection requirements can be focused on service-sensitive joints, with acceptance standards and inspection frequency derived from EPRI research. The NDE rules for fasteners should be modified to accommodate recent developments in NDE technology.

INSTITUTE OF NUCLEAR POWER OPERATIONS

INPO issued Significant Operating Event Report (SOER) No. 84-5, "Bolting Degradation or Failure in Nuclear Power Plants", on 20 September 1984, following an independent review of the issue. The INPO SOER depends heavily on AIF/MPC recommendations and EPRI research. The bolting issue is included in the Significant Event Evaluation and Information Network (SEE-IN), begun in 1980 following TMI-2, which has as its objective the screening of events and the dissemination of information aimed at reducing the frequency and severity of events at operating plants. All U.S. utilities and some foreign utilities participate in SEE-IN. SOER No. 84-5 is primarily aimed at assuring pressure boundary integrity and contains recommendations addressing operating and maintenance practices; procurement procedures; and training programs for maintenance, plant engineering and quality control personnel.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

Approximately one-half million bolts are used in each commercial nuclear plant. Two or three thousand of these are used in the primary reactor coolant pressure boundary components, their internals, and supports. While the number of reported bolting failures has increased over recent years (see Section 1 of this volume), there is some evidence indicating that the increase in failures is a function of the increased number of installed bolts. It appears also that, as plant maintenance personnel gain experience during early plant operation, the incidents of

leaking joints and reported failures decrease. The success history of fasteners is excellent when compared to the number of failures.

Potentially serious degradation of carbon and alloy steel fasteners used in the reactor coolant pressure boundary in PWR plants has occurred with increasing frequency in recent years. The observed degradation has been in the form of accelerated general corrosion (borated water or boric acid corrosion) of fasteners used in reactor coolant pumps, valves, etc., and stress corrosion cracking of steam generator primary manway cover studs.

SPECIFIC CONCLUSIONS AND RECOMMENDATIONS

Borated Water Corrosion

Borated water or boric acid corrosion can best be described as accelerated general corrosion that is confined to a relatively small area on fasteners. It should not be confused with erosion corrosion or "steam cutting". It is a phenomenon occurring in pressurized water reactors (PWR). Due to the nature of flanges and leakage the process produces an area of metal loss that appears as a groove extending around the circumference of the fasteners. In some valve studs, the corrosion process has progressed completely through the fasteners. In an extreme case, the cross-sectional areas of several reactor coolant pump studs were reduced by boric acid corrosion by 90%, a diametral reduction from 2 1/2 inches to approximately 1 inch.

Only a small amount of laboratory data on boric acid corrosion exists, and much of the relevant data were only recently published. In the concentrations used in PWR reactor coolant systems, boric acid is a relatively weak acid. However, under wetting and drying conditions, boric acid may concentrate in a slurry forming a saturated solution. Corrosion rates are rapid at around 200°F and a pH of approximately 3. The available data indicate that corrosion rates as high as 1.7 inches per year (reduction in diameter of cylindrical specimens) may result when carbon and alloy steels are exposed to borated environments under these conditions. The corrosion process may be active at PWR service temperatures (greater than 350°F) because of localized cooling of hot fasteners.

There appear to be no differences in corrosion rates for the common carbon and low-alloy steel bolting materials. Coatings, platings, and various surface treatments have generally not provided adequate corrosion resistance. Corrosion-resistant

materials such as austenitic and martensitic stainless steels and high strength nickel base alloys offer good protection against boric acid corrosion. These materials are not used in many fastener applications, but concerns about strength, degradation in toughness or other forms of corrosion have precluded their general use, particularly in the larger sizes. Sections 8 and 9 of this volume provide additional discussion in these areas. It should be noted that, without the leaking coolant, low-alloy steel fasteners have demonstrated exemplary experience.

Stress Corrosion Cracking

Compared to boric acid corrosion, stress-corrosion cracking (SCC) is a more insidious and potentially more serious form of corrosion, in which fasteners are not attached over most of their surface area, but fine cracks progress through the fasteners. Fortunately, the frequency of SCC is much lower than borated water corrosion. These cracks are frequently so fine that they are not visible to the unaided eye, and thus may go undetected until final fracture occurs. However, they are detectable using magnetic particle and liquid penetrant inspection techniques.

The SCC closure fastener failures have occurred in materials with apparently nominal chemical and mechanical properties. Service and laboratory failures are associated with conditions in water or steam environments containing various contaminants. Carbon and alloy steel fasteners are not intentionally exposed to water or steam, but inadvertent exposure may result from gasket leaks. If the leakage is combined with some contaminant species, such as sulfides or chlorides, an aggressive environment that will promote SCC may result. Decomposition products from lubricants and sealant compounds injected into leaking closures may produce environments capable of causing SCC in stressed carbon and alloy steel fasteners.

A common factor in several of the failures appears to be the use of lubricants containing MoS_2. Laboratory tests indicate that H_2S may result from MoS_2 decomposition in aqueous environments. There are no data available that conclusively show that MoS_2 decomposition will result in SCC. However, data generated by the oil and gas industry show that, even at low concentrations, H_2S will cause SCC in carbon and alloy steel fasteners. Consequently, MoS_2-induced SCC is viewed as a possible explanation for some of the reactor coolant pressure boundary bolted closure fastener failures.

The role of leak sealant compounds is not clear. Limited chemical data on sealants indicate variable compositions with respect to leakable contaminants such as fluorine, chlorine, and sulfur which could promote SCC. However, another and potentially more important role of leak sealants may be to form a moisture barrier, thereby creating, in effect, small static autoclaves which promote aggressive environments.

Support and Embedded Bolting Degradation Due to Stress Corrosion Cracking

In contrast to failures in pressure boundary fasteners, the failures in primary system support bolting have been largely attributed to stress corrosion cracking. A common feature of these failures is that high strength and/or overly hard materials have been installed in humid environments and subjected to high sustained tensile stresses. Contaminants, such as those from lubricants, may also be a contributing factor. The majority of stress corrosion cracking failures have occurred during plant construction, prior to commercial operation. Typical problem areas have included steam generator, reactor coolant pump, and reactor vessel supports. Table 11-1 summarizes most known structural support bolting failures.

U.S. industry bolting failure experience involves two general classes of steels: low-alloy quenched and tempered (LAQT) steels, and high nickel alloy and maraging steels. The stress corrosion cracking field experience involving these bolting materials can be categorized in two groups:

- Group I - Materials specified as ultra-high strength with specified minimum yield strengths greater than 150 ksi that failed due to the combination of stress and environmental factors. Failures that have occurred involve materials with intentionally high strength requirements, and the integrity of these materials is directly questioned by the field experience. Failure events occurred both during service and construction, and multiple fastener failures have been observed.
- Group II - High strength materials with specified minimum yield strengths equal to or less than 150 ksi that failed because of poor heat treatment and material variability. In contrast to Group I, the failure events associated with the Group II category involve materials that are unintentionally high strength. These failure events are related to poor quality control, and all bolt failures occurred and were detected during plant construction.

The component support and embedded bolting failures experienced by the U.S. nuclear industry have undergone generic examination in an effort to determine the effect of individual bolt degradation on the integrity of the overall support bolted joint.

The consequences of overall joint degradation, in terms of support stiffness and faulted load conditions, have been evaluated. This is an alternative approach to one of analyses of individual bolt integrity. Despite experiences of individual bolting failures, no instances of overall component support joint failure have been discovered, thus supporting analytical resolution of the issues based on the inherent redundance of the overall bolted joints. The conclusion reached by the AIF/MPC Task Group on Bolting is that generic resolution of potential support and embedded bolting concerns by individual utilities is not warranted unless failures are experienced. Utilities that have bolting materials with specified yield strengths greater than 150 ksi may wish to review their individual applications.

Pressure Boundary Bolting Integrity

Pressure boundary bolting has the highest priority in the industry program due to its direct influence on reactor coolant pressure boundary integrity. The generic joint integrity program being conducted by EPRI is aimed at demonstration of the inherent margins in the bolted closures considering leak-before-break. Based on the results of this program, reactor coolant pressure boundary joint degradation is not a safety issue but a reliability issue.

Leakage from a closure is generally considered a necessary, but not a sufficient, condition to define reactor coolant pressure boundary closure bolt degradation. Leaks are always undesirable, and all practical steps should be taken to minimize them.

Bolting Practices

There is a growing awareness that many bolted joint problems are exacerbated by poor bolting practices, such as improper assembly procedures and incorrect use of tools. Much of the difficulty can be traced to the challenge of controlling bolt preload. As a result of the efforts of the AIF/MPC Task Group on Bolting and the EPRI Generic Bolted Joint Integrity project, several aids are now available to help remedy these problems and are described in other sections of these two volumes. For example, a three-part video cassette training program for bolting personnel, including both engineers and mechanics, is described in Section 10 of this volume. Two reference manuals addressing "Good Bolting Practices", one for large bolts (e.g., pressure boundary bolts, structural support bolts) and the other for smaller fasteners (e.g., electrical connections, instruments, set screws), are also available from EPRI.

One extremely important area of bolting practice that deserves additional emphasis is bolt preload. Experience and experiment show that preloads produced in the field by current bolting practices tend to be lower than intended by the designer. This preload reduction is caused by a number of factors, including stress relaxation (both at room temperature and elevated temperature), thermal cycling (particularly for gaskets), creep and flow of gasket material during initial compression, vibration and shock, and elastic interactions between separately-tightened bolts. There are few factors, on the other hand, that lead to excessive preload. Therefore, most flanged pressure boundary bolted joint problems can be helped by an appropriate increase in bolt preload. Higher preload, in addition to improving the leak resistance of the joint, also helps to fight slippage, vibration loosening, and fatigue. Of course, where stress-corrosion cracking is of concern, excessive preload must be avoided.

A new technology is emerging that will some day make accurate preload easier to obtain -- ultrasonic measurement of bolt stress or strain. The technology has been used successfully to analyze bolted joint problems, to design more effective torquing procedures, to inspect sample bolts or joints for results achieved by conventional tooling, and to control assembly procedures in joints which have chronic problems and which have not responded to more conventional procedures.

Elastic interactions between bolts, during assembly, cause more loss of preload than do the other relaxation effects discussed earlier (with the possible exception of vibration loss). Residual preloads in the bolts of a gasketed joint typically vary by 10 to 1 or more, after a normal multi-pass, cross-bolting procedure. Such variations often contribute to leakage problems. The variations can be reduced, however, if several bolts are tightened simultaneously as the joint is assembled. Ganged tensioners or hydraulically-powered wrenches can be used for this purpose.

Material Considerations

All carbon and alloy steels are susceptible to boric acid corrosion if the joint is leaking. With proper attention to joint assembly and effective consideration of the factors presented above the likelihood of leakage is extremely low, and the need for boric acid corrosion resistant materials is negated. However, if one is desirous of redundant protection there are corrosion-resistant alloys which are not susceptible to boric acid corrosion, for example: (a) austenitic stainless steels (Type 304, 316, etc.); (b) martensitic stainless steels (Type 403, 410, etc.); (c)

precipitation hardening stainless (17-4 pH, SA A-286, etc.); and (d) high strength nickel base alloys (NiCrFe Alloy 718, NiCrFeMo Alloy 625, NiCrFe Alloy X-750, etc.)

The selection of an alternative material is not a trivial task for most fastener applications. There are a number of material characteristics that must be evaluated in the process.

The strength levels of the alternative materials must be approximately equivalent to those of the existing materials. The coefficients of thermal expansion must be considered since significant differences can result in joint relaxation and, thus, increase tendency to leak through a joint when the component heats up. The materials must possess adequate toughness.

With respect to toughness, the materials must also possess long-term thermal stability at operating temperatures. For example, some precipitation hardening martensitic stainless steels are susceptible to a secondary aging phenomenon that will cause a decrease in material toughness. The temperature range over which this phenomenon operates is undefined, but the lower end of the range may overlap operating temperatures for some fasteners. This may preclude the use of materials like 17-4 pH stainless steels in high temperature applications. Other considerations that must be evaluated include: (1) the potential for other forms of corrosion, (2) raw material costs (possibly an order of magnitude more expensive), and (3) fabricability.

Table 11-1

SUMMARY OF STRUCTURAL SUPPORT BOLTING FAILURES

Plants	Year	Application	Nom. Bolt Size	Relevant Material Specification	Specified Min. Yield Strength	Material Supplied	Failure Mode	Corrective Action
Ginna	1970	RCP Embedment Anchor Studs	1-3/8"	A490[1]	200 ksi[2]	4140	SCC	High Preload & Borated Water Environment
Haddam Neck	1973	SG Support Embedment Anchor Studs	2-5/8"		160 ksi	4340	SCC	High Preload & Moisture Environment
Surrey 1 & 2	1974	SG Support Bolts				Vascomax 250	SCC	
Sequoyah 1 & 2	1977	SG Support Holddown Bolts	1-1/2"	A564 XM16 (H900)	220 ksi	Custom 455	SCC	Improper Fabrication
Midland 1	1979	RPV Embedment Studs	2-1/2"	A354 Gr. BD	130 ksi	4140	SCC	Improper Heat Treatment (Under Tempered)
Midland 1	1980	Pipe Whip Restraint Connection Bolts	1-1/4"	A490 Type 3	130 ksi	4140	Ductile Fracture	Improper Heat Treatment (Over Tempered)
Midland 1	1980	Pipe Whip Restraint Connection Bolts	1-1/8"	A540 Gr. B23		1018	Ductile Fracture	Wrong Material Supplied
Prairie Island 1&2	1980	SG Support Bolts	1-1/2"	A538 Gr. B	230 to 260 ksi[3]	Vascomax 250	SCC	High Local Stress and Moisture Environment
Palo Verde	1981	Piping Restraint Embedment Anchor Bolts	1-1/2"	A354 Gr. BD	130 ksi	4140	SCC	Improper Heat Treatment (Under Tempered)

Table 11-1 (Continued)

SUMMARY OF STRUCTURAL SUPPORT BOLTING FAILURES

Plants	Year	Application	Nom. Bolt Size	Relevant Material Specification	Specified Min. Yield Strength	Material Supplied	Failure Mode	Corrective Action
Palo Verde	1981	Piping Restraint	1-1/2"	A354 Gr. BC	130 ksi	1020	[4]	Wrong Material Supplied
Waterford	1981	RCP Support Bolts		A490	130 ksi			Improper Torque

[1] This specification was reported to be used for heat treatment requirements.

[2] Based on specified minimum hardness of $45R_C$.

[3] This valve corresponds to 0.2% offset yield and strength. Specified minimum tensile strength is 240 ksi.

[4] During the investigation of the SCC-related failures, at least one bolt was found to be a low strength material.

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EPRI NP-5769
Volume 2
Project 2520-7
Final Report
April 1988

Degradation and Failure of Bolting in Nuclear Power Plants

Volume 2

Prepared by
Applied Science & Technology
Poway, California

REPORT SUMMARY

SUBJECTS	Safety margins, testing, and evaluation / Nuclear component reliability
TOPICS	Nuclear power plants Bolts Fasteners Joints Safety engineering In-service inspection
AUDIENCE	Generation managers and engineers

Degradation and Failure of Bolting in Nuclear Power Plants

Volumes 1 and 2

A four-year program to resolve the generic safety issue of bolting degradation and failure in nuclear power plants has developed guidelines for material selection, bolting preload control, and plant operation, as well as a realistic method for evaluating the structural integrity of bolted joints. These measures can help improve plant availability while reducing radiation exposure and costs of maintenance and inspection.

BACKGROUND In 1982, NRC issued IE Bulletin No. 82-02 and designated bolting degradation and failure in nuclear power plants as a new generic issue. To provide a technical basis for the resolution of this issue, a nuclear industry task group formed by the Atomic Industrial Forum and Materials Properties Council developed a coordinated research plan. This plan focused on identifying and developing tools and procedures for demonstrating safety margins in pressure boundary and structural joints and recommending realistic inspection and maintenance programs. EPRI carried out the research, working with industry owners groups.

OBJECTIVE To provide a basis for resolution of the generic issue of bolting degradation and failure in nuclear power plants.

APPROACH The task group outlined a comprehensive 19-point research program to ensure that no significant issue remained an open concern. A project team first collected and evaluated the service history of pressure boundary and structural joints. The task group then assigned tasks to several project teams, which studied the problems and recommended solutions. These tasks focused on procurement specifications, material selection and testing, design procedures and bolt preload control, in-service inspection, plant operation and maintenance, and evaluation of the structural integrity of degraded bolted joints.

RESULTS This two-volume report provides a single-source document to help utility engineers address plant-specific bolting and fastener problems. Volume 1 contains background information, the approach to issue resolution, a

summary of findings for each of the 19 tasks, and specific conclusions and recommendations. Volume 2 compiles detailed research results—a vast amount of data organized for ready use. Specific task groups produced the following:

- Guidelines for the purchase of bolts and threaded fasteners, including recommendations for bolting materials that resist boric acid wastage and stress corrosion cracking
- Analyses of the role of bolt preload in bolted joint problems
- Guidelines on the use of lubricants and leak sealants
- Recommendations for improvements to nondestructive examination of threaded fasteners
- Suggested revisions to ASME and ASTM codes and standards
- Methods for assessing the significance of degraded or failed bolts
- Training materials for plant mechanical maintenance personnel, including videotapes and reference manuals

Analyses determined that the structural redundancy of a bolted joint can tolerate considerable degradation before safety is compromised. Furthermore, in the absence of leaking coolant, low-alloy steel fasteners have demonstrated exemplary performance. The report confirms the importance of fastener material selection, bolt preload control, and elimination of leaking joints.

EPRI PERSPECTIVE

This report provides the technical basis for resolution of the generic issue of bolting degradation and failure in nuclear power plants. The task group, utility personnel who contributed their time and expertise, provided invaluable coordination with ASTM, ASME code bodies, the Institute of Nuclear Power Operations, and NRC.

PROJECT

RP2520-7
EPRI Project Managers: Richard W. Burke; T. U. Marston
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Contractor: Applied Science & Technology

Degradation and Failure of Bolting in Nuclear Power Plants
Volume 2

NP-5769, Volume 2
Research Project 2520-7

Final Report, April 1988

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ORGANIZATION(S) THAT PREPARED THIS REPORT:
Applied Sciences & Technology
Poway, California

ABSTRACT

These two volumes provide the documentation for industry resolution of the U.S. Nuclear Regulatory Commission (NRC) generic issue B-29, Degradation and Failure of Bolting in Nuclear Power Plants. The issue was identified as a consequence of concerns about the structural integrity of component supports circa 1980. When bolting integrity became a separate issue in 1982, the utility industry responded by forming a Task Group on Bolting under the aegis of the Atomic Industrial Forum (AIF) and the Metals Properties Council (MPC). The AIF/MPC Task Group on Bolting formulated a comprehensive nineteen-task action plan aimed at resolution of the issue, with implementation of the plan, the responsibility of EPRI and the affected Owner's Groups. EPRI organized a matrix-managed Generic Bolted Joint Integrity Program to carry out the research, with the results reported herein.

The scope of the EPRI Generic Bolted Joint Integrity Program was broad, in order to assure that no significant aspect of the issue remained as an open concern. The scope included:

- Documentation of the service history of pressure boundary and structural bolts;
- Recommendations for ASME and ASTM codes and standards;
- Guidelines for purchase specifications and receipt inspection of bolts and threaded fasteners;
- Recommendations for the selection of bolting materials to resist boric acid wastage and stress-corrosion cracking;
- Guidelines on the use of lubricants and leak sealants;
- Training materials for plant mechanical maintenance personnel, including videotapes and reference manuals;
- Improvements in the nondestructive examination of threaded fasteners; and
- Methods for assessing the safety significance of degraded or failed fasteners, in the context of the complete bolted joint.

The format of the two volumes is such that the results of the research are easily referenced. This format was chosen intentionally in order to aid the utility engineer in addressing plant-specific bolting and fastener problems by providing a single source document. Volume 1 consists of background information, a description of the AIF/MPC Task Group on Bolting action plan, the issue resolution outline, summary material on each of the issue resolution topics (i.e., lubricants), and the conclusions and recommendations. Volume 2 provides the more complete reference source and data for the topics. An index is included to assist the reader in using the two volumns as a reference.

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Section 1

UTILITY RECOMMENDATIONS AND GUIDELINES FOR THE PURCHASE SPECIFICATION AND RECEIPT/PREINSTALLATION INSPECTION REQUIREMENTS FOR ASME SECTION III, AISC, ANSI/ASME B31.1, AND ANSI B31.5 BOLTS AND THREADED FASTENERS

SCOPE AND APPLICABILITY

This document includes recommended guidelines for certification, identification, nondestructive examination (NDE), and storage requirements for bolting material (bolts, studs, and nuts) to be used in permanent features by utilities constructing or operating nuclear power plants. It includes recommended guidelines for tightening which may be followed when preloading and/or torquing of bolts is not specified by other documents and receipt of preinstallation inspection guidelines which if implemented will help assure fastener integrity.

These guidelines are applicable to threaded fasteners manufactured from specified bolting material furnished as forgings, rod, or bar stock. Threaded fasteners include bolts, studs, screws, and nuts whose general use is for closures in pressure systems, flanged joints, bolted structural supports, and bolted connections in structural steel assemblies.

The guidelines contained herein are written specifically for ASME Section III Code of Record plants. They are recommended as adequate for pre-ASME Section III Code of Record plants (i.e., ANSI B31.1 and B31.7). When used for plants of this vintage, the user is cautioned to consider system safety class in which the bolting is used and provide a commensurate level of quality. For instance, a plant having ANSI B31.1 as the code of record may choose to use ASME Section III Class 1 requirements for systems classified ANS Safety Class 1.

DEFINITIONS

ASME Section III Bolting Material

The following definitions are taken from ASME Section III (2) and are duplicated in this document for convenience.

Certificate of Compliance (COC). A COC (as required by ASME Section III) is a written statement attesting that the material is in compliance with the specified requirements of the material specification for the grade, class, and heat treated condition, as applicable. (It is equivalent to an ANSI N45.2.10 Certificate of Conformance but NOT equivalent to an ANSI N45.2.10 Certificate of Compliance; the ANSI Certificate of Compliance requires both CMTR and COC.)

Certified Material Test Report (CMTR). A CMTR is a document attesting that the material is in compliance with specified requirements, including the actual results of all required chemical analyses, tests and examinations in accordance with the guidelines of ASME Section III, NCA-3867.4 (NA-3767.4) and Appendix P. (Note: References to NA paragraphs are applicable to plants and equipment with a Code of Record earlier than the 1977 Edition of ASME Section III, Division 1, Nuclear Power Plant Components, Summer 1977 Addenda.)

Mill Test Report (MTR). An MTR is a document prepared by the manufacturer who poured the material melt. On an MTR, the manufacturer who poured the material melt attests that the material has been manufactured in accordance with the requirements of a material specification, provides the results of the chemical and/or physical tests required by the specification, and associates the report with a unique heat number (see Section 1.3.7 of Reference (6).

Non-ASME Section III Bolting Material

Materials Covered. Non-ASME Section III bolting material includes ASTM bolting materials covered by: ANSI/ASME B31.1, Power Piping; ANSI B31.5, Refrigeration Piping; and AISC Steel Structures; References (5,6,29,30 31).

Manufacturer's Certification. Manufacturer's certification as required by AISC (28) shall consist of objective evidence of conformance of the material to the material specification for grade, class, and heat-treated condition, as applicable. A COC or CMTR (defined above) meets this requirement. These guidelines may differ for those utilities committed to ANSI N45.2.10 definitions for Certification of Compliance and Certificate of Conformance.

For direct tension indicators, such as load indicator washers, manufacturer's certification shall consist of a CMTR certifying that the material is in confor-

mance with the requirements for direct tension indicators as required in reference 12.5.22. For alternate fasteners such as twist-off spline bolts, manufacturer's certification shall consist of a CMTR certifying that the fasteners are in conformance with the requirements of sections 2(d) and 5(a) of Ref. (34).

CERTIFICATION

General

All bolting material which is required by drawing, specification, or special purchase order requirements to have NDE, or mechanical tests, such as impact tests, in addition to those specified in the material specification, should be procured with a CMTR listing the results of all tests and examinations.

ASME Section III Bolting Material

All bolting material should be procured with either a CMTR or a COC as required by ASME Section III.

Non-ASME Section III Bolting Material

All non-ASME Section III bolting material, regardless of size, should be procured with a manufacturer's certification that the material is in accordance with the material specification, type, grade, or class, and heat-treated condition, as applicable.

IDENTIFICATION AND MARKING

Bolting material should be marked for identification by the manufacturer or supplier in accordance with the applicable material specification and the grade of material. If no specific identification mark is provided in the specification, a marking symbol or code may be used which identifies the material with the material certification. Any such symbol or code shall be explained in the CMTR or COC, as applicable. Table 1-1 summarizes identification marking requirements.

Bolting furnished with a CMTR should be further identified by the manufacturer or supplier with the heat number or heat code, when required by the material specification or by ASME Code Section III, and any additional marking required to facilitate traceability of the material to the reports of the results of all tests and examinations performed on the material.

Bolting material furnished with a COC does not require heat code traceability.

SA or A 307 (10) bolt heads shall be marked with the manufacturer's mark; no grade marks are required. Additional marks are optional and may be supplied by either the manufacturer or the utility for their own use.

Bolting material should be marked by a method that will permanently identify the material and will not result in any harmful contamination or discontinuities. Stamping, when used, should be done with low-stress stamps.

The utility should establish a control procedure that ensures material control and identification to the point of installation.

NONDESTRUCTIVE EXAMINATION (NDE)

Documentation

Documentation of supplier and plant or construction site nondestructive examination (NDE) results should be on file and available in the plant's documentation system. NDE includes requirements for visual examination.

Procurement

Bolting for components, component supports, and structural assemblies should be purchased with required NDE for the particular class of material. The required examination should be conducted and certified by the bolting material supplier. As an alternate, ASME purchased bolting material or bolting material manufactured on site which is required to be upgraded or classified in accordance with ASME Section III (2) may have NDE performed and documented on site.

Examination

All bolting material must meet the NDE requirements of the materials specification and any specified purchase order requirements. In addition, ASME bolting must conform to the applicable ASME Section III requirements for the code of record for the plant. Where the requirements include an examination also required by the material specification, only one examination need be performed, but the more stringent acceptance standards should apply.

ASME Bolting Material

NDE of ASME B&PV Code bolting material should conform to the requirements, using ultrasonic, magnetic particle examination, and/or liquid penetrant examination as required. Acceptance requirements should be in accordance with the applicable subsection of the code.

If the manufacturer did not certify performance of visual examination, then prior to any use, any bolting to be used for ASME Section III applications shall be visually examined by the site in accordance with the requirements of ASME Section III, NX-2580, by certified visual examination personnel, as applicable (2).

Non-ASME Bolting

NDE requirements for non-ASME bolting unless required by the material specification should be specified on the procurement specification or in the applicable specifications.

Receipt or Preinstallation Inspection

This section provides guidelines for receipt or preinstallation inspection of bolts, studs, and nuts for use in safety-related applications. It is recommended that the utility hardness test and visually examine a random number of items from each lot of fasteners for adequate cleanliness, physical damage, discontinuities, and conformance to dimensional requirements as described below.

Sample Size for Inspection - Definitions.

Lot Size. The number of items of the same size, nominal diameter, material type and property class, and material heat number received under a single purchase order and identified by the manufacturer as being from one production lot and one heat treat batch or lot.

Random Sample. A sample of items selected from a lot which is representative of the quality of the entire lot. Each individual item should be selected in a nonuniform manner from a different location in the lot.

Sample Size. The recommended number of items taken from each lot for inspection shall be as follows (37). The list below is from inspection level II and provides an AQL of 1.0. (Note: Other sampling plans can be used, if representative and statistically significant.)

Lot Size			Sample Size	Maximum Acceptable Failures
1	to	50	8	0
51	to	90	13	0
91	to	150	20	0
151	to	280	32	1
281	to	500	50	1
501	to	1,200	80	2
1,201	to	3,200	125	3
3,201	to	10,000	200	5
10,001	to	35,000	315	7
35,001	and over		500	10

Visual Inspection. The receipt visual inspection does not constitute an NDE activity (except as described in the "Discontinuities" section below) and need not be certified to the requirements of SNT-TC-1A-1975 (33). NDE activities were previously defined in the "ASME Bolting Material" section of this document.

Cleanliness. Fastener samples should be inspected for adequate freedom from moisture, foreign materials, and oxides or rust. If required, the fasteners should be cleaned to permit proper inspection and installation.

Dimensions. The fastener samples should be inspected for conformance to the applicable ANSI specification and purchase order.

Physical Damage and Discontinuities. The samples should be visually examined for physical damage and discontinuities on the areas of the threads, shanks and head for bolts, and on the areas of the threads, edges and flats for nuts. Examples of physical damage are nicks, gouges, dents, and scrapes. Discontinuities, such as laps, seams, cracks, bursts, folds, voids, or tool marks may be detrimental to the intended service. Samples showing discontinuities should be identified and evaluated further by qualified personnel. The utility should prepare an evaluation procedure for this activity and provide training and indoctrination of personnel who will perform the evaluation. This activity may fall under the provisions of NX-2580 and SNT-TC-1A-1975.

Acceptance/Rejection Criteria - Physical Damage and Discontinuities. If any sample from a lot shows unacceptable physical damage, a 100% inspection of the lot may be conducted to separate the usable acceptable fasteners from the damaged fasteners, or the entire lot may be returned to the manufacturer in accordance with the purchase contract. Samples showing discontinuities should be further evaluated for identification of the discontinuity and acceptance or rejection based on ASTM or ASME standard specifications for surface discontinuities for bolts and nuts. If any discontinuities in a lot sample are unacceptable, the entire lot should be rejected and returned to the manufacturer in accordance with the purchase contract.

Hardness Test. The random samples should be hardened tested by qualified personnel or laboratory. Failure to comply to the hardness requirements of the materials specification and/or special purchase order requirements shall be cause for the rejection of the material. If both hardness and tension testing have been performed, the bolting material may be accepted on the basis of the tension test if there is a controversy with low readings of the hardness test.

All hardness procedures and the choice of the various types of hardness tests, such as Brinell or Rockwell, should be in accordance with the requirement of the applicable ASTM procedure (see Ref. 18,19,20,21,22,24).

It may be necessary to substitute a lower test load, a smaller indentor, or another hardness test method. The hardness conversion tables may be used to obtain a value for comparison to the requirements of the materials specification (25).

The hardness test on bolts is usually taken on the side or top of the bolt head but may be taken on the opposite threaded end. On nuts, hardness is usually determined on the top or bottom face of the nut but may also be taken on the side of the nut.

Each fastener of the random sample should have a hardness in the range required by the applicable materials specification for acceptance of the lot. If hardness readings are obtained outside the required hardness range and tension testing was not required, final arbitration of the hardness of the fastener may be accomplished by additional hardness tests on the cross-section of the two samples of the softest and hardest fasteners.

For final arbitration on bolts, the hardness should be taken on a transverse section through the threaded section of the bolt at a point one-quarter of the nominal diameter from the axis of the bolt. The section through the bolt should be taken at a distance from the end of the bolt which is equivalent to the diameter of the bolt.

For final arbitration on nuts, the hardness should be taken on a transverse section parallel to the face of the nut through the threads at a mid-point between the inside diameter and outside diameter of the nut. The transverse section through the nut should be a minimum of two threads distance from the flat face of the nut.

Documentation. Documentation of the test and inspection results including evaluation of any discrepancies in the "Physical Damage and Discontinuities" and the "Hardness Test" sections should be maintained by the utility to support the receipt or preinstallation inspection activity.

STORAGE AND SEGREGATION REQUIREMENTS

Bolting One-Inch Nominal Diameter and Less

All bolting one inch in diameter and smaller, regardless of classification, may be stored together when segregated by certification requirements (see "Certification" section), materials specification, grade, type, size, etc.

Bolting Material Greater than One-Inch Nominal Diameter

All bolting larger than one inch in diameter should be segregated by certification requirements, materials specification, grade, type, size, heat treated condition, etc., in accordance with the following classifications:

- All ASME Section III, Class 1 bolting material
- All ASME Section III, Class 2, 3, or MC bolting material
- All ASME Section III, Subsection NF component support bolting for Class 1 components
- All ASME Section III, Subsection NF component support bolting material for Class 2, 3, or MC components for which impact tests are required
- All remaining ASME Section III, Subsection NF, Class 2, 3, or MC component support bolting materials

- All non-ASME Section III bolting material (but such bolting material shall be segregated when additional requirements, such as impact testing or NDE, are specified)

Cleanliness and Storage

During storage of all bolting material, the utility should ensure that storage requirements are maintained to ensure cleanliness and prevent corrosion.

Austenitic stainless steel bolting material should be stored and cleaned in accordance with the utilities cleanliness requirements for the appropriate quality level prior to installation.

REPLACEMENT BOLTING MATERIAL

All requirements for replacement bolting material, including that purchased for equipment, supplier-assembled joints, or structural steel assemblies shall be equal to or more stringent than the requirements for the original material, unless the original requirements have been modified by approved design changes.

For operating plants, or those coming under the jurisdiction of ASME Section XI, three options are available for selection of the procurement code or method:

1. Fasteners may be specified by manufacturer or supplier part number which applies to the original procurement contract.
2. If the fasteners are standard, they may be procured using a standard description, the appropriate material specification, and the latest NRC approved ASME Code requirements.
3. The fasteners may be procured as in (2) above except an earlier edition of the ASME Code may be used provided it is not earlier than the original component code of record. If the fasteners were procured to non-ASME Code requirements, later editions of that code may be used, provided all of the original requirements are met.

BOLTING MATERIAL RECEIVED WITH EQUIPMENT

Loose bolting material received as part of vendor-supplied equipment or prefabricated structural steel assemblies should be controlled by utility procedures that identify the bolting material with specific pieces of equipment to ensure that the bolting material is used on the equipment with which it was shipped. If the requirements of the "Certification", "Identification" and "Nondestructive Examination" sections are met, the bolting material should be stored in accordance with the "Storage Requirements" section.

MANUFACTURE OF BOLTING MATERIAL FROM CODE-APPROVED BAR STEEL FOR BOLTS AND NUTS

It is recommended that the following guidelines be followed when the utility elects to manufacture nonheaded (without one end enlarged or preformed) bolting material and studs which do not require heat treatment following machining on site.

Material

Material should be ordered to meet the requirements of applicable ASME or ASTM bolting material specifications. If bolting is to be used for ASME Section III applications, refer to ASME Section III for upgrading and classification requirements that must be met prior to use. CMTRs are recommended to permit segregation and maintenance of identification in storage.

Machining

Machining should be as detailed on approved utility or vendor drawings.

Examination

Examination should be in accordance with the requirements of the applicable material specification and the appropriate Section III requirement and the "Nondestructive Examination" section of this specification.

Unthreaded rods, bars, and pins which function as component support parts and are held at each end with a locking device, such as a cotter pin, or by deforming the ends to provide an alternate locking device should be examined at a minimum in accordance with the material specification.

Testing

Chemical and mechanical testing should be in accordance with the applicable bolting material specification or standard. The test report should identify the number of test samples and the lot size for each group of test samples.

If additional tests are required, it is recommended that an approved or qualified laboratory perform any testing of bolts and nuts necessary to supplement requirements of documentation received with the material.

Documentation

The results of all tests should be documented on a CMTR prepared by the utility and maintained in the files at the construction site.

Marking

The marking shall be in accord with the "Identification and Marking" section.

RECOMMENDED DISPOSITION OF NONCONFORMING MATERIAL

Improperly Marked Material

Bolting material that is not marked in accordance with the "Identification" section of this specification should be rejected or placed in "nonconforming" or "hold" status by the utility. The material should be dispositioned in accordance with applicable approved procedures.

Inadequately Certified Material

Bolting material received at the site with inadequate certification may be used for ASME applications, provided any additional tests and operations needed to meet the requirements of the material specification and the code have been performed by the utility (or an approved laboratory) and the results of all required tests, examinations, or treatments performed are documented on a CMTR prepared by the utility in accordance with approved procedures. The material should be placed on "hold" pending acceptance of test results of receipt of additional documentation. Nonconforming material should be dispositioned in accordance with applicable approved procedures. However, a detailed review of the available documentation may still permit use of inadequately certified material for non-ASME applications, if the material is properly identified and the application does not require traceability.

TREATMENT AND PRELOADING OF BOLTS AND THREADED FASTENERS

Thread and Contact Surface Cleanliness

All thread and contact surfaces of parts assembled for bolting should be free from scale, chips, or other deleterious material. Surfaces and edges to be joined should be smooth, uniform, and free from fins, tears, burrs, cracks, and other defects which would degrade the strength of the joint.

Contact surfaces for ASME component supports within friction-type joints should be free of oil, paint, or galvanizing in accordance with NF-4712 (2). References to the requirements of ASME Section III, NF component supports may be applicable to plants whose code of record implements subsection NF; these references are offered for guidance and use at earlier plants at the utilities discretion.

Thread Lubrication

Any lubricant or compound used in threaded joints should be suitable for the service conditions and should not react unfavorably with any bolted joint material, fluid boundary, or external environment. The use of lubricants containing molybdenum disulfide is not recommended, except on a case-by-case basis.

Lubricants for bolting materials, including stainless steel, high-strength low-alloy steel (HSLA), and precipitation hardening (PH) alloy steels (e.g., SA or A 564, Type 630) should be procured and controlled to preclude the possible contamination of materials with harmful elements such as halogen, sulfides, etc.

It is recommended that the utility utilize a single lubricant for all bolting materials on site to facilitate control.

Thread Engagement

The threads of all bolts and studs shall be engaged for the full length of the thread in the load-carrying nut unless otherwise specified in the design documents. There should be visible evidence of complete threading through the nut or threaded attachment.

As an alternative to the recommendations above, for ASME Section III construction of component supports, designs where a special nut (such as an Allen head cap nut) or a special function of a standard nut (such as locking) do not require full thread engagement, the requirements for the full length of thread engagement in the nut could be waived provided:

1. The design drawings used for construction or modification specify the minimum length of thread engagement required to assure the full load-carrying capacity of the fastener.

2. The minimum length of thread engagement is established by calculations or load rating. (The certification requirements of ASME Section III, NCA-3551 apply.)

3. The use of ASME B&PV Code Case N-314 is noted on the design documents for component supports.

Bolt Tension

All high-strength bolts over 80 ksi yield strength should be preloaded to a value not less than that given in the drawing, technical manual, or in the applicable

specifications. The preload can be applied either by torque applied to the nut or bolt or by direct tensioning of the stud followed by nut rundown. For stud tensioning, the initial tension should account for embedment relaxation to achieve the desired preload.

Locking Devices for Component Supports

All threaded fasteners, except high strength bolts, "Unistrut" cap screws, concrete expansion anchor bolts, and embeded anchors, shall be provided with locking devices to prevent loosening during service (2). The method of locking threaded fasteners should be shown on design drawings. Elastic stop nuts (when compatible with service temperature), lock nuts, jam nuts, and drilled and wired nuts are all acceptable locking devices. Upset threads (by peening or other approved methods) may serve as locking devices. Disk or helical spring lock washers shall not be used as locking devices.

Torquing and other preloading methods may be used as locking devices on threaded parts made of material with a yield strength of 80 ksi and greater, loaded in tension, if the resulting preload is at least 20% above the maximum load on the fastener for the specified loading conditions but not more than 70% of the specified minimum tensile strength of the fastener. The established preload shall be verified on the assembly by properly calibrated wrenches, direct extension indicators, or the turn-of-nut method. The required preload and specified thread lubrication shall be provided in a Design Report.

Flanged Joints with Flexitallic Gaskets or Soft, Rubber, or Other Pliable Gaskets

Table 1-2 contains recommended torque values (±10%) acceptable for use (unless other torque values are imposed by other documents, such as drawings, applicable specifications, or instruction manuals) for all steel bolt studs with 70,000 psi minimum yield strength used for flanged joints with flexitallic gaskets to provide a stress of 45 ksi (33).

The torque table recommendations assume that the male threads and the bearing surface of the turned element (nut or bolt head) are cleaned and well lubricated and proper assembly techniques are used (see the following "Flange Makeup Procedure" section). The lubricant is assumed to have a nut factor of approximately 0.17. This is a reasonable number for Fel Pro N5000 and Never Seeze (36). If a stress level other than 30 or 45 ksi is desired, or if a lubricant with a nut

factor other than 0.17 is used, the torque values of Table 1-2 may be scaled. The relationship between torque (T) and preload (F_p) is expressed as follows:

$$T = \frac{KD\,F_p}{12},$$

where

- T = Torque (ft lb);
- K = Nut factor (dimensionless);
- F_p = Load (lb); and
- D = Nominal fastener diameter (in).

Expressed in terms of root stress:

$$T_{xx} = \frac{12\,T}{KD\,A_r}$$

where

- T_{xx} = Root stress (psi)
- A_r = Thread root area (in^2)

The torque values specified in Table 1-2 at a stress of 30 ksi and 45 ksi are also recommended for soft or rubber and other pliable gaskets unless other requirements are specified by drawings or manufacturer's specifications (33).

Flange Makeup Procedure.

Preparation of Facing Finish.

(A) The gasket seating surface should be cleaned using suitable solvent and wire bristle brush (stainless steel bristles should be used on alloy components).

(B) After cleaning, the seating surface should be inspected visually for defects such as radial scores.

(C) The seating surface should be inspected for signs of warping. See the Good Bolting Practices Manual (39) for tolerances on flange warping.

Preparation of Bolting Material.

(A) Studs and nuts should be wire-brushed (when needed) to remove any dirt present on the threads. Brushes with stainless steel bristles shall be utilized on stainless materials.

(B) Studs and nuts should be visually examined after cleaning to assure freedom from burrs. Nuts should turn freely on the studs a distance equal to their in-service makeup. If any burrs are present, one of the following steps should be performed: (i) burrs of a minor nature may be filed off -- files utilized for stainless materials should not have previously been used on carbon steel materials; or (ii) the nut and/or stud should be returned to the storeroom and a new one of the same size, type, and qualification shall be issued for installation.

(C) Upon completion of the cleaning operations, studs should be coated with a film of an approved lubricant prior to installation.

(D) The bearing surface of the turned element (the nut or the bolt head) should be coated with the approved lubricant.

(E) It is desirable (not mandatory to use hardened washers between the turned element and the joint surface.

Flange Alignment and Gasket Installation.

(A) Once flanges have been lined up, they are to be visually examined by the workmen to assure that an acceptable fit has been obtained.

(B) A quantity of studs shall be inserted through the bolt holes of the flanges that will guarantee the sustained alignment of the flanges without blocking insertion of the gasket. Nuts shall be screwed on the studs to prevent their failing.

(C) Gaskets shall be visually examined by the workmen prior to installation to assure that they are free of defects. Gaskets found to be defective shall be returned to the storeroom and replaced with new ones of the same size, type, and qualification.

(D) Gaskets shall be carefully inserted between the flanges to assure that the gasket has attained proper placement.

(E) The remaining studs shall be installed and their nuts will be screwed on hand-tight.

Torquing.

(A) Bolts or nuts shall be torqued in a cross-bolting pattern.

(B) The joint shall be torqued using a minimum of four torquing passes; each pass to be done in a cross-bolting sequence. The torque values for each sequence are as follows:

Pass 1: All nuts are brought up snug-tight. Ensure that the flange surfaces are parallel.

Pass 2: The torque value for this pass shall be a maximum of 30% of the final torque required from Table 1-2. Check that the flange is bearing uniformly on the gasket.

Pass 3: Torque shall be a maximum of 60% of the final torque.

Pass 4: Torque to final torque.

(C) After the four basic torquing passes are completed, torquing of the nuts shall continue using the final torque in a clockwise manner until no further rotation of the nut is observed. This process may require an additional five to seven passes.

(D) General comments: All torque wrenches utilized in the performance of this procedure will be of adequate capacity and of current calibration status. All thread lubricants and antiseize compounds will be of an approved type. In all cases, torquing force will be applied at a uniform constant rate. In the event that setup or seizure of the nut being torqued is encountered, the nut will be backed off until seizure is eliminated and subsequently retorqued.

Gasket compression should be considered acceptable if compression is properly performed in conformance with the manufacturer's design and installation criteria applicable to the type of gasket used and the gasket appears to the assembler to have been compressed uniformly.

Tightening Recommendations for Component Supports

This section covers tightening recommendations when these are not specified on the applicable drawings or by ASME Section III, Division 1 (see "Bolt Tension").

When a preload or torque is not specified in a drawing or specification, the Good Bolting Practices Manual (39) may be used to select the tightening specifications. The applicable drawings should specify when a bolt or nut is to be locked to prevent loosening during service.

Turn-of-Nut Tightening. When the turn-of-nut method is used to provide the bolt tension, there shall first be enough bolts brought to a "snug-tight" condition to ensure that the parts of the joint are brought into good contact with each other. Snug-tight is defined as the tightness attained by a few impacts of an impact wrench or the full effort of a man using an ordinary spud wrench. Following this initial operation, bolts shall be placed in any remaining holes in the connection and brought to snug tightness. All bolts in the joint shall then be tightened

additionally by the applicable amount of nut rotation specified in Table 1-3 with tightening progressing systematically from the most rigid part of the joint to its free edges. During this operation, there shall be no rotation of the part not turned by the wrench (31).

Nut rotation from "snug tight" condition, except for SA/A 307, Grade A, bolts which should be tightened "snug tight" without additional nut rotation, should be as shown in Table 1-3. The table of nut rotation is applicable only for bolt materials ASTM A325 and ASTM A490. These bolts are designed to be installed to a minimum preload which is 70% of tensile strength. Turn-of-nut procedure using the table below will reliably produce these loads. Personnel performing this activity should be trained to perform the tightening as directed.

For threaded fasteners requiring locking devices, elastic stop nuts (when compatible with service temperature), lock nuts, jam nuts, and drilled and wired nuts are all acceptable locking devices. Upset threads (by peening or other approved methods) may also serve as locking devices.

Nut rotation is relative to bolt, regardless of the element (nut or bolt) being turned. For bolts installed by 1/2 turn and less, the tolerance should be ±30°; for bolts installed by 2/3 turn and more, the tolerance should be ±45°.

To establish a turn-of-nut procedure for bolt lengths exceeding 12 diameter and/or bolt diameters of greater than 1 1/2 inches, and for materials other than A325 and A490, the required rotation from snug shall be determined by test. The test shall use a suitable tension measuring device and in a joint which simulates the actual joint conditions.

PROCEDURES AND PERSONNEL

Personnel performing or interpreting NDE, including visual examinations specified by codes, should be qualified to the requirements of SNT-TC-1A-1975 (32) supplements and appendices, as applicable, for the techniques and methods used (reference paragraph 2, ASTM A 614 (Ref. 17) and paragraph NX-5522 (Ref. 2)).

PRECAUTIONS

Bolting and Nut Materials

Bolting materials with a minimum specified ultimate tensile strength greater than 150 ksi or a maximum actual ultimate tensile strength greater than 170 ksi should

not be used without consideration of potential for stress corrosion cracking and evaluation of adequate toughness by the designer.

SA or A 564, Type 630 should be used in the 1100°F minimum aged heat-treated condition.

A 563, Grade C nuts, which specify a hardness of 143 HB to minimum 352 HB, should be used in the heat-treated condition with a minimum hardness of 248 HB. If not available, A 194, Grade 2H should be substituted for A 563, Grade C. As an alternative, A 563, Grade DH or DH3 nuts with a hardness range of 248 HB to 352 HB may be substituted.

Welding, including tack welding, on bolts and nuts requires a qualified procedure meeting the requirements of ASME Section IX. No welding should be performed on the loaded portion of the bolts.

Welding of high strength low alloy bolting material (i.e., A 193, Grade B7, etc.) is not permitted.

Re-Use of Bolting Material

Bolts which are damaged, deformed, or otherwise affected during installation or service should not be re-used unless re-use is supported by engineering evaluation and analysis. The designer should determine if the bolting material has been specifically designed to that when re-used it will perform its function in accordance with the applicable design requirements and specifications.

Retightening of previously tightened bolts which may have loosened during the tightening of adjacent bolts should not be considered as re-use.

Galvanized bolts and nuts shall not be re-used.

A490 bolts shall not be re-used.

Any bolt or nut tightened by the turn-of-nut method shall not be re-used.

REFERENCES

American Society of Mechanical Engineers (ASME) and American National Standard Institute (ANSI)

The latest editions and addenda of the applicable Code of Record of the following sections/parts of the ASME Boiler and Pressure Vessel Code and ANSI shall apply where referenced in these guidelines.

1. ASME Boiler and Pressure Vessel Code, Section II, Material Specifications, Part A - Ferrous.

2. ASME Boiler and Pressure Vessel Code, Section III, Division 1, Nuclear Power Plant Components.

3. ASME Boiler and Pressure Vessel Code, Section XI, Rules for Inservice Inspection for Nuclear Power Plant Components.

4. ASME Boiler and Pressure Vessel Code, Section V, Nondestructive Examination.

5. ANSI/ASME B31.1, Power Piping.

6. ANSI B31., Refrigeration Piping.

American Society of Mechanical Engineers (ASME) Section II, Part A (SA), and American Society for Testing and Materials (ASTM) (A, E, F)

ASME(SA) basic material specifications and their ASTM(A) equivalents which may apply to this specification include, but are not limited to, the specifications listed below.

7. SA-/A 36. "Structural Steel." Note: See A 563, Grade A nuts for use with SA-/A 36 structural steel fabricated to SA-/A 307 bolts.

8. SA-/A 193. "Alloy-Steel and Stainless Steel Bolting Materials for High Temperature Service."

9. SA-/A 194. "Carbon and Alloy Steel Nuts for Bolts for High Pressure and High Temperature Service."

10. SA-/A 307. "Carbon Steel Externally Threaded Standard Fasteners."

11. SA-/A 325. "High-Strength Bolts for Structural Steel Joints."

12. SA-/A 354. "Quenched and Tempered Alloy Steel Bolts, Studs, and Other Externally Threaded Fasteners."

13. A 490. "Quenched and Tempered Alloy Steel Bolts for Structural Steel Joints." Note: A 194, Grade 2H or A 563, Grade DH nuts shall be used on A 490 bolts.

14. SA-/A 430. "Alloy Steel Bolting Materials for Special Applications."

15. A 563. "Carbon and Alloy Steel Nuts."

16. SA-/A 564. "Hot-Rolled and Cold Finished Age Hardening Stainless and Heat-Resisting Steel Bars and Shapes."

17. SA-/A 614. "Special Requirements for Bolting Material for Nuclear and Other Special Applications."

18. A 370. "Mechanical Testing of Steel Products."

19. E 18. "Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials."

20. E 92. "Vickers Hardness of Metallic Materials."

21. E 10. "Brinnel Hardness of Metallic Materials."

22. E 384. "Microhardness of Materials."

23. F 436. "Hardened Steel Washers."

24. F 606. "Conducting Tests to Determine the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, and Rivets."

25. E 140. "Standard Hardness Conversion Tables for Metals."

26. F 788. "Surface Discontinuities of Bolts, Screws, and Studs, Inch and Metric Series."

27. F 812. "Surface Discontinuities on Nuts, Inch and Metric Series."

28. F 844. "Steel Plane (Flat) Unhardened Washers."

<u>American Institute of Steel Construction (AISC)</u>

29. "Specification for the Design, Fabrication and Erection of Structural Steel for Buildings." November 1, 1978.

30. "Manual of Steel Construction." 8th Edition, 1980.

31. "Specification for Structural Joints Using ASTM A 325 or A 490 Bolts." AISC, 1980.

<u>American Society for Nondestructive Testing</u>

32. SNT-TC-1A-1975. "Recommended Practice."

<u>Miscellaneous</u>

33. Crane Co. "Crane Catalogue on Valves and Fittings, No. 60." Chicago, 1960, p. 383.

34. U.S. AEC Regulatory Guide 1.65. "Materials and Inspections for Reactor Vessel Closure Studs." October 1973.

35. J.H. Bickford. "An Introduction to the Design and Behavior of Bolted Joints." Dekker, New York, 1981, p. 114.

36. M.E. Looram, Raymond Bolting Services, Inc. "Steam Generator Manway Makeup Test." June 1984.

37. Military Standard 105D. "Sampling Procedures and Tables for Inspection by Attributes." April 29, 1983.

38. Research Council on Structural Connections Specification for Structural Joints Using A 325 or A 490 Bolts.

39. J.H. Bickford and M. Looram. "Good Bolting Practices: A Reference Manual for Nuclear Power Plant Maintenance Personnel, Vol. 1." EPRI NP-5067, 1987.

40. IFI-100 Prevailing - Torque Type Steel Hex Lock Nuts, Industrial Fastener Institute.

41. NUREG-0577. "Potential for Low Fracture Toughness."

42. NUREG-0933. "A Prioritization of Generic Safety Issues."

43. NUREG-0943. "Threaded Fastener Experience in Nuclear Power Plants."

44. IE Bulletin 80-36.

45. IE Bulletin 80-27.

46. IE Bulletin 82-02.

Table 1-1

SUMMARY OF IDENTIFICATION MARKING REQUIREMENTS

Description of Bolting	Code Class	Nominal Diameter	Marking Requirements
ASME Components	1, 2, 3, MC	≤ 1"	Note 1
		> 1"	Note 2
ASME NF Component Supports	1, 2, 3, MC	≤ 1"	Note 1
	1, 2, 3, MC	> 1"	Notes 1 & 3
Non-ASME Bolting	-	All	Note 1

Notes:

1. Marking should be in accordance with the material specification. Heat code traceability is not required unless it is a material specification requirement.

2. Marking should be in accordance with the material specification. Heat code traceability is required.

3. If a CMTR is required, heat code traceability is required.

Table 1-2

TORQUING REQUIREMENTS FOR QUENCHED AND TEMPERED* BOLTING

(These torque table recommendations assume that the stress is calculated using the root area, the threads and bearing surface are well lubricated, the nut factor is 0.17, and the torque-preload equation is $T = KD/12\ F_p$.)

				Stress	
Nominal Diameter	Threads Per Inch	Diameter (in.)	Thread Root Area (in^2)	30,000 psi Torque (ft-lb)	45,000 psi Torque (ft-lb)
1/4	20	0.185	0.027	4	6
5/16	18	0.240	0.045	8	12
3/8	16	0.294	0.068	12	18
7/12	14	0.345	0.093	20	30
1/2	13	0.400	0.126	30	45
9/16	12	0.454	0.162	45	68
5/8	11	0.507	0.202	60	90
3/4	10	0.620	0.302	100	150
7/8	9	0.731	0.419	160	240
1	8	0.838	0.551	245	368
1-1/8	8	0.963	0.728	355	533
1-1/4	8	1.088	0.929	500	750
1-3/8	8	1.213	1.155	680	1020
1-1/2	8	1.338	1.405	800	1200
1-5/8	8	1.463	1.680	1100	1650
1-3/4	8	1.588	1.980	1500	2250
1-7/8	8	1.713	2.304	2000	3000
2	8	1.838	2.652	2200	3300
2-1/4	8	2.088	3.423	3180	4770
2-1/2	8	2.338	4.292	4400	6600
2-3/4	8	2.588	5.259	5920	8880
3	8	2.838	6.324	7720	11580

*Quenched and tempered to enhance mechanical properties

Table 1-3

NUT ROTATION

Effective Bolt Length (Distance from Inside Face of Bolt Head to Outside Face of Nut Plus One Thread)	Disposition of Outer Faces of Bolted Parts: Both Faces Normal to Bolt Axis	One Face Normal to Bolt Axis & Other Face Sloped Not More than 1:20 (Bevel Washers Not Used)	Both Faces Sloped Not More than 1:20 From Normal to Bolt Axis (Bevel Washers Not Used)
Up to and Including 4 Diameters	1/3-Turn	1/2-Turn	2/3-Turn
Over 4 Diameters But Not Exceeding 8 Diameters	1/2-Turn	2/3-Turn	5/6-Turn
Over 8 Diameters But Not Exceeding 12 Diameters	2/3-Turn	5/6-Turn	1-Turn

LIST OF SUBJECTS

Section 2

STANDARD TEST METHOD FOR EQUOTIP HARDNESS TESTING OF METALLIC MATERIALS

SCOPE

This method covers the determination of the Equotip hardness of metallic materials, including the methods for the verification of Equotip hardness testing instruments and the calibration of standardized hardness test blocks.

DEFINITIONS

Equotip Hardness Test is a dynamic indentation hardness test using a calibrated instrument that impacts by spring propulsion a spherically tipped body from a fixed height onto the surface of the material under test. The ratio of the rebound velocity to the impact velocity of the impact body is a measure of the hardness of the material.

Equotip Hardness Number L is a number related to the ratio of the rebound belocity to the impact velocity, multiplied by 1000, of a spherically-tipped impact body. The hardness number L is named after the inventor of the Equotip measuring principle, Dietmar Leeb.

Equotip Hardness Tester is a patented registered trademark of the company Proceq SA for the Equotip hardness test device based on the acronym for Energy-Quotient (EQUO).

Verification is the checking of the testing of the instrument to assure conformance with the specification.

Calibration is the determination of the values of the significant parameters by comparison with values indicated by a reference instrument or by a set of reference standards.

TEST PROCEDURES FOR EQUOTIP HARDNESS TESTS

Apparatus

Description of Machine and Method of Test. The instrument used for Equotip hardness testing consists of: (1) a metallic tubular impact device which is equipped with a spherically-tipped impact body, a permanent magnetic/induction coil velocity measuring assembly, and a support ring; and (2) an electronic indicating device for processing the measured velocities and the digital display of the Equotip hardness number, L.

During the hardness test measurement, an impact device drives the impact body under spring force against the test surface and lets it rebound. The impact and rebound velocities are measured specifically at the instant when the test tip is located in the immediate vicinity of the test surface. This is accomplished by means of a permanent magnet mounted in the impact body which, during the test impact, moves through a coil on the impact device and induces an electric current during the impact and rebound movements. These induced currents are proportional to the respective velocities. The quotient of these measured current values derived from the impact and rebound velocities, multiplied by the factor 1000, produces a number which constitutes the Equotip hardness value, L.

$$L = \frac{\text{Rebound Velocity}}{\text{Impact Velocity}} \times 1000$$

Impact Devices and Impact Bodies. There are six sizes of impact devices and impact bodies used in Equotip hardness testing. These are the basic "D" unit, the "D+15" unit, the "DC" unit, the "G" unit, the "C" unit, and the "E" unit. Each unit has its own impact body and its specified impact energy. Only the unit "E" is equipped with a diamond, spherically-tipped impact body. All the other units have tungsten carbide spherically-tipped impact bodies.

Unit "D" is the basic unit and is used for most testing of steels, aluminum alloys, various copper alloys (brass, bronze), and cast iron (with lamellar and with spheroidal graphite) (20 mm diameter x 150 mm).

Unit "DC" is a special impact device with the impact body from the unit "D", designed to make hardness measurements in very restricted spaces such as inside boxes (20 mm diameter x 86 mm).

Unit "D+15" is a special impact device, very slim with the measuring coil set back for access to small holes and grooves (10,8/13,5 mm diameter x 162 mm).

Unit "G" is a special impact device, larger in size and with a higher impact energy than the other devices, for use on large, heavy specimens in the HB range, such as forgings and cast iron (30 mm diameter x 254 mm).

Unit "C" is a special impact device with very low impact energy designed to generate small remaining impressions, e.g., in testing surface hardened parts (20 mm diameter x 141 mm).

Unit "E" is a special impact device equipped with a diamond-tipped impact body and therefore especially well suited for testing of very hard metallic materials, e.g., rolls with very high hardness numbers (20 mm diameter x 156 mm).

Note: Each unit of impact device is supplied with its own conversion tables for conversion to other hardness scales.

Test Specimens

Form. The Equotip hardness tester is applicable to a broad variety of test specimens ranging from plates, bars, forgings, and castings to machined, finished surfaces.

Thickness and Weight. For specimens with a minimum weight of 3 kg (15 kg for impact device "G") and of compact shape, no particular precautions are necessary. Thin strips or sheets may be tested but must be rigidly coupled to a thicker, heavier non-yielding support such as a piece of steel weighing 5 kg (10 lbs) or more and at least one inch in thickness. Specimens less than a quarter of an inch thick (half an inch for impact device "G") should be so supported regardless of weight.

Note: In the case a support is used for coupling, the contact surfaces between test specimen and support device must be flat, plane parallel and ground.

Even large or heavy specimens having thin-wall regions or thinner protruding parts can yield upon impact. Depending on the frequency of the vibration due to impact, the measured hardness values may be too small or too large. Hence, if possible, such specimens should be supported too.

Curvature. Curved specimens are to be tested on either the convex or concave surfaces providing that this radius of curvature of the specimens is not less than 2-3/8 inches (60 mm) when using the standard support ring, or not less than 1-3/16 inch (30 mm) with use of the small diameter support ring. The large impact device "G" requires a minimum radius of 100 mm for the standard ring and of 50 mm for the small support ring.

Note: With use of special support rings the radius limitations can be considerably reduced.

Surface Finish/Preparation. The test surface should be carefully prepared to avoid any alterations in hardness caused by heating during grinding or by work hardening during machining and polishing operations. Any paint, scale, pits, or other surface coatings must be completely removed. Where decarburization is suspected, it should be removed. The surfaces can be machined, ground or polished to get the required surface finish. The maximum surface roughnesses are as follows:

Impact Device	CLA (Center Line Average)
"C"	32 in
"D", "DC", "D+15", "E"	80 in
"G"	280 in

Note: Inadequately prepared surfaces affect the measured values as follows: (1) an excessively coarse finish will yield low hardness values (the actual hardness is greater than indicated) and large variations of single readings; and (2) cold-worked surfaces yield too high hardness values (the actual hardness is smaller than measured).

Verification of Apparatus

Verification Method. The instrument shall be verified as specified in the "Verification of Equotip Hardness Instruments" section.

Procedure

Test Method. To perform a hardness test with the Equotip hardness tester, the impact device is connected to the indicator device and the instrument is turned on. The impact device is placed on the test surface and firmly held with one hand,

and the charging tube is depressed with the other hand until contact is felt and the tube is allowed to slowly return to the starting position. The impact body is now in its loaded or cocked position. Trigger the impact body by exerting a light pressure on the release button. The Equotip hardness value L is read on the indicator device. The indicated value is automatically extinguished with the next test impact.

Alignment. To prevent errors resulting from misalignment, the support ring of the impact device must be held snugly and perpendicular to the surface of the test piece.

Impact Direction. The impact device is calibrated for the down vertical impact direction (perpendicular to a horizontal surface). For other impact directions such as 45° from the horizontal plane (all quadrants) or from underneath (the bottom side), measured hardness values can be determined in accordance with established correction factors.

Spacing Indentations. The minimum distance between any two indentations or between the indentation point and a specimen edge shall not be less that 1/8 inch (3 mm) or less than 5/32 inch (4 mm) for the large impact device "G". No impact test point shall be impacted more than once.

Reading the Equotip Hardness Instrument. Hardness values in Leeb units are read directly on a three-digit electronic display of the indicator device. At least three hardness determinations should be made and their average taken as representative of the hardness of a particular area of the specimen.

Note: For specimens requiring the use of a support, the sound of the impact is an indication of the effectiveness of the support: a dull thud indicates that the specimen has been supported solid, whereas a hollow ringing sound indicates that the specimen is not tightly coupled or is warped and not properly supported.

Use of Standardized Test Blocks. Standardized test blocks shall never be reground or otherwise resurfaced after being used, because it is the top surface that was originally standardized and it may be of a different hardness from the new surface. The impressions due to impact workharden the block to a considerable depth, and this may result in the new test surface being in a work-hardened condition and not of the same hardness as the original test surface.

Conversion to Other Hardness Scales or Tensile Strength Values

Equotip hardness numbers L can be related to other hardness measures on the basis of comparison tests, and curves and tables have been devised which allow Equotip numbers L to be expressed in terms of HRC, HB, and HV values for specific materials such as steel, aluminum alloys, copper alloys and cast iron. While these relationships are usually adequate for practical purposes, it should be realized that they are empirical and approximate. Hardness is a practical measurement, and there are no theoretical relationships between the different scales. Therefore, it is good practice to state the hardness value in the units in which it was measured.

Report

The report shall include the following information:

1. The Equotip hardness number L, with a suffix following L designating the type of impact device used such as: LD, LD+15, LDC, LC, LE, or LG.
2. The test conditions (method of support, if any, and impact direction).
3. If conversions to other hardness scales are given (HRC, HB, HV, HS), those values and their related L values must be reported, as well as the source of the conversion.

VERIFICATION OF EQUOTIP HARDNESS INSTRUMENTS

Scope

The previous subsection covers the procedure for the verification of Equotip hardness instruments by a standardized block method.

General Requirements

Before an Equotip hardness instrument is verified, the instrument shall be examined to ensure that:

1. The batteries in the indicating device are not discharged and that faulty batteries are replaced as required.
2. The impact device is clean and the spherical tip of the impact body is free of all foreign matter.
3. The spherical tip of impact body is free from cracks or flat spots.
4. The test block is placed on a clean, level, firmly-supported base.
5. The test surface of the test block is clean and free of all foreign matter.

Verification by Standardized Test Blocks

An Equotip hardness testing instrument may be checked by making a series of hardness tests on standardized test blocks.

Note: Because errors due to the Equotip hardness instrument (e.g., damage of the test tip, too low or too high impact velocity of the impact body, loosening in the connection between test tip and impact body and errors on the indicating device) have a greater effect at large L numbers than at small L numbers, an impact device may be verified by means of only one test block. For this purpose the standardized test block must show a hardness which amounts at least to 60% of the hardness of the range to be verified, e.g., use of impact device "D" in the range L = 500 to L = 900. To verify this range the standardized test block must show a calibration value of at least 500 + (900 - 500) x 0.060 = 740 LD.

Make at least five hardness tests on the standardized test block being valid for the impact device under investigation. Make tests no closer than 1/8 inch (3 mm) together, and no closer than 1/4 inch (6 mm) from the edge of the block.

The Equotip hardness instrument shall be considered verified if 80% of the L readings taken on the test block deviate no more than ±6 L points from the mean in L hardness numbers marked on the block.

Procedure for Periodic Checks by the User

Verification by the standardized test block method is too lengthy for daily use. Instead, the following procedure is recommended.

Make at least one routine check at the beginning of and at the close of each day the instrument is to be used. The instrument should be rechecked at least after every 500 hardness tests performed.

Before making the check, clean the spherical tip of the impact body and clean the test surface of the test block.

Make a least three hardness tests on the appropriate standardized test block for the impact device which is being used. If each hardness value falls within the range of the standardized test block (±6 L points) the instrument may be regarded as satisfactory. If not, the instrument should be verified as described in the previous subsection.

CALIBRATION OF STANDARDIZED HARDNESS TEST BLOCKS FOR EQUOTIP HARDNESS INSTRUMENTS

Scope

This subsection covers the calibration of standardized hardness test blocks used for the verification of Equotip hardness instruments.

Manufacture

Each test block shall be made of steel with dimensions not less than 90 mm diameter x 54 mm or 120 mm diameter x 70 mm for the impact device "G". The two opposite plane surfaces shall be parallel.

Each block shall be specially prepared and heat treated to give a specific hardness and the necessary homogeneity and stability of structure.

Each steel block shall be demagnetized by the manufacturer and maintained demagnetized by the user.

The two test surfaces (upper and lower) of the block shall be polished or fine ground and free of scratches and other surface discontinuities which would influence the rebound characteristics of the test block.

The mean surface roughness height rating of the two test surfaces shall not exceed 12 micro-inches (0.003 mm) center line average.

To ensure that no material is subsequently removed from the test surface of the standardized test block, an official mark, or the thickness to an accuracy of ±0.005 inches (±0.1 mm) at the time of calibration, shall be marked on the test surface.

Standardizing Procedure

The standardizing hardness test blocks shall be calibrated employing a standardizing Equotip instrument which meets the more stringent requirements given in the "Standardizing Instrument" section.

Ten hardness determinations, randomly distributed, shall be made on each of the two test surfaces of the block.

The hardness value assigned to each surface of the test block shall be the mean of the single ten readings on each surface.

Uniformity of Hardness

A test surface (upper or lower) of a block shall be regarded as sufficiently uniform for standardization purposes if the range of the ten hardness values, i.e., the difference between the largest and the smallest value, does not exceed the value of 10 L points.

Marking

Each block shall be marked with the following:

1. Arithmetic mean of the hardness values found in the standardization test prefixed by the impact device designation symbol and followed by the tolerance range.
2. The name or mark of the supplier.
3. The serial number of the block, and the last two digits of the year of calibration.

Note: All the individual markings should be placed on each of the two opposite test surfaces.

Standardizing Instrument

The standardizing EQUOTIP instrument used for calibrating the test blocks (comprising the impact device and the indicating device) shall satisfy the requirements of one of the two methods, M1 or M2, described as follows.

Method M1 - Verification by Means of Special Test Blocks for Calibration Purposes

A regular EQUOTIP hardness instrument may be used for calibration purposes if it fulfills the following more stringent requirements of verification.

The examinations described in the "General Requirements" subsection should be performed.

A special test block having the following characteristics must be used:

1. The L hardness number marked on the block is the mean of 18 L readings.

2. The range of the 18 L readings, i.e., the difference between the largest and the smallest value, does not exceed the value of 7 L points.

3. The report issued by the standardizing laboratory of the special test block shall contain a listing of each single hardness reading of the 18 values and the calculation of the mean and of the range.

Make ten randomly distributed hardness tests on the special test block being valid for the impact device under investigation. Make tests no closer than 1/8 inch (3 mm) together and no closer than 1/4 inch (6 mm) from the edge of the block.

The Equotip hardness instrument shall be considered verified for calibration purposes if: (a) the mean of 10 L readings taken on the special test block deviate no more than ±3 L points from the mean in L hardness numbers marked on the special test block; and (b) the range of the 10 L readings, i.e., the difference between the largest and the smallest value does not exceed the value of 10 L points.

The hardness level of the test blocks to be calibrated shall be within the range of ±100 L points of the mean in L hardness numbers marked on the special test block.

The instrument should be reverified after every 300 hardness tests performed.

Method M2 - Special Verification of Indicating Device and Use of Special Controlled Impact Device

Indicating Device. The indicating device shall be verified by means of an artificially generated reference signal such as can be produced by a function generator or the like. The reference signal shall have time and amplitude curves similar to those generated by the impact device. The uncertainty of the reference signal in the range L = 200 to L = 900 may not exceed ±0.25 L points.

The indicating device may be used to calibrate a standard test block provided the following requirements are fulfilled:

Input of Reference Signal in L	Reading on Digital Display of Indicating Device in L	Acceptable Deviation in L
400	400	± 1
600	600	± 1
700	700	± 1
800	800	0
900	900	± 1

Five figures per stage shall be checked. The permissible deviation of ±1 L may occur once in five readings.

Impact Device. An impact device shall be used in conjunction with 2 impact bodies, S1 and S2. The impact device and impact bodies shall be of certified calibration quality. For calibrating the test blocks exclusively, impact body S1 shall be used; while impact body S2 is used as a check on S1.

Twenty hardness tests shall be taken with each impact body on a standard test block before they are used for the first time. The 2 means calculated from this shall be noted and serve as the basis for future tests.

After every 300 test impacts with S1, ten hardness measurements on a standard test block shall again be performed with each impact body, S1 and S2, after which new means shall be determined.

Impact body S1 shall be replaced if the difference between the two new means deviates by more than ±2 L from the difference between the base measurements.

Table 2-1

ASTM XXXX-83 EQUOTIP
APPROXIMATE HARDNESS CONVERSION VALUES FOR
NON-AUSTENITIC STEELS LEEB D TO OTHER HARDNESS NUMBERS

Equotip Leeb Hardness Impact Device D	Brinell Hardness 300 Kg Load 10MM Ball	Rockwell C Scale 150 Kg Load Diamond Indenter	Rockwell B Scale 100 Kg Load 1/16" Ball	Vickers Hardness Number	Shore Hardness Number	Tensile Strength 1,000 Lbs. Per Sq.In.
HL_D	HB	HRC	HRB	HV	HS	Tens. Str.
900					99.5	
898					99.1	
896					98.6	
894					98.2	
892		-		-	97.7	
890		68.0		940	97.3	
888		67.8		933	96.9	
886		67.6		926	96.4	
884		67.4		919	96.0	
882		67.3		912	95.6	
880		67.1		905	95.2	
878		66.9		899	94.7	
876		66.7		892	94.3	
874		66.5		886	93.9	
872		66.3		879	93.5	
870		66.1		873	93.1	
868		65.9		866	92.6	
866		65.7		860	92.2	
864		65.5		854	91.8	
862		65.3		847	91.4	
860		65.0		841	91.0	
858		64.8		835	90.6	
856		64.6		829	90.2	
854		64.4		823	89.8	
852		64.2		817	89.4	
850		64.0		811	89.0	
848		63.8		805	88.6	
846		63.6		799	88.2	
844		63.4		794	87.8	
842		63.2		788	87.4	
840		63.0		782	87.0	
838		62.8		777	86.6	
836		62.6		771	86.2	
834		62.4		765	85.9	
832		62.2		760	85.5	
830		62.0		755	85.1	
828		61.8		749	84.7	
826		61.6		744	84.3	
824		61.4		738	83.9	
822		61.1		733	83.6	
820		60.9		728	83.2	

Table 2-1 (Continued)

Equotip Leeb Hardness Impact Device D	Brinell Hardness 300 Kg Load 10MM Ball	Rockwell C Scale 150 Kg Load Diamond Indenter	Rockwell B Scale 100 Kg Load 1/16" Ball	Vickers Hardness Number	Shore Hardness Number	Tensile Strength 1,000 Lbs. Per Sq.In.
HL_D	HB	HRC	HRB	HV	HS	Tens. Str.
818		60.7		723	82.8	
816		60.5		718	82.4	
814		60.3		713	82.1	
812		60.1		708	81.7	
810		59.9		703	81.3	
808		59.7		698	81.0	
806		59.5		693	80.6	
804		59.2		688	80.2	
802		59.0		683	79.9	
800		58.8		678	79.5	
798		58.6		673	79.1	
796		58.4		669	78.8	
794		58.2		664	78.4	
792		58.0		659	78.1	
790		57.7		655	77.7	
788		57.5		650	77.3	
786		57.3		645	77.0	
784		57.1		641	76.6	
782		56.9		636	76.3	
780		56.7		632	75.9	
778		56.4		628	75.6	
776		56.2		623	75.2	
774		56.0		619	74.9	
772		55.8		615	74.5	
770		55.6		610	74.2	
768		55.3		606	73.8	
766		55.1		602	73.5	-
764		54.9		598	73.1	30
762		54.7		594	72.8	
760		54.4		590	72.4	
758		54.2		586	72.1	
756		54.0		581	71.8	291
754		53.8		577	71.4	
752		53.5		574	71.1	
750		53.3		570	70.7	
748		53.1		566	70.4	
746		52.9		562	70.1	282
744		52.6		558	69.7	
742		52.4		554	69.4	
740		52.2		550	69.1	
738		51.9		547	68.7	273
736		51.7		543	68.4	
734		51.5		539	68.1	
732		51.2		535	67.7	
730		51.0		532	67.4	264

Table 2-1 (Continued)

Equotip Leeb Hardness Impact Device D	Brinell Hardness 300 Kg Load 10MM Ball	Rockwell C Scale 150 Kg Load Diamond Indenter	Rockwell B Scale 100 Kg Load 1/16" Ball	Vickers Hardness Number	Shore Hardness Number	Tensile Strength 1,000 Lbs. Per Sq.In.
HL_D	HB	HRC	HRB	HV	HS	Tens. Str.
728		50.8		528	67.1	
726		50.5		525	66.7	
724		50.3		521	66.4	
722		50.1		517	66.1	255
720		49.8		514	65.7	
718		49.6		510	65.4	
716		49.4		507	65.1	
714		49.1		503	64.8	246
712		48.9		500	64.4	
710		48.6		497	64.1	
708		48.4		493	63.8	
706		48.2		490	63.5	
704		47.9		487	63.1	237
702	-	47.7		483	62.8	
700	455	47.4		480	62.5	
698	453	47.2		477	62.2	
696	450	46.9		473	61.9	229
694	447	46.7		470	61.5	
692	444	46.4		467	61.2	
690	442	46.2		464	60.9	
688	439	46.0		461	60.6	221
686	436	45.7		458	60.3	
684	434	45.5		454	59.9	
682	431	45.2		451	59.6	
680	428	45.0		448	59.3	214
678	425	44.7		445	59.0	
676	423	44.4		442	58.7	
674	420	44.2		439	58.4	
672	417	43.9		436	58.0	207
670	415	43.7		433	57.7	
668	412	43.4		430	57.4	
666	409	43.2		427	57.1	
664	407	42.9		424	56.8	200
662	404	42.7		421	56.5	
660	402	42.4		419	56.2	
658	398	40.1		416	55.9	
656	396	41.9		413	55.5	194
654	394	41.6		410	55.2	
652	391	41.4		497	54.9	
650	389	41.1		404	54.6	188
648	386	40.8		402	54.3	
646	383	40.6		399	54.0	
644	381	40.3		396	53.7	
642	378	40.0		393	53.4	182
640	376	39.8		391	53.1	

Table 2-1 (Continued)

Equotip Leeb Hardness Impact Device D	Brinell Hardness 300 Kg Load 10MM Ball	Rockwell C Scale 150 Kg Load Diamond Indenter	Rockwell B Scale 100 Kg Load 1/16" Ball	Vickers Hardness Number	Shore Hardness Number	Tensile Strength 1,000 Lbs. Per Sq.In.
HL_D	HB	HRC	HRB	HV	HS	Tens. Str.
638	373	39.5		388	52.8	
636	371	39.2		385	52.5	
634	368	38.9		383	52.2	177
632	366	38.7		380	51.8	
630	363	38.4		377	51.5	
628	361	38.1		375	51.2	
626	358	37.9		372	50.9	171
624	356	37.6		369	50.6	
622	353	37.3		367	50.3	
620	351	37.0		364	50.0	166
618	348	36.7		362	49.7	
616	346	36.5		359	49.4	
614	344	36.2		357	49.1	
612	341	35.9		354	48.8	162
610	339	35.6		352	48.5	
608	336	35.3		349	48.2	
606	334	35.1		347	47.9	157
604	332	34.8		344	47.6	
602	329	34.5		342	47.3	
600	327	34.2		339	47.0	
598	324	33.5		337	46.7	153
596	322	33.6		334	46.4	
594	320	33.3		332	46.1	
592	317	33.0		330	45.8	148
590	315	32.7		327	45.5	
588	313	32.4		325	45.2	
586	311	32.1		322	44.9	
584	308	31.9		320	44.6	142
582	306	31.6		318	44.3	
580	304	31.3		315	44.0	
578	301	31.0		313	43.7	140
576	299	30.7		311	43.4	
574	297	30.4		309	43.1	
572	295	30.0		306	42.8	136
570	292	29.7		304	42.5	
568	290	29.4		302	42.2	
566	288	29.1		299	42.0	132
564	286	28.8		297	41.7	
562	284	28.5		295	41.4	
560	281	28.2		293	41.1	
558	279	27.9		291	40.8	129
556	277	27.6		288	40.5	
554	275	27.3		286	40.2	
552	273	26.9		284	39.9	126
550	271	26.6		282	39.6	

Table 2-1 (Continued)

Equotip Leeb Hardness Impact Device D	Brinell Hardness 300 Kg Load 10MM Ball	Rockwell C Scale 150 Kg Load Diamond Indenter	Rockwell B Scale 100 Kg Load 1/16" Ball	Vickers Hardness Number	Shore Hardness Number	Tensile Strength 1,000 Lbs. Per Sq.In.
HL_D	HB	HRC	HRB	HV	HS	Tens. Str.
548	269	26.3		280	39.3	
546	267	26.0		277	39.0	123
544	264	25.7		275	38.7	
542	262	25.4		273	38.5	
540	260	25.0		271	38.2	120
538	258	24.7		269	37.9	
536	256	24.4		267	37.6	
534	254	24.1		265	37.3	117
532	252	23.7		263	37.0	
530	250	23.4		260	36.7	
528	248	23.1		258	36.4	115
526	246	22.7		256	36.2	
524	244	22.4		254	35.9	
522	242	22.1		252	35.6	112
520	240	21.7		250	35.3	
518	238	21.4	-	248	35.0	
516	236	21.0	100	246	34.7	110
514	234	20.7	100	244	34.5	
512	232	20.4	99	242	34.2	
510	230	20.0	99	240	33.9	108
508	228	-	99	238	33.6	
506	226		98	236	33.3	107
504	224		98	234	33.1	
502	222		98	232	32.8	104
500	221		97	230	32.5	
498	219		97	228	-	
496	217		97	226		103
494	215		97	224		
492	213		96	222		102
490	211		96	220		
488	209		96	218		100
486	208		95	216		
484	206		95	215		99
480	202		94	211		97
478	200		94	209		95
476	199		93	207		
474	197		93	205		93
472	195		93	203		
470	193		92	201		91
468	192		92	200		
466	190		92	198		90
464	188		91	196		
462	186		91	194		89
460	185		90	192		
458	183		90	191		88

Table 2-1 (Continued)

Equotip Leeb Hardness Impact Device D HL_D	Brinell Hardness 300 Kg Load 10MM Ball HB	Rockwell C Scale 150 Kg Load Diamond Indenter HRC	Rockwell B Scale 100 Kg Load 1/16" Ball HRB	Vickers Hardness Number HV	Shore Hardness Number HS	Tensile Strength 1,000 Lbs. Per Sq.In. Tens. Str.
456	181		90	189		
454	180		89	187		87
452	178		89	185		85
450	176		88	183		
448	175		88	182		84
446	173		88	180		
444	172		87	178		83
442	170		87	176		82
440	168		86	175		
438	167		86	173		81
436	165		85	171		
434	164		85	170		80
432	162		85	168		
430	160		84	166		78
428	159		84	164		
426	157		83	163		
424	156		83	161		76
422	154		82	159		
420	153		82	158		74
418	151		81	156		
416	150		81	155		
414	148		80	153		72
412	147		80	151		
410	145		79	150		70
408	144		78	148		
407	143		78	147		
404	141		77	145		68
402	140		77	143		
400	138		76	142		
398	137		76	140		66
396	136		75	139		
394	134		74	137		
392	133		74	136		64
390	131		73	134		
388	130		72	133		
386	129		72	131		62
384	127		71	130		
382	126		70	128		
380	125		70	127		60
378	123		69	126		
376	122		68	124		
374	121		68	123		58
372	120		67	121		
370	118		66	120		56
368	117		65	119		

Section 3

EVALUATION OF BOLTING EXPERIENCES IN PRIMARY PRESSURE BOUNDARY CLOSURES

INTRODUCTION

The bolt failure data base for pressure boundary fasteners was compiled mostly from utility responses to IE Bulletin 82-02 (82%) and Licensee Event Report (LER) searches. A few incidences were from NUREG 0943. A total of 125 incidences were recorded. Three incidences concerned with the reactor coolant pump (RCP) diffuser adapter are included, but these are not pressure boundary bolting failures since they are internal to the pumps. However, they were reported in the IE Bulletin 82-12 response of one utility so they were included in the data base.

In this project we are able to segregate the data into five major bolting categories:

- Steam generator manways
- Pressurizer manways
- Reactor coolant pump seals
- Reactor coolant pump flanges
- Valves

These are the only categories where it was possible to establish either an absolute value for the total number of bolts at risk or a reasonable statistically derived value.

There are several error sources in the data base which affect the final failure rates in some small unresolved way. There were three methods used by the utilities to date failures. In some cases, no failure date is given so the date of response is used. When only the month and year of the failure incident was reported, the first of the month was used to calculate time to failure. When refuel dates are given as a three-month interval, the 30 or 31 of the first refuel month was used to calculate time to failure.

STEAM GENERATOR MANWAY BOLT REJECTION RATES

To present rejection rates which reflect both the number of bolts at risk and time at risk the data are conditioned by multiplying number of bolts by the time at risk to give bolt years. Time at risk was calculated from the date each reactor became critical to September 30, 1984, since this was the termination date of the LER search. However, in all cases, the data are summarized in terms of bolts and bolt years at risk, irrespective of material differences since these data were unavailable at report date. In Table 3-1, the steam generator manway bolts and bolt years at risk are listed for each reactor in operations as of September 30, 1984. The bolts rejected for cause are summarized for each incident in Table 3-2.

The failure data for steam generator manway bolts are broken into terms of percent of total bolts at risk by vendor in Tables 3-3 and 3-4. This segregation was deemed desirable since there appeared to be a significant difference between the results by vendor. In Table 3-3, the reject rate is given as a percentage of the total population of bolts at risks. Industry wide, the total failure rate on the basis of number of bolt failures is 5.81%. In Table 3-4, the failure rate is shown as a percentage of the total bolt years at risk. This accounting for the year of bolt service gives a lower rejection rate of 3.98%. When the breakdown is taken as a percentage of each vendor's at risk population, the vendor difference becomes highly visible. This is shown in Table 3-5 in terms of bolt years. The reject rate for Babcock & Wilcox steam generator manway bolts is twice that for Westinghouse manway bolts. For Combustion Engineering manway bolts, the reject rate is four times the Westinghouse reject rate. The reason is not readily apparent as to whether these differences in rejection rates are related to different designs, maintenance practices, or different aged plants.

Figures 3-1 through 3-3 are histograms showing reject rates on the basis of number of bolts for plant service years in 1.5 yearly increments from the date of criticality through September 30, 1984. From plots of the failure data versus at risk populations (basis: both number of bolts and bolt years), it is concluded that bolt rejections are not dependent on either the numbers at risk or plant age. This leaves differences in designs and/or maintenance practices as suspects causing the large differences in failure between vendors.

Causes for Rejections of Steam Generator Manway Bolts/Studs

In Table 3-6, causes for the rejections for manway bolts are listed. By far the most common rejection cause was for boric acid corrosion (BAC) with 115 rejections

(37.1% of the total). Boric acid corrosion and stress corrosion cracking (SCC) account for 47.4% of the total bolt rejections. The utility reporting 61 bolts rejected in one event for pitting or removal damage did not separate these causes, which would have been desirable. Therefore, it appears that the category galled/ mechanical damage/thread damage/removal damage is larger than reported in Table 3-6. The question has to be asked as to whether this category represents the failure of the thread lubricant in use.

In Table 3-7, there is a breakdown of the total rejections by vendors in bolt years into those bolt years rejected for BAC and SCC. Babcock & Wilcox plants experienced a rejection rate over twice that for Combustion Engineering plants and almost three times the experience of Westinghouse plants. These reject rates are based on each individual vendor's total rejects in bolt years. For BAC, Combustion Engineering has the lowest incidences with almost one-fourth less than either Westinghouse or Babcock & Wilcox. Since both of these causes may be precipitated by poor maintenance (leaking gaskets/seals), there is little to be gained from this statistic that has not already been apparent in the industry. Combustion Engineering's rejection rate is low in both the BAC and SCC categories but highest overall because of the single incident of 61 rejections for pitting/removal damage (Table 3-6).

The at risk population of pressurizer manway studs was calculated using the time from criticality to September 30, 1984, and the number of studs at risk. These data for each reactor are summarized in Table 3-8.

Pressurizer manway bolt rejections are limited in number. The bolts rejected, failure years, and bolt years to fail are in Table 3-9. Based on the total number and pressurizer manway bolts at risk of 876, the rejection rate is 2.28%. Based on 7915.2 bolt years at risk, the rejection rate is 1.2%. Causes for these rejections include steam erosion, BAC, and corrosion/erosion. The number and percentages of total are in Table 3-10. The number of rejections and utilities represented are too small to make meaningful comments regarding rejection causes other than no cases of SCC were reported.

REACTOR COOLANT PUMP FLANGE BOLT REJECTION RATES

The number of RCP flange bolts and bolt years at risk for each reactor are summarized in Table 3-11. The information was solicited directly from the manufacturers, also given in Table 3-11. Flange bolt rejections are listed individually

in Table 3-12 and total 107. This total may be larger if Surry 2 rejected any of the 16 bolts reported to have visual marks but not dispositioned at the time of the IE Bulletin 82-02. Consequently, their contribution does not appear in the statistics. On the basis of total bolts at risk, the RCP flange bolt rejection rate is 1.85%.

In terms of bolt years at risk, the reject rate is 2.48%. The breakdown of causes for rejection comes to 6.54% for corrosion/erosion and 93.46% for BAC. Again, there was no reported SCC.

REACTOR COOLANT PUMP SEAL BOLT REJECTION RATES

Reactor coolant pump seal bolt rejections are summarized in Table 3-13. The rejection rate without the data for Surry 2 is well below 1%. Surry 2 reported a "replace as required" for four bolts with corrosion on three and a scratch on one. This was not resolved as of this date. Based on the number of bolts at risk, the reject rate is 0.82%. With bolt years at risk as a basis, the reject rate is 0.85%.

VALVE BOLT REJECTION RATES

Valve bolt rejections for the primary pressure boundary are limited to those valve sizes six inches or greater, which the U.S. Nuclear Regulatory Commission (NRC) established in IE Bulletin 82-02. The number of bolts rejected, bolt years to rejection, and causes for rejection are in Table 3-14. Rejection causes are summarized in Table 3-15. Boric acid corrosion caused 79% of the valve bolt rejections.

To calculate a rejection rate, it is necessary to statistically estimate the bolt population at risk since the number of valves at an individual plant depends to a large extent on the NSSS contractor, the A&E contractor, and utility preferences. The data in Table 3-16 were summarized from utility responses to IE Bulletin 82-02s for those plants which identified the valves at risk. The valve bolt rejection rate is defined as:

$$\text{Valve Bolt Rejection Rate} = \frac{\text{Total Number of Rejections}}{24\ X_2Y_2 + 28\ X_{3,4}Y_{3,4}} \times 100$$

where

X_2 = Mean number of valves for two-loop systems

Y_2 = Mean number of studs/valves for two-loop systems

$X_{3,4}$ = Mean number of valves for three- and four-loop systems

$Y_{3,4}$ = Mean number of studs/valves for three- and four-loop systems

In Table 3-17, the estimated valve population parameters are listed. From the available data, it appears reasonable to assume that $Y_2 = Y_{3,4}$. Therefore, the estimated mean rejection rate is:

$$\text{Valve Bolt Rejection Rate} = \frac{334}{24(14.6)14.77 + 28(32.33)14.77} \times 100 = 1.80\%$$

The 95% confidence limits for this mean ranges from 1.28% to 2.91%.

There are several weak areas in this estimation. First, it is assumed that all bolting materials are the same, and this is known not to be true. So, the estimation of bolts at risk is high. The data base for calculation of the number of valves in two-loop plants is essentially only three plants. The base for three- and four-loop plants is only five plants. The data base for estimation of bolts/valves for three- and four-loop plants consists of only one plant. The failure rate estimation can be improved most easily by expansion of the data base.

THE LUBRICANT AS A CONTRIBUTOR TO STRESS CORROSION CRACKING

The issue has been raised by the NRC and the Electric Power Research Institute (EPRI) as to whether thread lubricants containing molybdenum disulfide cause SCC when exposed to primary water. No conclusive laboratory experiments under simulated field conditions have linked commercially used lubricants to SCC. A summary of bolt rejections and related lubricants used at the time of submission of IE Bulletin 82-02 responses to the NRC is shown in Table 3-18 for steam generator manway bolts. It is highly likely that molybdenum disulfide lubricants were in use in prior years. In fact, Combustion Engineering found traces of both molybdenum and sulfur in the cracks of bolts which failed by SCC at Maine Yankee where molybdenum disulfide is not presently in use. It is highly probable that the bolts rejected for SCC all received prior exposure to molybdenum disulfide. Therefore, any

statistical inferences with regards to field experience linking SCC to the presently used lubricants are subject to reanalysis if molybdenum disulfide was in fact in widespread use in the industry in earlier years. In Table 3-19, we list the bolt rejections and associated bolt years for Molykote G and FEL PRO N5000 in use at the time of IE Bulletin 82-02 answers by utilities. The bolts and bolt years at risk are in Table 3-20. The test data for determining a significant difference between Molykote G and FEL PRO N5000 in causing SCC is in Table 3-21.

A chi-square test (1) establishes that these two lubricants do not differ with regards to SCC at a 95% confidence level. However, if prior use of Molykote G in the case of the Maine Yankee would shift ten rejects into the Molykote G totals, then there is a significant difference at the 95% confidence level, and the field data support the hypothesis that the use of molybdenum disulfide leads to SCC. This test is shown in Table 3-21. It may very well be also that the eight rejects at San Onofre 1 resulted from prior use of molybdenum disulfide.

WHICH THREAD LUBRICANT FUNCTIONS BEST TO PREVENT THREAD DAMAGE UPON DISASSEMBLY

In this case, the data base in Table 3-2 may be relatively pure. It is not contaminated by prior uses of different lubricants. In our hypothesis testing to answer the question of which thread lubricant functions best to prevent thread damage on disassembly, the rejects are classified together for any one or multiple causes, which include galling, mechanical damage, removal damage, and thread damage. A description of the lubricants is in Table 3-22, and bolt rejections for cause are in Table 3-23. In our hypothesis testing, we compare pairs of lubricants. In each case, the significance between pairs is tested both on the basis of number of bolts rejected and the basis of bolt years.

In Table 3-24, the tests for significant differences in the lubrication properties concerned with the prevention of galling/mechanical damage/removal damage/thread damage reveals that Molykote G has a significantly lower defect rate than FEL PRO N5000 at the 90% significance level on the basis of bolt numbers and at the 95% significance level on the basis of bolt years. It is concluded that Molykote G has statistically significant better lubrication properties than FEL PRO N5000 in the prevention of galling, etc.

The test results for significant differences between the lubrication properties of Molykote G and Neolube/Never Seez are shown in Table 3-25. When compared on the

basis of number of defect bolts, there is no significant difference between these lubricants. However, when the data are conditioned by the years in service to failure (bolt years), there is a significant difference at the 95% significance level indicating that Molykote G has superior lubrication properties.

Finally, the test results for a difference between FEL PRO N5000 and Neolube/Never Seez in Table 3-26 show none at the 90% confidence level. A summary of these tests is shown in Table 3-27. When compared on the more equitable bolt years basis, Molykote G has better lubrication properties in preventing galling/mechanical damage/removal damage/thread damage than either FEL PRO N5000 or Neolube/Never Seez. There is no significant difference between the latter two at the 90% confidence level. If the comparison is made directly on a bolt basis, there was no significant difference between Molykote G and FEL PRO N5000 at the 90% confidence level. On a bolt basis, there were no significant differences between Molykote G, Neolube/Never Seez, and FEL PRO N5000 at the 90% confidence level. All of the foregoing are based on field experience.

CONTROL ROD DRIVE MECHANISMS FLANGE BOLT REJECTIONS

The bolt failure statistics for primary pressure boundary components do not include the control rod drive mechanism (CRDM) flange bolt rejections. These are listed in Table 3-28. Control rod drive mechanism flange bolts were highest in number of rejections of all components. There are a number of reasons for separating these statistics from the other component bolting statistics. In the Palisades IE Bulletin 82-02 report on threaded fasteners, it was stated that failure of the studs would not cause degradation of the primary coolant boundary because the autoclave nut, which is threaded into the upper housing, is the primary closure device. The studs prevent the autoclave nut from backing out. It is assumed that the other Combustion Engineering reactor, Fort Calhoun, has a similar design.

Control rod drive mechanism flanges in Westinghouse reactors are seal welded and cannot cause bolting failures. The Babcock & Wilcox CRDM design does appear to be a generic issue with 194 bolt rejections. However, the problem of determining the bolts at risk could only be solved by contacting each Babcock & Wilcox owner or Babcock & Wilcox engineering since the number of CRDMs is design and power level dependent. This was considered to be outside the scope of this contract. However, all of the Babcock & Wilcox rejects were for galling or thread damage from over torquing, which does not influence the BAC or SCC statistics. These rejections

were not addressed in the hypothesis testing in the previous two subsections because of the lack of bolts at risk numbers.

CONCLUSIONS

The predominate problem with primary pressure boundary bolting is BAC accounting for 60.9% of the reported bolt rejections. This does not take into account the 194 CRDM rejections, which are a generic Babcock & Wilcox problem.

The second ranked problem is the result of removing bolts for inspections or maintenance, thereby causing galling, mechanical damage, thread damage, or removal damage (9.2%). The third ranked cause for bolting rejections (8.2%) is pitting, which may or may not cause removal damage. Stress corrosion cracking is sixth ranked, causing 4.0% rejections. An overall summary of the statistics collected for the program is shown in Table 3-29. The bolt rejections by primary pressure boundary components are shown in Table 3-30.

Boric acid corrosion is a leak problem and is, therefore, reducible by aggressive maintenance practices. Leaks are a major problem. They may require shutdowns. If bolting material changes are made, this will lead to a greater tendency to delay maintenance until the next scheduled shutdown, which may compound the problem. There appears to be an abnormally high BAC rate associated with both Combustion Engineering and Babcock & Wilcox steam generator manway cover bolts, which is not age or number at risk related. Therefore, these higher rates are probably due to design differences and/or maintenance problems.

Another big contributor to BAC is RCP flange bolts. On the basis of each vendor's bolts at risk, flange bolts on Byron-Jackson pumps have a corrosion failure rate 3.6 times the Westinghouse failure rate and 1.9 times the Bingham-Willamette Company failure rate. With the seal located above the flange bolts, it is likely that seal leakage contributes significantly to the flange bolt corrosion problem. EPRI has in past reports pin-pointed the most prominent maintenance-induced seal failures (2); however, these reports do not indicate why Byron-Jackson seal failures may be higher thereby causing higher flange bolt rejection rates for Byron-Jackson pumps.

Valve bolting rejections for BAC number 264, which represents 54.5% of the total bolts rejected according to this survey. However, on the basis of our estimated

valve bolts at risk, BAC accounts for only a mean rejection rate of 1.42%. Based on the bolts at risk concept, this ranks BAC driven failures for valve bolts third behind RCP flange bolts and steam generator manway bolts. A summary of this data is in Table 3-31. Without an actual count of the number of valve bolts at each plant, the failure rate for valve bolts cannot be given in terms of bolt years at risk.

According to a recent EPRI report (3), valve packing leak problems, which lead to BAC of valve bolts, are faulty maintenance or lack of maintenance problems. An improved valve stem packing gland design could lead to fewer incidences of packing leaks and thereby reduce bolt corrosion.

Since BAC dominates as a failure mechanism, the ranking of overall rejection rates is mostly determined by this factor. However, there are changes in ranking based on total numbers as the overall rate data in Table 3-32 indicate. The failure rate for steam generator manway bolts ranks highest with a rate of 5.81% followed by RCP flange bolts and pressurizer manway bolts. This elevation of steam generator manway bolt rejection rate in the overall statistics from the second place in BAC statistics is caused by the higher numbers rejected for galling/mechanical damage/thread damage/removal damage. The statistics were further increased by 61 rejects for pitting/removal damage for one event at Calvert Cliffs 2, the highest number of rejects in the data base.

Apparently, with the supplemental metallographic evidence provided by Combustion Engineering in the case of the Maine Yankee steam generator manway bolt failures, which established a link to molybdenum disulfide, there is sufficient evidence to conclude that lubricants containing molybdenum disulfide contribute to failures by SCC. However, there is also evidence that molybdenum disulfide is a better thread lubricant than any of the other lubricants. Consequently, its use decreases the percent of bolts that are rejected for galling/mechanical damage/thread damage/removal damage almost in half based on bolts at risk. The lack of splitting the 61 bolts rejected for pitting/removal damage into specific causes precludes estimating the plus or minus gain from everyone using molybdenum disulfide on steam generator manway bolts. Without this statistic, it appears that there would be one less rejectable bolt if everyone used Molykote G. However, if all of the SCC rejectable bolts were for exposure to molybdenum disulfide, then there would be a higher total rejectable rate due to SCC than the present combined use gives. Of course, this argument considers such a scenario only from an economic viewpoint, not as a

safety-related issue. Since SCC may lead to a catastrophic failure of the primary pressure boundary and the link to molybdenum disulfide is strong, the conservative thing to do is strongly recommend against its use.

RECOMMENDATIONS

The following recommendations result from this study of bolting material rejections:

- Do not use molybdenum disulfide lubricants on steam generator manways.
- Combustion Engineering and Babcock & Wilcox owners groups should initiate a program to uncover the reason or reasons that their steam generator manway bolt rejection rates are so much higher than for Westinghouse steam generator manways.
- EPRI should fund the development of a high temperature lubricant with better anti-galling, etc., properties than those presently in use.
- There is a need for better leak detection of steam generator manways and prompt maintenance when detected. The same need exists for valves.
- Maintenance procedures for closure of steam generator manways and valves should be upgraded.
- There is a need, once again, for improved valve stem packing gland designs.
- Where appropriate, bolting material changes should be made on valve bolting only as a last resort. This may lead to a delay in maintenance directed at stopping leaks.
- Repacking valves which are cycled frequently on a regular maintenance schedule should be attempted.
- To reduce BAC, which accounts for 61% of the bolting rejections, the name of the game is leak prevention.

REFERENCES

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2. C.E. Fair, G.A. Marsi, and A.O. Greer. "Main Coolant Pump Shaft Seal Reliability Investigation." Byron Jackson Pump Company, EPRI Report NP-2611, Vol. 1, September 1982.
3. Anon. "Valve Stem Packing Improvement Study. Stone and Webster Engineering Corp., EPRI Report NP-2560, August 1982.

Table 3-1

STEAM GENERATOR MANWAY BOLTS AND BOLT YEARS AT RISK
FROM CRITICALITY TO SEPTEMBER 30, 1984

Reactor	Size MW_{net}	NSSS	No. SG	Number of Manway Bolts	Bolt Service Years	Bolt Years
Arkansas 1	820	BW	2	64	10.15	649.60
Arkansas 2	860	CE	2	80	5.82	465.60
Beaver Valley 1	852	W	3	96	8.39	805.44
Calvert Cliffs 1	850	CE	2	80	9.98	798.40
Calvert Cliffs 2	850	CE	2	80	3.83	626.40
Cook 1	1054	W	4	128	9.70	1241.60
Cook 2	1065	W	4	128	6.55	838.40
Crystal River 3	825	BW	2	64	7.71	493.44
Davis Besse 1	906	BW	2	64	7.28	465.92
Farley 1	829	W	3	96	7.14	685.44
Farley 2	829	W	3	96	3.41	327.36
Fort Calhoun 1	457	CE	2	80	11.15	892.00
Ginna	490	W	2	64	14.89	952.96
Haddam Neck	575	W	4	128	17.19	2200.32
Indian Point 2	864	W	4	128	11.36	1454.08
Indian Point 3	965	W	4	128	8.48	1085.44
Kewaunee	540	W	2	64	10.50	672.00
Maine Yankee	790	CE	3	120	11.94	1432.80
McGuire 1	1180	W	4	128	3.15	403.20
McGuire 2	1180	W	4	128	1.40	179.20
Millstone 2	796	W	2	80	8.96	716.80
North Anna 1	943	W	3	96	6.49	623.04
North Anna 2	907	W	3	96	4.30	412.80
Oconee 1	871	BW	2	64	11.45	732.80
Oconee 2	871	BW	2	64	10.89	696.96
Oconee 3	871	BW	2	64	10.07	644.48
Palisades	700	CE	2	80	13.36	1068.80
Point Beach 1	497	W	2	64	12.91	826.24*
Point Beach 2	497	W	2	64	12.34	789.76
Prairie Island 1	520	W	2	64	10.83	693.12
Prairie Island 2	520	W	2	64	9.79	626.56
Rancho Seco	913	BW	2	64	10.04	642.56
Robinson 2	700	W	3	96	13.35	1281.60*
Salem 1	1090	W	4	128	7.80	998.40
Salem 2	1115	W	4	128	4.15	531.20
San Onofre 1	430	W	3	96	17.30	1660.80
San Onofre 2	1070	CE	2	80	2.18	174.40
San Onofre 3	1127	CE	2	80	1.09	87.20
Sequoyah 1	1148	W	4	128	4.24	542.72
Sequoyah 2	1148	W	4	128	2.90	371.20
St. Lucie 1	802	CE	2	80	8.44	675.20
St. Lucie 2	804	CE	2	80	1.33	106.40
Summer 1	900	W	3	96	1.94	186.24

Table 3-1 (Continued)

Reactor	Size MW_{net}	NSSS	No. SG	Number of Manway Bolts	Bolt Service Years	Bolt Years
Surry 1	788	W	3	96	8.21	788.16*
Surry 2	788	W	3	96	5.91	567.36*
TMI 1	792	BW	2	64	10.32	660.48
Trojan	1130	W	4	128	8.79	1125.12
Turkey Point 3	693	W	3	96	8.68	833.28*
Turkey Point 4	693	W	3	96	9.33	895.68*
Yankee Rowe	175	W	4	128	24.11	3086.08
Zion 1	1050	W	4	128	11.28	1443.84
Zion 2	1050	W	4	128	10.77	1378.56
Point Beach 1				64	0.48	30.72**
Surry 1				96	3.23	310.08**
Surry 2				96	4.11	394.56**
Turkey Point 3				96	2.48	238.08**
Turkey Point 4				96	1.38	132.48**
Totals				5336		43643.40

Notes:

* Time on old steam generators

**Time of new steam generators

Table 3-2

LUBRICATION/REJECTION CAUSE OF STEAM GENERATOR MANWAY BOLTS/STUDS

Reactor	Bolts Rejected	Rejection Cause	Yrs. to Reject. Service	Yrs. to Reject. Bolt	Thread Lubricant
Arkansas 1	1	Boric Acid Corrosion	2.49	2.49	Molykote G
Arkansas 1	2	Stress Corros. Crack.	3.59	7.18	Molykote G
Arkansas 1	3	SCC	5.96	17.88	Molykote G
Arkansas 1	16	Boric Acid Corrosion	6.94	111.04	Molykote G
Arkansas 1	3	Galled	8.73	26.19	Molykote G
Arkansas 2	3	Pitting	4.02	12.06	Molykote G
Beaver Valley 1	32	Boric Acid Corrosion	2.32	74.24	Never Reported
Beaver Valley 1	8	Linear Indication	6.31	50.48	Never Reported
Beaver Valley 1	22	Boric Acid Corrosion	7.14	157.08	Never Reported
Calvert Cliffs 1	11	Boric Acid Corrosion	5.98	65.78	Neolube
Calvert Cliffs 2	61	Pitting, Removal Dmg.	6.00	366.00	Neolube
Cook 1	1	Thread Damage	8.94	8.94	FEL PRO N5000
Cook 1	1	Loss of Thread	8.94	8.94	FEL PRO N5000
Cook 2	2	Thread Damage Steam Cut	5.06	10.12	FEL PRO N5000
Davis Besse 1	4	Thread Damage	4.80	19.20	Molykote G
Haddam Neck	4	Linear Indication	15.79	63.16	FEL PRO N5000/N1000
Indian Point 2	7	5 Cracks, 1 Thread Damage, 1 Tool Dmg.	9.19	64.33	FEL PRO N5000, Neolube, Never Seez Molykote 2
Indian Point 2	5	Boric Acid Corrosion	9.78	48.90	FEL PRO N5000, Neolube, Never Seez Molykote 2
Kewaunee	2	Linear Indication	9.35	18.70	FEL PRO N5000
Kewaunee	3	2 Removal Damage, 1 Excess Wear	9.35	28.05	FEL PRO N5000
Maine Yankee	10	SCC	9.38	93.80	FEL PRO N5000
Maine Yankee	4	Removal Damage	9.94	39.76	FEL PRO N5000
Maine Yankee	4	Removal Damage	9.94	39.76	FEL PRO N5000
Maine Yankee	2	Removal Damage	9.94	19.88	FEL PRO N5000
Millstone 2	5	Mechanical Damage	7.38	36.90	Never Seez Special
Oconee 3	2	Unnecessary Hardness	7.82	15.64	Molykote G - Rapid
Oconee 3	9	SCC	5.86	52.74	Molykote G - Rapid
Rancho Seco	1	Pitting Corrosion	8.65	8.65	Molykote G
San Onofre 1	8	SCC	10.30	82.40	FEL PRO N5000
San Onofre 2	8	Boric Acid Corrosion	0.76	6.08	FEL PRO N5000
Sequoyah 2	19	8 Mech. Dmg., 6 BAC, 3 BAC + Mech. Damage, 2 Linear Indication	2.04	38.76	Neolube/Never Seez
St. Lucie 1	13	Boric Acid Corrosion	0.96	12.48	FEL PRO N5000
Surry 1	26	Removal Damage	2.32	60.32	FEL PRO N5000
Trojan	2	Boric Acid Corrosion	7.27	14.54	FEL PRO N5000
Turkey Point 4	1	Galled	8.65	8.65	Never Seez/ FEL PRO N5000
Turkey Point 4	2	Galled	8.66	17.32	Never Seez/ FEL PRO N5000
Zion 2	1	Mechanical Damage	9.27	9.27	Neolube, Molykote G
Zion 2	2	Corrosion/Erosion	9.27	18.54	Neolube, Molykote G

Table 3-3

STEAM GENERATOR MANWAY BOLT REJECTIONS FOR ALL CAUSES THROUGH 9/30/84
(Basis: Actual Numbers)

Vendor	Rejects	% of Total Rejects	% of Total Bolts at Risk
Westinghouse	148	47.8	2.77
BW	41	13.2	0.77
CE	121	39.0	2.27
Total	310	100.0	5.81

Total Population of Bolts at Risk = 5336

Table 3-4

STEAM GENERATOR MANWAY BOLT REJECTIONS FOR ALL CAUSES THROUGH 9/30/84
(Basis: Bolts x Service Years = Bolt Years)

Vendor	Rejects, Bolt Years	% of Total	% of Total Bolt Years at Risk
Westinghouse	782.70	45.1	1.79
BW	261.01	15.0	0.60
CE	692.50	39.9	1.59
Total	1736.21	100.0	3.98

Total Population at Risk = 43,643.4 Bolt Years

Table 3-5

STEAM GENERATOR MANWAY BOLT REJECTIONS FOR ALL CAUSES THROUGH 9/30/84
(Basis: Bolts Years at Risk for Each Vendor)

Vendor	Rejects, Bolt Years	At Risk Population, Bolt Years	Rejects, % of Population at Risk
Westinghouse	782.7	31,613.1	2.48
BW	261.0	4,986.2	5.23
CE	692.5	7,044.0	9.83

Table 3-6

STEAM GENERATOR MANWAY STUD REJECTIONS BY CAUSE

Cause for Rejection	Bolts Rejected	% of Total
Boric Acid Corrosion	116	37.1
Galled/Mechanical Damage/Thread Damage/Removal Damage	65	21.3
Pitting/Removal Damage	65*	21.0
Stress Corrosion Cracking	32	10.3
Linear Indications	16	5.5
Cracks	5	1.6
Corrosion/Erosion/Steam Cut	4	1.2
Corrosion/Mechanical Damage	3	1.0
Other	4	1.0
Total	310	100.0

*61 at one facility for one event (Calvert Cliffs 2 - Source 82-02)

Table 3-7

STEAM GENERATOR BOLT REJECTIONS FOR BORIC ACID CORROSION AND STRESS CORROSION CRACKING THROUGH 9/30/84

	Total Rejects		Rejects for BAC		Rejects for SCC	
Vendor	Bolt Years	% of Total at Risk	Bolt Years	% of Total Rejects	Bolt Years	% of Total Rejects
Westinghouse	782.7	2.48	333.5	42.6	82.4	10.5
BW	261.0	5.23	113.5	43.5	77.8	29.8
CE	692.5	9.83	84.3	12.2	93.8	13.5

Table 3-8

PRESSURIZER MANWAY BOLTS AT RISK

Reactor	NSSS	Total Pressurizer Bolts	Bolt Years at Risk	Service Years 9/30/84
Arkansas 1	BW	16	162.40	10.15
Arkansas 2	CE	20	116.40	5.82
Beaver Valley 1	W	16	134.24	8.39
Calvert Cliffs 1	CE	20	199.60	9.98
Calvert Cliffs 2	CE	20	156.60	7.83
Cook 1	W	16	155.20	9.70
Cook 2	W	16	104.80	6.55
Crystal River 3	BW	16	123.36	7.71
Davis Besse 1	BW	16	116.48	7.28
Farley 1	W	16	114.24	7.14
Farley 2	W	16	54.56	3.41
Fort Calhoun 1	CE	20	223.00	11.15
Ginna	W	16	238.24	14.89
Haddam Neck	W	16	275.04	17.19
Indian Point 2	W	16	181.76	11.36
Indian Point 3	W	16	135.68	8.48
Kewaunee	W	16	168.00	10.50
Maine Yankee	CE	20	238.80	11.94
McGuire 1	W	16	50.40	3.15
McGuire 2	W	16	22.40	1.40
Millstone 2	CE	20	179.20	8.96
North Anna 1	W	16	103.84	6.49
North Anna 2	W	16	68.80	4.30
Oconee 1	BW	16	183.20	11.45
Oconee 2	BW	16	174.24	10.89
Oconee 3	BW	16	161.12	10.07
Palisades	CE	20	267.20	13.36
Point Beach 1	W	16	222.56	13.91
Point Beach 2	W	16	197.44	12.34
Prairie Island 1	W	16	173.28	10.83
Prairie Island 2	W	16	156.64	9.79
Rancho Seco	BW	16	160.64	10.04
Robinson 2	W	16	224.48	14.03
Salem 1	W	16	124.80	7.80
Salem 2	W	16	66.40	4.15
San Onofre 1	W	16	276.80	17.30
San Onofre 2	CE	20	43.60	2.18
San Onofre 3	CE	20	21.80	1.09
Sequoyah 1	W	16	67.84	4.24
Sequoyah 2	W	16	46.40	2.90
St. Lucie 1	CE	20	168.80	8.44
St. Lucie 2	CE	20	26.60	1.33
Summer 1	W	16	31.04	1.94
Surry 1	W	16	196.00	12.25

Table 3-8 (Continued)

Reactor	NSSS	Total Pressurizer Bolts	Bolt Years at Risk	Service Years 9/30/84
Surry 1	W	16	196.00	12.25
Surry 2	W	16	184.96	11.56
TMI 1	BW	16	165.12	10.32
Trojan	W	16	140.64	8.79
Turkey Point 3	W	16	191.20	11.95
Turkey Point 4	W	16	180.80	11.30
Yankee Rowe	W	16	385.76	24.11
Zion 1	W	16	180.48	11.28
Zion 2	W	16	172.32	10.77
Totals		876	7915.20	

Table 3-9

PRESSURIZER MANWAY BOLT REJECTIONS

Reactor	NSSS	Bolts Rejected	Years to Fail	Bolt Years to Fail
Calvert Cliffs 2	CE	2	4.09	8.18
Cook 2	W	2	3.13	7.26
Kewaunee	W	4	0.31	1.24
St. Lucie 1	CE	5	2.62	13.10
Zion 2	W	7	9.27	64.89
Totals		20		94.67

Rejection Rate Based on Number: $\frac{20}{876} \times 100 = 2.28\%$

Based on Bolt Years: $\frac{94.67}{7915.2} = 1.20\%$

Table 3-10

CAUSES FOR PRESSURIZER MANWAY BOLT REJECTIONS

	Number of Rejects	% of Total
Steam Erosion	8	40
Boric Acid Corrosion	5	25
Corrosion/Erosion	7	35
Total	20	100

Table 3-11

REACTOR COOLANT PUMPS FLANGE AND SEAL BOLTS AT RISK

Reactor	Pump Mfgr	No. Pumps	Bolt Service Years to 9/30/84	Total Flange Bolts	Total Seal Bolts	Flange Bolt Years At Risk	Seal Bolt Years At Risk
Arkansas 1	B-J	4	10.15	64	64	649.60	649.60
Arkansas 2	B-J	4	5.82	64	64	372.48	372.48
Beaver Valley 1	W	3	8.39	72	36	604.08	302.04
Calvert Cliffs 1	B-J	4	9.98	64	64	638.72	638.72
Calvert Cliffs 2	B-J	4	7.83	64	64	501.12	501.12
Cook 1	W	4	9.70	96	96	931.20	931.20
Cook 2	W	4	6.55	96	96	628.80	628.80
Crystal River 3	B-J	4	7.71	64	64	493.44	493.44
Davis Besse 1	B-J	4	7.28	64	64	465.92	465.92
Farley 1	W	3	7.14	72	72	514.08	514.08
Farley 2	W	3	3.41	72	72	245.52	245.52
Fort Calhoun 1	B-J	4	11.15	64	64	713.60	713.60
Ginna	W	2	14.89	48	36	714.72	536.04
Haddam Neck	W	4	17.19	96	48	1650.24	825.12
Indian Point 2	W	4	11.36	96	72	1090.56	817.92
Indian Point 3	W	4	8.48	96	72	814.08	610.56
Kewaunee	W	2	10.50	48	48	504.00	504.00
Maine Yankee	B-J	3	11.94	64	64	764.16	764.16
McGuire 1	W	4	3.15	96	96	302.40	302.40
McGuire 2	W	4	1.40	96	96	134.40	134.40
Millstone 2	B-J	4	8.96	64	64	573.44	573.44
North Anna 1	W	3	6.49	72	36	467.28	233.64
North Anna 2	W	3	4.30	72	72	309.60	309.60
Oconee 1	W	4	11.45	96	96	1099.20	1099.20
Oconee 2	BIN	4	10.89	80	32	871.20	348.48
Oconee 3	BIN	4	10.07	80	32	805.60	322.24
Palisades	B-J	4	13.36	64	64	855.04	855.04
Point Beach 1	W	2	13.91	48	36	667.68	500.76
Point Beach 2	W	2	12.34	48	36	592.32	444.24
Prairie Island 1	W	2	10.83	48	48	519.84	519.84
Prairie Island 2	W	2	9.79	48	48	469.92	469.92
Rancho Seco	BIN	4	10.04	80	32	803.20	321.28
Robinson 2	W	3	14.03	72	54	1010.16	757.62
Salem 1	W	4	7.80	96	48	748.80	374.40
Salem 2	W	4	4.15	96	48	398.40	199.20
San Onofre 1	W	3	17.30	72	36	1245.60	622.80
San Onofre 2	B-J	4	2.18	64	64	139.52	139.52
San Onofre 3	B-J	4	1.09	64	64	69.76	69.76
Sequoyah 1	W	4	4.24	96	96	407.04	407.04
Sequoyah 2	W	4	2.90	96	96	278.40	278.40
St. Lucie 1	B-J	4	8.44	64	64	540.16	540.16
St. Lucie 2	B-J	4	1.33	64	64	85.12	85.12
Summer 1	W	3	1.94	72	36	139.68	69.84

Table 3-11 (Continued)

Reactor	Pump Mfgr	No. Pumps	Bolt Service Years to 9/30/84	Total Flange Bolts	Total Seal Bolts	Flange Bolt Years At Risk	Seal Bolt Years At Risk
Surry 1	W	3	12.25	72	36	882.00	441.00
Surry 2	W	3	11.56	72	36	832.32	416.16
TMI	W	4	10.32	96	96	990.72	990.72
Trojan	W	4	8.79	96	96	843.84	843.84
Turkey Point 3	W	3	11.95	72	54	860.40	645.30
Turkey Point 4	W	3	11.30	72	54	813.60	610.20
Yankee Rowe	W		24.11	0	0		
Zion 1	W	4	11.28	96	48	1082.88	541.44
Zion 2	W	4	10.77	96	48	1033.92	516.96
Total				3824	3086	33169.76	25498.28

Table 3-12

REACTOR COOLANT PUMP FLANGE BOLT REJECTIONS

Reactor	Bolt Rejects	Service Years To Rejection	Bolt Years To Rejection	Cause for Rejection
Calvert Cliffs 1	27	6.07	163.89	Boric Acid Corrosion
Calvert Cliffs 2	12	4.09	49.08	Boric Acid Corrosion
Fort Calhoun	9	6.78	61.02	Boric Acid Corrosion
Fort Calhoun	14	8.32	116.48	Boric Acid Corrosion
Fort Calhoun	3	9.40	28.2	Boric Acid Corrosion
Indian Point 2	24	9.19	220.56	Boric Acid Corrosion
Oconee 2	1	7.23	7.23	Boric Acid Corrosion
Oconee 2	2	10.21	20.42	Corrosion/Erosion
Oconee 3	1	6.42	6.42	Boric Acid Corrosion
Oconee 3	5	7.91	39.55	Corrosion/Erosion
Surry 1	6	9.24	55.44	Boric Acid Corrosion
Surry 1	3	11.3	33.99	Boric Acid Corrosion
Surry 2	?	(10.65)	(170.40)	Visual Marks on 16
Total	107		802.28	

Reject Rate Without Surry 2

Flange Bolts at Risk = 3824 - 72 = 3752 $\qquad \frac{107}{3752} \times 100 = 2.85\%$

Bolt Years at Risk = 33,169.76 - 832.32 = 32,337.44 $\qquad \frac{802.28}{32,337.44} \times 100 = 2.48\%$

Table 3-13

REACTOR COOLANT PUMP SEAL BOLT REJECTIONS

Reactor	Bolt Rejects	Service Years To Rejection	Bolt Years To Rejection	Cause for Rejection
Arkansas 1	1	8.73	8.73	Linear Indications
Arkansas 2	1	4.02	4.02	Linear Indication
Oconee 1	11	8.38	92.18	Linear Indication
Surry 2	?	(10.65)	(42.60)	Corrosion on 3, Scratch on 1
Zion	12	9.27	111.24	?
Total	25		216.17	

Seal Bolt Rejection Rate Without Surry 2

Bolts at Risk = 3086 - 36 = 3050 $\frac{25}{3050} \times 100 = 0.82\%$

Bolt Years at Risk = 25,498.28 - 416.16 = 25,082.12 $\frac{216.17}{25,082.12} \times 100 = 0.85\%$

Table 3-14

VALVE BOLT REJECTIONS

Reactor	Bolts Rejected	Identification	Yrs. to Reject. Service	Yrs. to Reject. Bolt	Rejection Cause
Arkansas 1	4	PSV-1001	8.73	34.92	Damaged Threads
Arkansas 1	1	PSV-1002	8.73	8.73	Damaged Threads
Beaver Valley 1	12	SI-22	5.06	60.72	Boric Acid Corrosion
Beaver Valley 1	12	SI-25	5.06	60.72	Boric Acid Corrosion
Calvert Cliffs 2	16	2-SI-217	4.09	65.44	Boric Acid Corrosion
Cook 1	16	Check, RH-134	6.80	108.80	Never Reported
Cook 1	2	Check, SI-170L3	8.94	17.88	Damaged Threads
Cook 1	1	SI-158L4	6.80	6.80	Never Reported
Cook 2	12	Check	3.57	42.84	Boric Acid Corrosion
Indian Point 2	16	SI Check	9.19	147.04	Precautionary
Indian Point 2	2	SI Check	9.19	18.38	Boric Acid Corrosion
Indian Point 2	16	SI 731	9.78	156.48	Boric Acid Corrosion
Indian Point 2	16	SI 897A	9.78	156.48	Boric Acid Corrosion
Indian Point 2	16	SI 897D	9.78	156.58	Boric Acid Corrosion
Kewaunee	2	Check	8.06	16.12	Boric Acid Corrosion
Kewaunee	3	PSV (Spray)	8.12	24.36	Boric Acid Corrosion
Kewaunee	5	SI Valve	9.35	46.75	Linear Indication
Kewaunee	4	PSV (Safety)	9.35	37.40	Linear Indication
Kewaunee	16	SI 2A	7.03	112.48	Boric Acid Corrosion
Kewaunee	2	SI (Check)	8.12	16.24	Boric Acid Corrosion
Maine Yankee	2	SFP Pump	9.32	18.64	Broke
Maine Yankee	1	PSV (Spray)	6.37	6.37	Fatigue
Millstone 2	1	SI Check	7.38	7.38	Boric Acid Corrosion
North Anna 1	12	Stop Valve	4.29	51.48	Boric Acid Corrosion
North Anna 1	5	SI Check	4.45	22.25	Boric Acid Corrosion
North Anna 2	20	2-SI-187	3.05	61.00	Boric Acid Corrosion
North Anna 2	12	2-SI-118	3.05	36.6	Boric Acid Corrosion
North Anna 2	12	2-SI-99	3.05	36.6	Boric Acid Corrosion
Point Beach 1	1	Check	11.00	11.00	Boric Acid Corrosion
Point Beach 2	4	RC-559A	10.91	43.64	Boric Acid Corrosion
Point Beach 1	4	RC-559B	13.00	52.00	Boric Acid Corrosion
Prairie Island 1	12	SI-9-1	0.83	9.96	Boric Acid Corrosion
Rancho Seco	8	RCS-002	5.34	42.72	Boric Acid Corrosion
Rancho Seco	3	PRV (Relief)	8.75	26.25	2 Linear Indication, 1 Thread Damage
Sequoyah 2	4	Isolation	0.47	1.88	Corrosion/Erosion
Sequoyah 2	16	RHR	2.04	32.64	Boric Acid Corrosion
Surry 2	16	MOV/RH-2700	8.72	139.52	Boric Acid Corrosion
Surry 2	16	MOV/RH-2700	4.87	77.92	Boric Acid Corrosion
Zion 2	11	SI 9001A	9.27	101.97	Never Reported
Total	334			2074.88	

Table 3-15

CAUSES FOR VALVE BOLTING REJECTIONS

Cause	Number	% of Total
Boric Acid Corrosion	264	79.0
Not Reported	28	8.4
Precautionary	16	4.8
Linear Indications	11	3.3
Damaged Threads	8	2.4
Corrosion/Erosion	4	1.2
Broke	2	0.6
Fatigue	1	0.3
Total	334	100.0

Table 3-16

PRIMARY PRESSURE BOUNDARY VALVES AND STUDS

2 Loop Plants	NSSS	A&E	Valves	Studs/Bolts	Bolts/Valve
Calvert Cliffs 1	CE	Bechtel	18	272	15.11
Calvert Cliffs 2	CE	Bechtel	18	272	15.11
Point Beach 1	W	Bechtel	11	160	14.55
Point Beach 2	W	Bechtel	11	160	14.55
Kewaunee	W	Pioneer Services	15	216	14.40
3, 4 Loop Plants					
Beaver Valley (3)	W	Stone & Webster	31	NR	-
North Anna 1 (3)	W	Stone & Webster	37	NR	-
North Anna 2 (3)	W	Stone & Webster	37	NR	-
McGuire 1 (4)	W	Duke Power	33	NR	-
McGuire 2 (4)	W	Duke Power	33	NR	-
Zion 1 (4)	W	Sargent & Lundy	36	NR	-
Zion 2 (4)	W	Sargent & Lundy	36	NR	-
Watts Bar 1 (4)	W	TVA	24	356	14.83
Watts Bar 2 (4)	W	TVA	24	356	14.83

NR = Not Reported

Table 3-17

ESTIMATED VALVE POPULATION PARAMETERS

Mean Number of Valves, $\overline{X}_2$ (2 Loop Plants)	14.6
Standard Deviation	3.507
Mean Number of Valves, $\overline{X}_{3,4}$ (3 & 4 Loop Plants)	32.33
Standard Deviation	5.15
Mean Number of Bolts/Valve (2, 3 & 4 Loop Plants)	14.77
Standard Deviation	0.2805

Table 3-18

STEAM GENERATOR MANWAY BOLT/STUD REJECTIONS
FOR STRESS CORROSION CRACKING AND THREAD LUBRICANTS

Lubricant	Bolt/Stud Rejections	Service Years To Rejection	Bolt Years To Rejection
Molykote G	2	3.59	7.18
	9	5.86	52.74
	3	5.96	17.88
Total	14		77.80
FEL PRO N5000	10	9.38	93.80
	8	10.30	82.40
Total	18		176.20

Table 3-19

STEAM GENERATOR MANWAY BOLTS/STUDS AT RISK AND THREAD LUBRICANTS

	Number of Bolts At Risk	Bolt Years At Risk
Molykote G, Molykote G/Neolube	944	9,079.68
FEL PRO N5000/N1000	2,232	20,072.16
Neolube/Never Seez	720	5,969.28
FEL PRO N5000/Never Seez/Neolube	768	5,614.08
Loctite Antisize	128	1,666.00

Table 3-20

HYPOTHESIS: DOES MOLYKOTE G CAUSE A HIGHER STRESS CORROSION CRACKING RATE THAN FEL PRO N5000 IN STEAM GENERATOR MANWAY BOLTS?

Bolt Basis	No Stress Corrosion Cracking	Stress Corrosion Cracking	Total	% SCC
Molykote G	930.0	14.0	944.0	1.483
FEL PRO N5000	2,214.0	18.0	2,232.0	0.806

$(\chi^2) = 2.40$

$(\chi^2)\ 1,.95 = 3.84$

$(\chi^2)\ 1,.90 = 2.71$

Since 2.40 > 3.84 and < 2.71, conclude that these two lubricants do not differ with regards to stress corrosion cracking rates.

Bolt Year Basis	No Stress Corrosion Cracking	Stress Corrosion Cracking	Total	% SCC
Molykote G	9,001.9	77.8	9,079.1	0.857
FEL PRO N5000	19,895.0	176.2	20,072.2	0.877

$(\chi^2) = 2.40$

Since 0.0122 < 3.84 and < 2.71, conclude that these two lubricants do not differ with regards to stress corrosion cracking rates.

Table 3-21

HYPOTHESIS: DOES MOLYKOTE G CAUSE A HIGHER STRESS CORROSION CRACKING RATE THAN FEL PRO N5000 (MAIN YANKEE SWITCHED TO MOLYKOTE G)?

Bolt Basis	No Stress Corrosion Cracking	Stress Corrosion Cracking	Total	% SCC
Molykote G	1,040.0	24.0	1,064.0	2.256
FEL PRO N5000	2,104.0	8.0	2,112.0	0.379

$(\chi^2) = 23.142$

(χ^2) 1,.95 = 3.84

(χ^2) 1,.90 = 2.71

Since 23.142 < 3.84, conclude Molykote G and FEL PRO N5000 differ as to stress corrosion cracking rates at 95% confidence level.

Bolt Year Basis	No Stress Corrosion Cracking	Stress Corrosion Cracking	Total	% SCC
Molykote G	10,340.9	171.6	10,512.5	1.632
FEL PRO N5000	18,557.0	82.4	18,639.4	0.442

$(\chi^2) = 108.88$

Since 108.88 > 3.84, conclude Molykote G and FEL PRO N5000 differ as to stress corrosion cracking rates at 95% confidence level.

Table 3-22

THREAD LUBRICANTS

Molykote G - Rapid Molykote G	Molybdenum Disulfide in Mineral Oil
FEL PRO N1000	Copper and Graphite Flakes in Silicon Oil
FEL PRO N5000	Nickel and Graphite in Silicon Oil
Neolube	Graphite in Isopropanol-Thermoplastic Resin
Never Seez	Nickel Base in Petroleum Carrier

Table 3-23

CAUSES FOR REJECTION AND THREAD LUBRICANTS

	Molykote G		FEL PRO N5000		Neolube/Never Seez	
	Bolts	Bolt Years	Bolts	Bolt Years	Bolts	Bolt Years
Stress Corrosion Cracking	14	77.80	18	176.20	0	0
Galled/Mechanical Damage/ Removal Damage/ Thread Damage	8	54.66	40	196.30	13	53.22
Pitting/Removal Damage	4	20.71	0	0	61	366.00

Table 3-24

HYPOTHESIS: IS THERE A SIGNIFICANT DIFFERENCE BETWEEN THE LUBRICATION PROPERTIES OF MOLYKOTE G AND FEL PRO N5000?

Bolt Basis	No Galling, etc.	Galling, etc.	Total	% Galled, etc.
Molykote G	936.0	8.0	944.0	0.847
FEL PRO N5000	2,192.0	40.0	2,232.0	1.792

$(\chi^2) = 3.37$

$(\chi^2)\ 1,.95 = 3.84$

$(\chi^2)\ 1,.90 = 2.71$

Since 3.37 > 3.84, conclude no significant difference at 95% confidence level. Since 3.37 > 2.71, conclude there is a significant difference at 90% confidence level.

Bolt Year Basis	No Galling, etc.	Galling, etc.	Total	% Galled, etc.
Molykote G	9,025.02	54.66	9,079.68	0.602
FEL PRO N5000	19,876.36	196.30	20,072.66	0.978

Since 9,917 > 3.84, conclude there is a significant difference at the 95% confidence level.

Table 3-25

HYPOTHESIS: IS THERE A SIGNIFICANT DIFFERENCE BETWEEN THE LUBRICATION PROPERTIES OF MOLYKOTE G AND NEOLUBE/NEVER SEEZ?

Bolt Basis	No Galling, etc.	Galling, etc.	Total	% Galled, etc.
Molykote G	936.0	8.0	944.0	0.847
Neolube/ Never Seez	707.0	13.0	720.0	1.806

$$(\chi^2) = 2.289$$

$$(\chi^2)\ 1,.95 = 3.84$$

$$(\chi^2)\ 1,.90 = 2.71$$

Since 2.289 > 3.84 and 2.289 > 2.71, conclude that there is no significant difference at either the 95% or the 90% confidence level.

Bolt Year Basis	No Galling, etc.	Galling, etc.	Total	% Galled, etc.
Molykote G	9,025.02	54.66	9,079.68	0.602
Neolube/ Never Seez	5,916.06	53.22	5,969.28	0.892

$$(\chi^2) = 3.846$$

Since 3.846 > 3.84, conclude there is a significant difference at the 95% confidence level.

Table 3-26

HYPOTHESIS: IS THERE A SIGNIFICANT DIFFERENCE BETWEEN THE LUBRICATION PROPERTIES OF FEL PRO N5000 AND NEOLUBE/NEVER SEEZ?

Bolt Basis	No Galling, etc.	Galling, etc.	Total	% Galled, etc.
FEL PRO N5000	2,192.0	40.0	2,232.0	1.792
Neolube/ Never Seez	707.0	13.0	720.0	1.806

$(\chi^2) = 0.0189$

$(\chi^2)\ 1,.95 = 3.84$

$(\chi^2)\ 1,.90 = 2.71$

Since 0.0189 < 2.71, conclude that there is no significant difference at either the 95% or the 90% confidence level.

Bolt Year Basis	No Galling, etc.	Galling, etc.	Total	% Galled, etc.
FEL PRO N5000	19,876.36	196.30	20,072.16	0.978
Neolube/ Never Seez	5,916.06	53.22	5,969.28	0.892

$(\chi^2) = 0.276$

Since 0.276 < 2.71, conclude there is no significant difference at either the 95% or the 90% confidence level.

Table 3-27

SUMMARY OF TESTS FOR LUBRICATION PROPERTIES

Lubricants Compared	SIGNIFICANT DIFFERENCE? Bolt Basis Confidence Level 95%	Bolt Basis Confidence Level 90%	Bolt Year Basis Confidence Level 95%	Bolt Year Basis Confidence Level 90%
Molykote G vs. FEL PRO N5000	No	Yes	Yes	Yes
Molykote G vs. Neolube/Never Seez	No	No	Yes	Yes
FEL PRO N5000 vs. Neolube/Never Seez	No	No	No	No

Table 3-28

CRDM FLANGE BOLT REJECTIONS

Reactor	NSSS	Rejects	Lubricant	Cause for Rejection
Davis Besse	BW	50	Neolube/FEL PRO N1000	47 Thread Damage, 3 Cracks (All Over Torqued)
Fort Calhoun	CE	6	Never Seez #65	Boric Acid Corrosion
Oconee 1	BW	16	Molykote G/Never Seez/ FEL PRO N5000	Galled
Oconee 3	BW	112	Molykote G/Never Seez/ FEL PRO N5000	Galled
Palisades	CE	192	Neolube/Never Seez/ DC-41	Boric Acid Corrosion
Rancho Seco	BW	8	FEL PRO N1000	Mechanical Damage
TMI 1	BW	8	Molykote G	Precautionary
Total		392		

Table 3-29

CAUSES OF FAILURE

	Number of Bolts	% of Total
Boric Acid Corrosion	485	60.9
Galled/Mechanical Damage/Thread Damage/Removal Damage	73	9.2
Pitting/Removal Damage	65	8.2
Linear Indications	40	5.0
Not Reported	40	5.0
Stress Corrosion Cracking	32	4.0
Corrosion/Erosion/Steam Cut	30	3.8
Precautionary	16	2.0
Other	10	1.3
Cracks	5	0.6
Total	796	100.0

Table 3-30

SUMMARY BOLT REJECTION STATISTICS FOR PRIMARY PRESSURE BOUNDARY COMPONENTS

Bolting Component	Number Rejected	% of Total
Valves	334	42.0
Steam Generator Manway	310	38.9
RCP Flange Bolts	107	13.4
RCP Seal Bolts	25	3.1
Pressurizer Manway	20	2.6
Total	796	100.0

Table 3-31

BORIC ACID CORROSION BOLT FAILURE RATES

Pressure Boundary	Bolt Failure Rate, % of Bolts at Risk	Bolt Year Failure, % of Bolt Years at Risk
Steam Generator Manway	2.160	1.220
Pressurizer Manway	0.571	0.166
RCP Seal	0	0
RCP Flange	2.670	2.300
Pressure Boundary Valves	1.420	-

Table 3-32

TOTAL BOLTING FAILURE RATES BY PRESSURE BOUNDARY COMPONENTS

Pressure Boundary	Bolt Failure Rate, % of Bolts at Risk	Bolt Year Failure, % of Bolt Years at Risk
Steam Generator Manway	5.81	3.98
Pressurizer Manway	2.28	1.20
RCP Seals	0.82	0.85
RCP Flanges	2.85	2.48
Pressure Boundary Valves	1.80	-

Section 4

SAMPLING INSPECTION AND ACCEPTANCE CRITERIA FOR BOLTED CONNECTIONS

INTRODUCTION

The main concerns in the use of highly-stressed, high-strength fasteners in nuclear structural connections are failures due either to the external load exceeding the preload across the joint (overload) or to stress-corrosion cracking. Criteria to define the range of acceptable preload values, hereafter referred to as acceptable range and denoted by R_A, are reviewed in Ref. (1). The lower limit of this range, F_A^-, corresponds to the minimum required preload and depends on the choice of load-combination rule. The upper limit of R_A^+, F_A^+, is controlled by the yield strength of the material or, for fasteners that are susceptible to stress-corrosion cracking, by the assumed flaw size or flaw factor.

If one knew the preload F of a given fastener, then one could decide about preload adequacy by simply checking whether F is inside or outside the acceptable range $R_A = [F_A^-, F_A^+]$ for that fastener. Unfortunately, uncertainties exist about the actual value of preload, so that the previous deterministic checking procedure must be replaced with a probabilistic criterion. We propose the following simple rule: Let m and σ^2 be the mean value and variance of preload F. Then we define the uncertainty range R_U of F as

$$R_U = [F_U^-, F_U^+] = [m - \beta\sigma, m + \beta\sigma] \qquad (4\text{-}1)$$

where β is a chosen constant. A fastener whose preload is uncertain is considered adequate if R_U is entirely contained in the acceptable range R_A for that fastener. An equivalent statement is that a fastener is accepted if the following inequalities are satisfied:

$$\begin{cases} F_U^- > F_A^- \\ F_U^+ < F_A^+ \end{cases} \qquad (4\text{-}2)$$

Examples of acceptable and non-acceptable situations are shown in Figure 4-1.

A set of fasteners with the same acceptable range R_A and the same uncertainty range R_U is referred to here as a uniform population of fasteners or simply as a population of fasteners. If a population of fasteners does not pass the criterion of Eq. 4-2 because the associated ranges R_A and R_U do not overlap (Figure 4-1 b and e), then the fasteners should be detensioned or retightened using a procedure that guarantees satisfaction of Eq. 4-2. If the population is rejected but R_A and R_U overlap (Figure 4-1 c and d), then sampling inspection becomes necessary to reduce uncertainty on preload. Inspection consists of: (1) measuring the preload of a few fasteners, and (2) re-evaluating m and σ^2 using the measured preloads. If the new values of m and σ^2 are such that the population is still considered inadequate, then the fasteners should be detensioned or retightened in such a way that Eq. 4-2 is satisfied.

Equation 4-1 represents the simplest form of uncertainty range. There are cases when the values of β and σ should be different for the lower and upper limits of the range. In addition, it may be better to define the uncertainty range in terms of log preload $F' = \ell n\ F$, rather than directly in terms of F. These and other problems related to the definition of the uncertainty range for a population of fasteners are addressed in the following subsection, whereas in a later subsection, guidelines for the design of sampling inspection plans are provided and simple rules for the re-evaluation of m and σ^2 on the basis of the measured preloads are given.

UNCERTAINTY RANGE PRIOR TO SAMPLING INSPECTION

A model for preload uncertainty has been proposed (2). Fasteners are grouped according to the connection they belong to, and connections are grouped into homogeneous populations. The log preload F'_{ijk} for fastener k of connection j of population i is then expressed as

$$F'_{ijk} = \overline{F}'_i + b + \Delta_i + \Delta_j + \Delta_k \qquad (4\text{-}3)$$

where $\overline{F}'_i$ is the logarithm of the nominal (design) preload $\overline{F}_i$ for all the fasteners of the i'th population, b is a systematic bias term, and $(\Delta_i, \Delta_j, \Delta_k)$ are the effects of (the variations associated with) population, connection and fastener, respectively.

Prior to sampling, the value of b is reasonably well known (b depends mainly on the method of preloading and on long-term relaxation effects), but the Δ terms are not. The latter terms may be modeled as random variables with mean zero (any non-zero mean is included in b) and variances σ_i^2, σ_j^2 and σ_k^2, respectively. Estimates of b, σ_j^2 and σ_k^2 for various preloading methods and levels of loading relative to yielding are given in Ref. (3) and are reproduced here in Table 4-1. These estimates are based in part on experience and in part on the results of a field test conducted under the present project.

Example calculations of the entries in Table 4-1 for tensioning by torque at high loads are as follows.

Log Preload Bias b

$$b = \text{Expected value of } \ell n(F/\bar{F})$$

$$= E[\ell n(F/\bar{F}) \text{ due to short-term relaxation}]$$

$$+ E[\ell n(F/\bar{F}) \text{ due to long-term relaxation}]$$

From Ref. (3), the first expectation term is $\ell n(1 - 0.061) = -0.063$; from Ref. (4), the second expectation term is $\ell n(1 - 0.15) = -0.163$. Therefore, $b = -0.063 - 0.163 = -0.226$, which is rounded off to -0.23 in Table 4-1.

Standard Deviations σ_j, σ_k, and σ_n

Under the assumption that F has lognormal distribution, the standard deviation σ_j can be obtained as

$$\sigma_j = [\ell n(1 + V_j^2)]^{1/2}$$

where V_j is the coefficient of variation of F (standard deviation divided by mean) from connection to connection. This last quantity is estimated to be 0.13 (3). Therefore,

$$\sigma_j = [\ell n(a + 0.13^2)]^{1/2} = 0.13$$

Similarly, for σ_k, the above reference gives $V_k = 0.057$ so that

$$\sigma_k = [\ell n(1 + 0.057^2)]^{1/2} = 0.057$$

Finally, for σ_η,

$$\sigma_\eta = (0.13^2 + 0.057^2)^{1/2} = 0.142$$

In Table 4-1, σ_k and σ_η are reported with two decimals, as 0.06 and 0.14, respectively. The same procedure has been used to obtain the other entries of Table 4-1, with the two following exceptions. For the Hydraulic Tensioner, the analysis gives $\sigma_j = 0.085$ at low loads and 0.11 at high loads. Because it is reasonable to believe that σ_j should not increase with the level of loading, the value 0.11 has been used for both cases. In the second exception, estimates of σ_j and σ_k could not be obtained directly from the field test for the case of Turn-of-Nut and Extensometer. For the extensometer, the total standard deviation calculated from data is about 0.07. However, this value includes uncertainty on measured load, which probably accounts for the most part of the variation. Based on both empirical and theoretical analyses (3,4), values of σ_η around 0.05 are indicated. The corresponding variance, $\sigma_\eta^2 = 0.0025$, is split in Table 4-1 into equal parts between connection (σ_j^2) and fastener (σ_k^2). For Turn-of-Nut, the main source of uncertainty is the snugging torque, which may produce large non-zero intercepts in the plot of stretch versus turn (3). The values of σ_k and σ_j in Table 4-1 are again based partly on theoretical and partly on experimental evidence.

Estimates of the variances σ_i^2, which express uncertainty on the average log preload for the i'th population of fasteners, could not be obtained from the test results due to the limitations of the testing program. This uncertainty is affected by many plant-, connection-, and fastener-specific factors as well as by the type of equipment, crew training, and quality of control during assembly. The value of σ_η^2 should therefore be assessed on a judgmental basis, using past experience with the type of fastener, joint, and tightening procedure under consideration. Indicative values of σ_i are given in Table 4-2. They have been obtained by assuming the following coefficients of variation of F due to job-to-job variation

	Quality of Control	
	Good	Poor
Extensometer	0.05	0.10
Other Methods	0.10	0.15

These are judgmental estimates, which will need to be revised as more empirical information will become available. Also, the estimates are generic and should be modified depending on job-specific information.

The mean value m' and variance $\sigma^{2'}$ of log preload F' are calculated as

$$\begin{cases} m' = \overline{F}_i' + b \\ \sigma^{2'} = \sigma_i^2 + \sigma_j^2 + \sigma_k^2 \end{cases} \tag{4-4}$$

For example, if a population of fasteners has been assembled to high preload levels using the torque method and under good quality control of preload, then from Tables 4-1 and 4-2,

$$\begin{aligned} b &= -0.23 \\ \sigma_i &= 0.10 \\ \sigma_j &= 0.13 \\ \sigma_k &= 0.06 \end{aligned} \tag{4-5}$$

so that

$$\begin{cases} m' = \overline{F}_i' + b \\ \sigma^{2'} = 0.031 = (0.175)^2 \end{cases} \tag{4-6}$$

Box plots of b and b ± σ' for different levels of preload, assembly methods, and levels of quality of control are shown in Figure 4-2. Notice how the Extensometer outperforms all the other methods with respect to both bias and variability. Varying the level of preload control has an appreciable effect only for the more accurate methods.

The values of m' and $\sigma^{2'}$ from Eq. 4-4 can be used in a formula of the type in Eq. 4-1 to obtain the uncertainty range of F':

$$R_U' = [m' - \beta\sigma', m' + \beta\sigma'] \tag{4-7}$$

The choice of β in this last equation depends on the consequences of violating the overload and stress-corrosion limits of the acceptable range and is to some degree judgmental. If F' has normal distribution and P* is the maximum acceptable probability for overloading and stress-corrosion cracking, then β can be obtained as the value that satisfies

$$\phi(\beta) = 1 - P^* \tag{4-8}$$

where ϕ is the standard normal cumulative distribution function. For example, for P^* = 0.1, 0.01, and 0.001, Eq. 4-8 gives β = 1.28, 2.33, and 3.09, respectively.

From the above considerations, it is clear that β needs not be the same for the upper and lower limits of the uncertainty interval. If, for example, one sets P^* = 0.001 for overload and P^* = 0.01 for stress-corrosion cracking, then the uncertainty range is asymmetric, of the type

$$R_U' = [m' - 3.09\sigma', m' + 2.33\sigma'] \tag{4-9}$$

Values of β from 2 to 4 are common in structural design against overloading (5). One should however consider that, in the present case, conservatism may be built into the acceptable limits for overloading and cracking. Accordingly, lower values of β may be appropriate for the uncertainty range. For example, it is not advisable to use the same value of β for the upper limit of R_U' in cases when the upper limit of the acceptable range has been obtained using stress-corrosion formulas with different built-in conservatism. Similarly, β for F_U^- should depend on the loads and load-combination rule used in the definition of F_A^-.

Another fact to be kept in mind is that the standard deviation σ' may have different values for the upper and lower limits of R_U'. For example, consider the case of a connection subjected to pure axial load. In this case, the overloading criterion should be stated in terms of the average preload of the fasteners in the connection, whereas the stress-corrosion criterion is better applied to the preload of individual fasteners. Under the assumptions of Eq. 4-3, the average log preload of n fasteners (here we assume for simplicity that one may average the log preloads instead of the preloads) has a variance $\sigma_n^{2'}$ given by

$$\sigma_n^{2'} = \sigma_i^2 + \sigma_j^2 + \frac{\sigma_k^2}{n} \tag{4-10}$$

The uncertainty range of F' should then be calculated as

$$R_U' = [m - \beta\sigma_n', m + \beta\sigma'] \quad (4\text{-}11)$$

where n is the number of bolts in the connection and β may be different for the two limits.

Variance reduction was possible in Eq. 4-10 because of mechanical interaction among the fasteners of a connection. The degree to which the variance is reduced depends on the number of participating fasteners and on the behavior of the system; e.g., it is very different for series and parallel configurations. In cases when several connections share the applied load, reduction in the term σ_J^2 may also be possible. Considerations of this type are specific to each bolting and loading situation and must be made on a case-by-case basis.

After the uncertainty range of F' has been determined, say as $[F_U'^-, F_U'^+]$, the corresponding range of F is found from

$$R_U = [e^{F_U'^-}, e^{F_U'^+}] \quad (4\text{-}12)$$

In summary, the present method for checking the adequacy of fasteners consists of the following steps:

1. Determine the acceptable range R_A of each population of fasteners (see Ref. 1).
2. Calculate m' and $\sigma^{2'}$ for the log preload F' using Eq. 4-4. Possibly modify $\sigma^{2'}$ for the overloading case, as exemplified by Eq. 4-10.
3. Decide levels of protection P* for overload and stress corrosion cracking and calculate the associated values of β from Eq. 4-8. In deciding about P*, consider the load combination rule and the stress-corrosion formula used to define the acceptable range.
4. Calculate the range of uncertainty for F' and the associated range for F using Eq. 4-12.
5. Check whether R_U is included in R_A. If it is, the population of fasteners is accepted; otherwise the fasteners are inspected, detensioned or retightened, depending on whether R_U and R_A overlap or not (see Figure 4-1).

6. In the case of sampling inspection, m' and $\sigma^{2'}$ are modified accounting for the results of sampling (see following subsection), and the uncertainty interval R_U is calculated again. If the fasteners are still considered inadequate, they should be detensioned or retightened using a procedure and a level of quality control that guarantee acceptance.

SAMPLING INSPECTION AND RE-EVALUATION OF UNCERTAINTY RANGE

The objective of sampling inspection is to reduce uncertainty on the terms Δ_i, Δ_j, and Δ_k in Eq. 4-3. Because sampling is informative only on the Δ terms that affect the preload of the tested fasteners, uncertainty is reduced by different amounts for sampled and non-sampled fasteners.

The correct method for quantifying uncertainty on the Δ terms after sampling is to form a prior distribution using the variances in Tables 4-1 and 4-2 and then calculate the posterior distribution given the results of sampling. The effect of measurement errors can be included in the analysis. However, such an approach is impractical for routine use. A simpler method is proposed here. The method is exact if preloading is measured for n fasteners that belong to n different connections and provides the state of uncertainty on fasteners in non-sampled connections. With good approximation, results apply also to fasteners in sampled connections and to the case when some of the sampled fasteners belong to the same connection.

For the purpose of analysis, it is convenient to rewrite Eq. 4-3 as

$$F'_{ijk} = c_i + \eta_{ik} \tag{4-13}$$

where

$$c_i = \overline{F}'_i + b + \Delta_i$$

$$\eta_{ik} = \Delta_j + \Delta_k$$

If, prior to sampling, the Δ terms have independent normal distributions, then also the distributions of c_i and η_{jk} are normal, with the following parameters:

$$c_i \sim N(\overline{F}'_i + b,\ \sigma_i^2)$$

$$\eta_{ik} \sim N(0,\ \sigma_\eta^2 = \sigma_j^2 + \sigma_k^2) \tag{4-14}$$

Values of σ_η are given in Table 1. Suppose further that preload measurements are affected by errors, so that the measured values X_{ijk} are related to the true log preloads F'_{ijk} as

$$X_{ijk} = F'_{ijk} + \xi_{ijk} \tag{4-15}$$

The errors ξ_{ijk} may be assumed to have independent normal distribution with mean value zero and variance σ_ξ^2. Estimates of σ_ξ (4) are given in Table 4-3. Under the previous assumptions, the posterior distribution of c_i is

$$c_i \sim N(m_{c_i}, \sigma_{c_i}^2) \tag{4-16}$$

where

$$\begin{aligned} \sigma_{c_i}^2 &= \left(\frac{1}{\sigma_i^2} + \frac{n}{\sigma_\eta^2 + \sigma_\xi^2}\right)^{-1} \\ m_{c_i} &= \sigma_{c_i}^2 \left(\frac{\overline{F}'_i + b}{\sigma_i^2} + \frac{n\overline{X}}{\sigma_\eta^2 + \sigma_\xi^2}\right) \end{aligned} \tag{4-17}$$

and $\overline{X}$ is the average of the measurements X_{ijk}.

After sampling, the log preload in an unsampled fastener of an unsampled connection has normal distribution with mean value and variance given by

$$\begin{cases} m' = m_{c_i} \\ \sigma^{2'} = \sigma_{c_i}^2 + \sigma_\eta^2 \end{cases} \tag{4-18}$$

where, from Eq. 4-14, $\sigma_\eta^2 = \sigma_j^2 + \sigma_k^2$. Note, the log preload variance after sampling still contains the variance components due to connection and fastener, and is smaller than the a priori variance because $\sigma_{c_i}^2$ is smaller than σ_i^2. The reduction of uncertainty may be substantial if σ_i^2 is the main contributor to the a priori variance of F'. Tables 4-1 and 4-2 indicate that this is the case when using the extensometer.

An interesting feature of Eqs. 4-17 and 4-18 is that the posterior mean depends on the outcome of sampling (through $\overline{X}$), whereas the posterior variance depends only on the sample size n. This fact allows one to rationally design a sampling plan based on the desired amount of uncertainty reduction. Suppose that the target of sampling is to reduce $\sigma^{2'}$ to a value not larger than σ^{2*}, where σ^{2*} is a given variance larger than σ_η^2. From Eqs. 4-17 and 4-18, the sample size n should be such that

$$\left(\frac{1}{\sigma_i^2} + \frac{n}{\sigma_\eta^2 + \sigma_\xi^2}\right)^{-1} \leq \sigma^{2*} - \sigma_\eta^2 \tag{4-19}$$

For example, consider the following variances, which correspond to poor quality control, high loads, and preloading by the extensometer method:

$$\begin{aligned} \sigma_i^2 &= (0.10)^2 \\ \sigma_j^2 &= (0.04)^2 \\ \sigma_k^2 &= (0.04)^2 \end{aligned} \Big\} \; \sigma_\eta^2 = (0.05)^2 \tag{4-20}$$

Also suppose that, during sampling inspection, preload is measured using an ultrasonic extensometer. This means that an appropriate value for σ_ξ is 0.05 (see Table 4-3). Prior to sampling, the total variance of F' is

$$\sigma^{2'} = \sigma_i^2 + \sigma_\eta^2 = 0.0125 \tag{4-21}$$

If the aim of sampling is to reduce this variance to $\sigma^{2*} = (0.06)^2 = 0.0036$, at most, then the sample size n should satisfy

$$\left[\frac{1}{(0.1)^2} + \frac{m}{(0.05)^2 + (0.05)^2}\right]^{-1} \leq 0.0036 - 0.0025 \tag{4-22}$$

This gives n = 4 and a posterior variance from Eqs. 4-17 and 4-18 equal to $(0.06)^2$.

Suppose further that the mean value of F' prior to sampling is $\overline{F}_i' + b = \ln$ (500,000 lb) = 13.12, and that the sample average for the tested fasteners is 13.00 (e^{13} = 442,400). From Eqs. 4-17 and 4-18, the posterior mean of F' is

$$m' = 0.00111 \left[\frac{13.12}{(0.10)^2} + \frac{(4)\ (13)}{(0.05)^2 + (0.05)^2}\right] = 13.013 \tag{4-23}$$

corresponding to $F = e^{13.013} = 448,350$ lb. Clearly, sample information is more heavily weighted in this estimate than prior information.

Because the posterior variance of F' is the sum of two terms, $\sigma_{C_i}^2$ and σ_η^2, of which one (σ_η^2) is irreducible and the other ($\sigma_{C_i}^2$) is roughly inversely proportional to the sample size n, the marginal reduction of variance from increasing n becomes small after $\sigma_{C_i}^2$ has become a fraction of σ_η^2. For example, there is little advantage in reducing $\sigma_{C_i}^2$ below 0.1 σ_η^2, a value which is attained in all cases with n = 10.

Up to now, it has been assumed that the variances σ_j^2 and σ_k^2 are known, hence that $\sigma_\eta^2 = \sigma_j^2 + \sigma_k^2$ is known. The values given in Table 4-1 are, however, generic and do not necessarily correspond to the variances for a specific population of fasteners. Prior to sampling, the values of Table 4-1 are appropriate to use, but after sampling, one may want to revise them based on the measured preloads. Instead of using elaborate estimates of σ_η^2 that combine prior information with sample information, one may just use the unbiased sample estimate

$$S_\eta^2 = \left[\frac{1}{n-1} \sum_{k=1}^{n} (X_k - \overline{X})^2\right] - \sigma_\xi^2 \qquad (4\text{-}24)$$

where X_k is the measured preload for the k'th sampled fastener and $\overline{X}$ is the average measured preload,

$$\overline{X} = \frac{1}{n} \sum_k X_k$$

As a general rule, one should used S_η^2 instead of σ_η^2 if the sample size is sufficiently large, say $n \geq 10$. Equations 4-17, 4-18, and 4-19 continue to hold with σ_η^2 replaced by S_η^2. Notice, however, that this replacement makes the posterior variance of F' not pre-computable and Eq. 4-19 less useful for the choice of sample size. The considerations on n that follow Eqs. 4-23 and 4-24 are still valid, suggesting appropriate sample sizes of 10 to 15.

It is emphasized that the previous analysis applies to homogeneous populations of bolts. If several populations of fasteners exist (e.g., bolts of different type, with different preload specification, assembled by different crews, using different methods, etc.), each population should be analyzed and inspected independently.

In summary, we propose the following sampling inspection procedure. For each population of fasteners that does not pass the criteria of Eq. 4-2 and for which R_A and R_U overlap:

1. Decide the sample size n. If σ_n^2 is to be estimated from the sample data, then n = 10-15 is appropriate. Otherwise, even smaller samples from Eq. 4-19 may suffice.

2. Measure preload (we recommend using an accurate procedure such as the ultrasonic extensometer) for n fasteners that belong to different connections. If this is not possible, minimize the number of fasteners from each connection.

3. If $n \geq 10$, estimate σ_n^2 through Eq. 4-24; use this estimate in place of σ_n^2 to calculate the posterior mean and variance of log preload from Eqs. 4-17 and 4-18.

4. Use the posterior mean and variance of log preload to check adequacy of the population of fasteners by the method discussed in the previous subsection. If the population fails to satisfy the acceptance criteria, then all the fasteners should be detensioned or retightened.

CONCLUSIONS

An ideal procedure for setting standards for bolted connections under the threat of overload and stress-corrosion cracking would be to establish maximum acceptable probabilities for the occurrence of each failure mode, based on the severity of the consequences. In order to apply such criteria, one should quantify uncertainty on the external loads during the lifetime of the plant, on the state of preload of the fasteners, and on the maximum flaw size for possible crack initiation.

Unfortunately, our state of knowledge (e.g., about stress-corrosion cracking) and current deterministic practice make it impossible to implement fully probabilistic standards. A semi-probabilistic format, which explicitly recognizes uncertainty on fastener preload but avoids the calculation of failure probabilities, is proposed here. Three actions may result from initial verification of the proposed standards on a population of fasteners: accept population, reject population and detension or retighten all fasteners, or inspect some of the fasteners to acquire more information about the existing preload level (sample inspection). In absence of preload measurements, quantification of preload uncertainty is based on past experience and varies with method of preload, level of loading, and quality of control. This state of uncertainty is changed by sampling inspection, for which a simple method of sample size determination and uncertainty updating is proposed, consistent with the format of the acceptance criteria.

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Table 4-1

ESTIMATES OF b, σ_j, σ_k AND σ_η FOR DIFFERENT ASSEMBLY METHODS AND LOAD LEVELS

	Low Loads (<33% of Yield)				High Loads (>33% of Yield)			
	b	σ_j	σ_k	σ_η*	b	σ_j	σ_k	σ_η*
Torque	-0.70	0.65	0.36	0.74	-0.23	0.13	0.06	0.14
Turn-of-Nut	-1.53	1.00	2.20	2.42	-0.58	0.13	0.14	0.19
Hydraulic Tensioner	-0.53	0.11	0.20	0.23	-0.42	0.11	0.13	0.17
Extensometer	-0.20	0.04	0.04	0.05	-0.20	0.04	0.04	0.05

* $\sigma_\eta = [\sigma_j^2 + \sigma_k^2]^{1/2}$

Table 4-2

ESTIMATES OF σ_i FOR DIFFERENT QUALITY OF CONTROL AND FOUR ASSEMBLY METHODS

	Quality of Control	
	Good	Poor
Torque	0.10	0.15
Turn-of-Nut	0.10	0.15
Hydraulic Tensioner	0.10	0.15
Extensometer	0.05	0.10

Table 4-3

ESTIMATES OF THE STANDARD DEVIATION σ_ξ OF THE MEASUREMENT ERROR IN EQ. 4-15
WHEN USING DIFFERENT METHODS TO DETERMINE EXISTING PRELOAD

	σ_ξ
Torque	0.25
Hydraulic Tensioner	0.10
Extensometer	0.05

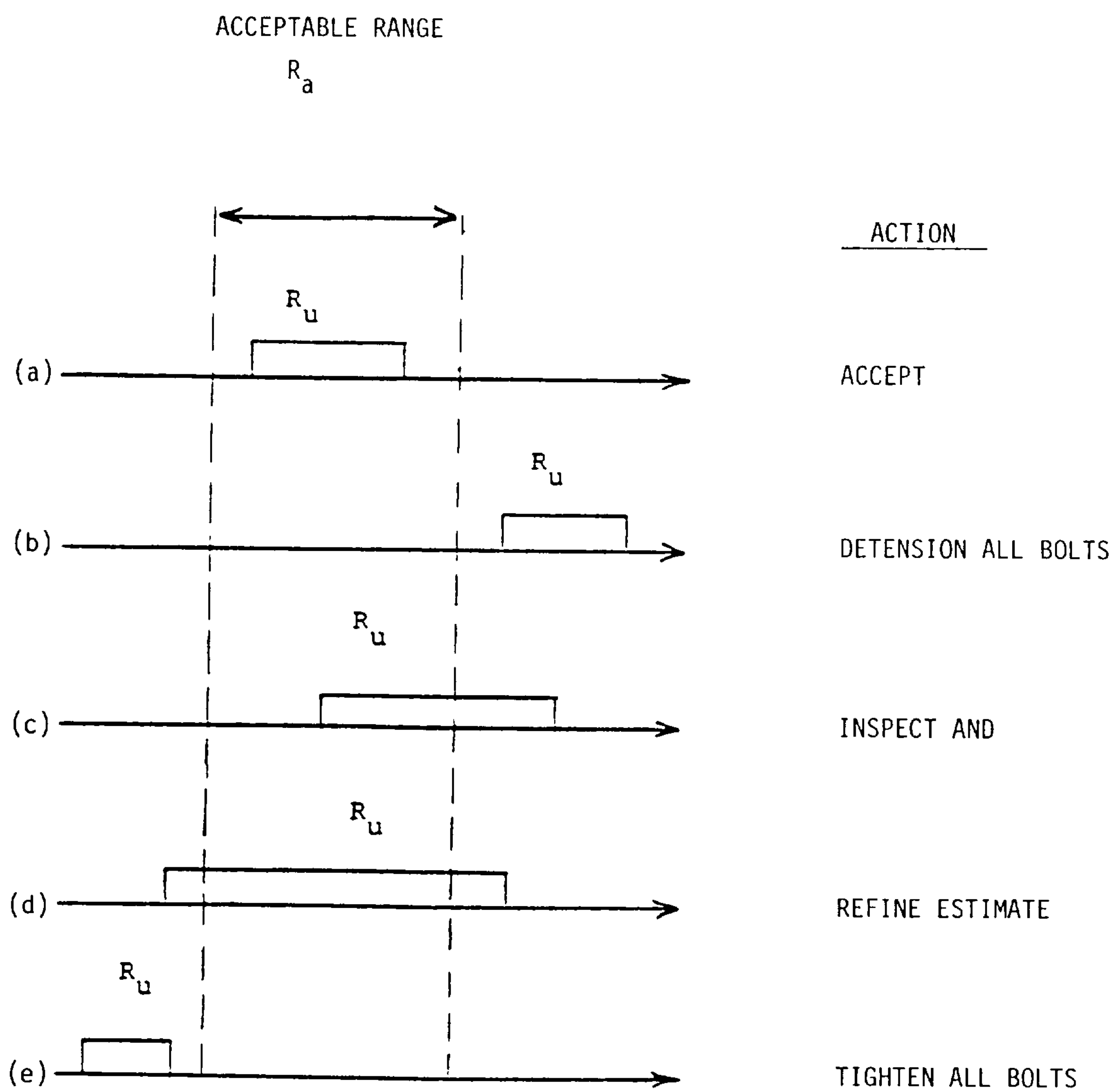

Figure 4-1. Schematic of Acceptable and Unacceptable Uncertainty Ranges for Preload, According to Criteria of Eq. 4-2

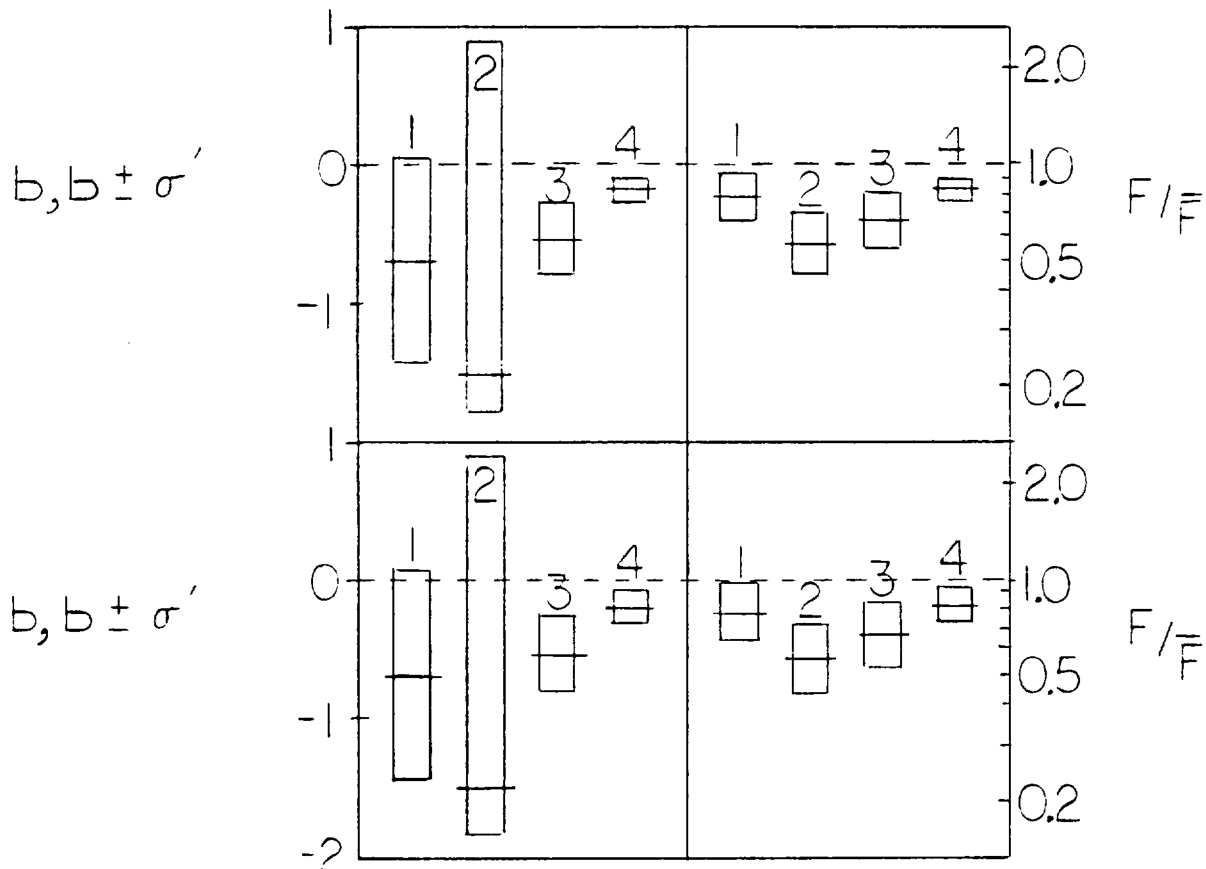

Figure 4-2. Comparison of Different Tightening Methods, Showing Bias, b, and One-Sigma Ranges of Log Preload Ratio of Actual to Nominal Preload: (1) Torque; (2) Turn-of-Nut; (3) Hydraulic Tensioner; and (4) Extensometer

Section 5

NUCLEAR STRUCTURAL BOLTING PRELOAD EVALUATION

Task 16 of the Joint AIF/MPC Task Group on Bolting action plan consisted of an evaluation of the need for high preloads, the identification of potential relief in preload requirements, and the investigation of preload application techniques and variability. The previous section of this volume (Section 4, Volume 2) has provided a discussion of the statistical nature of the preloading process. This section of this report evaluates existing preload design requirements, the relationship of the specified joint preload to the minimum preload required to carry design loads, and the effect of potential loading relief on minimum preload requirements for one heavy component support structural joint. The work is due to the efforts of W. Bak of Combustion Engineering, Inc. and M. Looram of Looram Engineering, Inc.

INTRODUCTION

The use of high preloads in bolted connections of structural members has raised a concern for stress corrosion cracking (SCC) in high strength fasteners where moist environments exist. Because high preloads may not be required for many applications, design load evaluations and detensioning are possible mitigating actions if the fastener material is susceptible to SCC, and if the fasteners in question have not been preloaded beyond their gross yield strength. As a baseline criterion, it is assumed that a screening strategy that considers material properties and fracture mechanics has been applied to the fasteners of heavy component supports that are susceptible to SCC failure. Preload reduction is a viable alternative provided the role of preload in the original design is considered, access is available to the joint, and risk to damage of bolting by the detensioning process is considered. In addition, the following should be considered:

- Is a reduction in bolt preload acceptable from a design standpoint?
- How can the existing preload in the fasteners be determined?

This section evaluates existing preload design requirements for structural joints, with one heavy component support structural joint evaluated in detail. A review of

typical design documentation that was used to determine the structural preload requirement is performed. The relationship of the specified joint preload to the minimum preload required, the effect of potential loading relief in minimum preload requirements, and an estimate of the acceptable preload range are determined.

The heavy component support structural joint evaluated in detail was a reactor coolant pump support column-embedment joint. The pump support system is shown in Figure 5-1 and is designed to support the pump and motor for normal operation, seismic and design basis pipe breaks. The 17-inch by 4 1/2-inch horizontal and vertical ASME SA 533 Class 2 columns are attached through a spherical bearing and 5 1/2-inch diameter ASME SA 540 Class 2 pin to a clevis which is anchored to the concrete by means of embedded bolts. The clevis is shown in Figure 5-2. Four 3-inch diameter bolts are used to anchor the clevis to the concrete. ASTM A-540 Class 4 ($Sy_{min.}$ = 120 ksi, $Su_{min.}$ = 135 ksi) and A-354 Grade BD ($Sy_{min.}$ = 115 ksi, $Su_{min.}$ = 140 ksi) are typical bolting materials used. The loads transmitted to the concrete through the clevis and embedment bolts are dead weight, thermal, seismic, and pipe breaks. Preload design requirements for this joint are discussion in the next subsection along with the relationship of the specified joint preload to the minimum required. The effect of potential loading relief on minimum preload requirements is described, an estimate of the maximum acceptable preload is determined (based on several stress corrosion cracking criteria), and conclusions and acceptable preload ranges based on the various maximum and minimum preload criteria are presented in the following subsections.

PRELOAD DESIGN REQUIREMENTS

Heavy component support structural joints connect and transmit loads between components and their supports or between different segments of supports. Generally, bolted structural interfaces are designed to prevent joint separation under worst case postulated accident conditions (combined safe shutdown earthquakes and pipe break loadings). Preloads must be of sufficient magnitude to: (1) carry external loads, (2) prevent slippage, (3) maintain joint stiffness, (4) minimize fatigue loading, (5) minimize prying loads, and (6) prevent vibration loosening.

The ASME Boiler and Pressure Vessel Code (1) specifies that "All high strength bolts shall be preloaded to a value not less than that given in the Design Specifications" for component support bolts. No specific maximum limit is specified. Excessive preloads and the use of susceptible materials can increase the potential

for stress corrosion cracking. Should reduction in preload be a viable mitigating action to minimize the potential for stress corrosion cracking, the precision of methods employed to reduce preload needs to be consistent with the acceptable preload range. The maximum limit on preload could be defined by satisfying a threshold criterion for stress corrosion cracking, with the minimum preload defined by addressing the six conditions described above. Each of these six conditions is discussed in more detail in the following.

External Loads

Component support bolted joints are designed and preloads determined such that the structural integrity of the joint is maintained when the joint is subjected to external loads. Tension loads transmitted through the joint result from the combination of dead weight, thermal, seismic (operational basis earthquake and safe shutdown earthquake) and pipe break loads. Minimum preloads are generally based on maintaining contact (net compressive force between clamped surfaces) under the most severe loading condition of dead weight plus thermal plus safe shutdown earthquake (SSE) plus pipe break. Maintaining contact between the clamped surfaces minimizes the load variation in the bolts and maintains joint stiffness. If the preload is not sufficient to maintain contact under the maximum loads all of the applied external load would be carried by the bolts. This would result in undesirable cyclic loading of the bolts and significant stiffness variations between tension and compressive loadings. A detailed discussion of the behavior of a preloaded bolted joint subjected to tensile loadings can be found in Ref. (2).

Slippage

Preloads are generally sized to prevent joint slippage under all loading conditions. Slippage is prevented by ensuring frictional resistance greater than external transverse loads. This may require additional preload above that required to carry the external tensile loads in order to assure lack of slippage under the most severe tensile loading conditions.

Joint Stiffness

As discussed previously, preloads of sufficient magnitude are specified in order to maintain joint stiffness. Support stiffnesses are an integral part of maintaining an acceptable level of seismic response of components. To preserve existing hardware, nonlinear analyses could be performed to account for the different stiff-

nesses in a separating joint. This type of analysis may be feasible for pipe break events; however, the cost associated with seismic reanalysis may be prohibitive.

Fatigue and Prying Loads

Sufficient preload to maintain joint stiffness and carry external loads minimizes fatigue loading by minimizing the cyclic loadings in the bolt. Prying action can be of concern in some flanged joints and in support plates. Since the line of action of the applied tensile force does not generally coincide with the center of individual bolts, the load seen by the bolt is increased. The effects of prying action may be taken into account in the joint analysis, demonstrated in Ref. (3). Sufficiently rigid support plates and flanges and proper preloading of the joint minimize prying action.

Vibration Loosening

In many applications preloading has been used as a locking device to prevent vibration loosening. Should reducing preloads be employed to alleviate SCC, alternate means of locking to prevent vibration loosening may be required.

For the reactor coolant pump support clevis joint evaluated in detail, preloads were specified based on the required ability of the joint to carry the external loads without joint separation and to maintain joint stiffness. Since no significant horizontal loads exist, slippage was not a concern. Also, prying was not a concern due to the rigidity of the clevis, and fatigue is not a significant concern due to the limited number of tensile load applications. Preload was the method employed to prevent vibration loosening.

A review of the design documentation which determined the required preloads revealed that the required minimum preload was calculated to be 385 kips (64% Sy) based on generic seismic and pipe break load estimates. Conservative generic seismic and pipe break load estimates based on previous experience were the basis for the joint design since detailed plant specific analyses are not typically completed prior to the need for joint design and preload specification. The preload was conservatively specified at 450 kips. A reduction in preload of 14% is therefore acceptable without further analytical justification, based on the margin built into the design of 450 kips specified versus 385 kips required.

POTENTIAL LOADING RELIEF - MINIMUM PRELOAD REQUIREMENTS

Potential loading relief that could reduce minimum preload requirements is available from three potential sources:

1. Load combinations (NUREG-0484, decoupling of LOCA and seismic loads)
2. Site specific versus generic seismic loadings
3. Elimination of guillotine pipe break loadings (use of leak-before-break criteria)

An evaluation of preload requirements, considering the above potential sources of relief, was performed based on satisfying the six conditions of the previous subsection, including maintenance of joint stiffness. The following reduced preload requirements, therefore, do not impact the system performance relative to the design requirements.

Site Specific Seismic Loadings

The generic seismic design criteria (which was a basis for the originally calculated preload requirement of 385 kips) envelope the requirements for plants with a broad range of ground excitation levels, soil properties, and structural design variations. Therefore, when site specific seismic design criteria are considered, a significant reduction in preload is obtained. For the East Coast plant considered, use of site specific seismic loads at the pump clevis joint resulted in a minimum preload required of 266 kips. This is a 31% reduction from the original as-calculated preload and a 41% reduction from the originally specified preload. A significant reduction in the preload requirement would also be expected for a West Coast plant, based on a comparison of clevis joint seismic loads between the plant considered and a West Coast plant.

Load Combinations

The NRC has required that the structural responses due to accident loads and loads caused by earthquakes be combined when analyzing structures important to safety. The original preload requirements for the reactor coolant pump clevis joint were based on the linear summation of dead weight, thermal loads, and the peak structural responses due to pipe breaks and safe shutdown earthquake (SSE). NUREG-0484 (4) allows the square root of the sums of the squares (SRSS) technique of combining dynamic responses from SSE and pipe break within the reactor coolant pressure boundary and its supports, contingent upon the performance of a linear elastic dynamic analysis to meet the appropriate ASME Code, Section III, Service Limit. That is:

$$\text{Design Load} = \text{Dead Weight} + \text{Thermal} + (\text{Seismic}^2 + \text{Pipe Break}^2)^{1/2}$$

Considering this loading combination and incorporating plant-specific seismic loads, the minimum preload required is 208 kips. This is a 46% reduction from the original design basis, a 54% reduction from the originally specified preload, and a 22% reduction from the absolute sum considering plant-specific seismic loads.

Elimination of Guillotine Pipe Breaks

Since the largest contributing external load to heavy component structural joints is typically a guillotine pipe break, application of the leak-before-break approach to the licensing process would provide the most relief in terms of applied loadings and subsequent preload requirements. The leak-before-break approach requires the application of fracture mechanics technology to demonstrate that high energy fluid piping is very unlikely to experience double-ended ruptures or their equivalent as longitudinal or diagonal splits. For the evaluation of the reactor coolant pump clevis joint, it was assumed that the leak-before-break approach has been applied and that 10% of the original loss of coolant accident load remains to envelope other large dynamic loads such as double-ended guillotine breaks in tributary piping. It should be noted that modification of the double-ended guillotine break design bases for components, piping and their supports will require some effort. Considerable efforts have been expended to eliminate pipe whip restraints, asymmetric reactor pressure vessel loads, jet impingement loads and reactor cavity overpressurization that result from postulated double-ended guillotine breaks (10). For the specific joint considered, an SRSS combination of pipe break (10% of the presently defined pipe break load) and plant specific SSE added to thermal and dead weight would reduce the required minimum preload to 80 kips per bolt. This is an 82% reduction from the originally specified preload and a 62% reduction from the original SRSS loading combination.

In order to provide a base of reference, the preload required considering pipe break loads to be zero and only the effects of dead weight, thermal, and plant specific SSE is 40 kips per bolt or approximately 10% of the originally specified preload. Establishing minimum preload requirements based on maintaining joint stiffness for only the effects of dead weight, thermal, and SSE without applying a leak-before-break approach to eliminate double-ended guillotines may be possible. A nonlinear system analysis considering stiffness variations in a separating joint would be required to determine and evaluate pipe break effects for both components

and supports. Favorable results from these evaluations and analyses could justify preload specifications based only on normal and safe shutdown earthquake loads.

Table 5-1 presents a summary of acceptable minimum preloads. Note that the minimum required preloads discussed above are exclusive of relaxation effects. Both long-term and short-term relaxation effects should be considered, as discussed later in this section.

MAXIMUM ACCEPTABLE PRELOADS

An estimate of maximum acceptable preloads can be determined by assessing the potential for stress corrosion cracking. When coupled with the minimum required preloads, an acceptable preload range can be determined. The magnitude of the range impacts the feasibility of preload reduction and defines the required precision of preload reduction techniques.

The potential for stress corrosion cracking (SCC) can be minimized by assuring that long-term applied loads are sufficiently low that crack growth to critical length will not occur for any defects that may be present. In assessing the potential for SCC under long-term loading (preload), important parameters in the analysis are the depth of the reference flaw that is postulated, material resistance, applied stress (preload) and the expected service environment. Acceptable preloads that will not cause SCC can be determined by satisfying the condition that

$$K_I < K_{ISCC} \quad ,$$

where K_I is the applied stress intensity factor for a postulated flaw and K_{ISCC} is the threshold level below which subcritical crack growth will not occur.

For the clevis joint evaluated in detail, four different criteria for determining an acceptable long-term stress were employed. The first three criteria were suggested by the NRC (5,6,9) while the fourth was developed as a result of industry efforts for the AIF/MPC Task Group on Bolting (7).

1. $K_{ISCC} = 2.1\ (\sigma)\ (\text{BOLT DIA.}/10)^{1/2}$
2. $K_{ISCC} = 2.1\ (\sigma)\ (\text{Thread Depth} + 0.05)^{1/2}$
3. $K_{ISCC} = 2.1\ (\sigma)\ (\text{Thread Depth} + 0.02)^{1/2}$
4. $\sigma_a^{scc} = C_k\ \bar{K}_{ISCC}$

For the first three critical criteria, σ is the preload or steady state stress while the term in the radical represents a postulated flaw size. K_{ISCC} is defined as a function of yield stress (5). A detailed discussion and evaluation of the NRC proposed criteria is found in Ref. (11). The minimum specified yield stress for ASTM A-540 Class 4 (120 ksi) was used to determine K_{ISCC}. The allowable preload was then determined from:

$$\text{Maximum Acceptable Preload} = \sigma A_S,$$

where A_S is the net tensile stress area of a 3-inch diameter 4 thread/inch bolt.

For the fourth criterion σ_a^{scc} is the allowable steady state stress, C_k is a flaw factor and $\bar{K}_{ISCC}$ is a lower bound K_{ISCC} at maximum material hardness. C_k is the reciprocal of the applied stress intensity factor for a unit applied stress based on a reference flaw at the root of a thread with a depth of 0.01 inches and a flaw aspect ratio of 1/2. $\bar{K}_{ISCC}$ was determined based on data collected from the literature for environments involving water, aqueous solutions of NaCl and sea water and are presented as a function of hardness in Ref. (7). These environments are viewed as being representative of the plant environments for structural bolting. In determining the maximum allowable preload for the clevis joint, a hardness of 352 BHN (R_c38) was used to determine $\bar{K}_{ISCC}$. The hardness range allowed by the material specifications for the typically used bolting materials (A-540 Class 4 and A-354 Grade BD) is 277 to 352 BHN (28.8 - 38 R_c).

Table 5-2 summarizes the maximum acceptable preloads. For the bolts evaluated, it is evident that the originally specified preload (450 kips) exceeds the maximum acceptable preload of the first criterion. With a minimum amount of analytical effort (NUREG-0484 load combinations) to determine the minimum required preload, a significant range of acceptable preload exists (208 to 375 kips) even considering the most severe stress corrosion cracking criteria.

PRELOAD TECHNIQUES

There are four methods commonly used to preload studs similar to the RCP clevis studs: (1) torque, (2) turn-of-nut, (3) hydraulic tensioning, and (4) stretch control. Each of these methods relies on different physical principles for developing the preload and controlling it. To estimate the preload accuracy for each of these methods, the following factors must be considered:

- Nominal Preload
- Tool Accuracy
- Operator
- Preload Control
- Short Term Relaxation
- Long Term Relaxation

These factors are discussed below:

- Nominal Preload - Depending on the assembly method, the nominal preload is usually specified as: residual load, torque, stretch, tensioner pressure or an angle of turn.

- Tool Accuracy - The output of high torque tools and hydraulic tensioners are subject to a number of errors, including: calibration error, gage error, variance of the pressure controlling device.

- Operator - The human element is important in preloading joints. This aspect of the joint assembly is often overlooked; consequently, there is wide latitude for error. EPRI Report NP-2174, "A Study of Bolting Tools and Practices in the Nuclear Industry" discusses the influence of human factors on bolting.

- Preload Control - Controlling the preload requires a measurement of some quantity related to the preload: torque, turn, tensioner pressure, or stretch. The control process employed has a significant impact on the preload achieved. Normally the control is exercised on the input to the process, as is the case when preload is controlled by torque, turn, or hydraulic tensioning. Stretch control, however, exercises control by measuring stretch after the load has been applied; therefore it controls the output of the process, rather than the input.

- Short Term Relaxation - During the joint makeup and shortly thereafter (within 24 hours), the preload in the fasteners changes. The changes are caused by the yielding of highly loaded surface irregularities of threads and other bearing surfaces, which tend to reduce the fastener preload.

  The assembly procedure has a major influence on the resulting preloads in the fasteners. Preload in a fastener can change significantly as other fasteners in the joint are loaded, and in some cases it is possible to find "loose" bolts after a complete loading pass has been made on the joint. The short term relaxation was estimated to be 6%.

- Long Term Relaxation - Long term relaxation is loss of preload which occurs over the service life of the assembly. Long term relaxation is any relaxation which occurs after the short term relaxation, and can be influenced by external loads (pressure, temperature, etc.).

The most common forms of long term relaxation are due to stress relaxation of stressed parts at elevated temperature, and for embedded bolts long term concrete creep.

PRELOAD MODELS

As with any process, a suitable model must be developed if output predictions (preload) are to be made from an input, such as torque. The following preload control models can be used to represent the four assembly methods.

Torque

The short form torque-preload model was chosen to characterize the preload developed in a stud when a measured torque is applied:

$$T = \frac{KDF}{12} ,$$

where T is the torque, in ft.lb.; K is a dimensionless nut factor; D is the fastener diameter, in in.; and F is the fastener preload, in lb. A nut factor of 0.15 was used in the torque calculation. The variability of preload resulting from applied torque is well documented and widely debated. Most estimates of the variance are derived from tests on relatively small (less than 2" diameter) fasteners. A common estimate of torque control accuracy is that preloads can be controlled to within ± 30% (2).

Prior to testing, this estimate seemed quite optimistic for 3" diameter studs, set in concrete and loaded to 450,000 lb. It was expected that all the factors which operate causing preload variance in the smaller sizes would be magnified by the increased size and loads causing greater preload variation.

Hydraulic Tensioning

Hydraulic tensioners are widely used to preload large threaded fasteners greater than 1 1/2" diameter. Many believe that tensioners provide near perfect preload control since the tool's hydraulic ram exerts a controlled and accurate tensile force on the fastener while hydraulic pressure is applied. Unfortunately, however, the fastener does not retain all of this load when the tensioner is removed. This loss of load is accounted for by use of the "tensioner efficiency".

Tensioner efficiency (ξ) may be defined as the residual preload (F) divided by the tensioner load (F_t).

The loss of preload during tensioning is actually a decrease of stud elongation as the tensioner load is transferred from the tensioner base to the nut after the nut is run down and tensioner hydraulic pressure is released. Tensioner efficiency is generally a function of the length to diameter ratio (L/d). Longer studs have higher efficiency; since the loss of stretch as a percentage of the overall stretch is lower than for a shorter stud. For this configuration a tension efficiency of 78% was expected.

Stretch

"Measurement of bolt stretch is an accurate indicator of preload, provided the actual stretch is measured and the measurement is made with sufficient precision" (2). This statement is generally accepted, and its validity is evidenced by the use of stretch measurements to control preload in the most critical assemblies of a power plant, for example the reactor pressure vessel head.

When using stretch measurements to control load, it is assumed that the load is uniaxial, and that the material behaves elastically.

$$\Delta L = \frac{F}{E} \Sigma_i \; L_i/A_i \quad ,$$

where ΔL is the stretch of the fastener; L_i/A_i is the length-area fraction of various portions of the stud, body, etc.; and E is the modulus of elasticity.

Turn-of-Nut

The simple lead screw equation was used to model this process.

$$F = \frac{\alpha P}{360} \times \frac{E}{\Sigma_i \; L_i/A_i} \quad ,$$

where α is the turn-of-nut angle and P is the thread pitch. This model assumes that the joint components are infinitely stiff which allows all the turn to result in fastener stretch (i.e., none of the turn is lost to compression of the joint members). The model also neglects the effect of the snugging torque, which is normally applied before the turn angle is measured.

PRELOAD ESTIMATES

Preload estimates for the four assembly methods were developed by Looram (8) and Veneziano (see Section 4, Volume 2). These estimates considered the influence of the six factors discussed above. The estimates were very sensitive to the selection of friction, efficiencies and relaxation effects for the preload models. Unfortunately, there is little information available to aid in making these estimates; therefore, many of the estimates were based on extrapolation from test data on smaller fasteners and on engineering judgment.

Table 5-3 compares the estimates of preload mean and coefficient of variation to the full scale mockup testing results. Estimates were not made for turn-of-nut, since the available data showed extremely poor correlation with the proposed model.

TESTING PROGRAM

The preliminary objective of the test program was to validate the proposed preload estimation process and the preload models. In addition, techniques to determine existing preloads and to de-tension to lower preloads were investigated. The testing employed a 4"-thick clevis installed on a test block as shown in Figure 5-2. The studs are 3" in diameter with a grip length of 62.6" and were nominally preloaded to 450 kips. The following describes the test procedures and results.

Stretch Control

An ultrasonic extensometer was used to measure the preload in the studs for all tests. The transducers were left in place and the stretch monitored as the studs were being loaded from the clevis side of the joint. The stretch (i.e., the preload) developed by the tool was measured immediately, and this gave a measure of the tool performance. After a complete loading pass around the joint, the stretch in each stud was measured again. This second measurement showed the load relaxation which occurred due to elastic interactions as the joint was tightened. The stretch-load relationship was verified by measuring the stud stretch while a calibrated tensioner was pressurized to a known load. The average stretch was found to be within 1.5% of the expected value.

Torque

A 25,000 ft. lb. torque wrench was mounted on the clevis, and a reaction bar provided a 20,000 lb. reaction load for the wrench. Figure 5-4 shows the results of four successive loading sequences numbered 1 to 4. Each loading sequence included:

- Application of FelPro N5000 lubricant to the threads and the nut bearing surface.
- The torquing sequence was done in two passes: the first at 50% of target, and the second at 100%.

It is evident that the preload achieved for a given torque decreases when the nut and stud were reloaded. The nut factor (K) for sequence 1 was 0.16, which is approximately as expected. By sequence 4, the average nut factor had climbed to K = 0.238. One nut galled during sequence 4. All this occurred in spite of the fact that the studs were re-lubed before each sequence.

Tensioners

On average, the residual preload after nut run-down and release of tensioner pressure was 80% of the tensioner applied load. The tensioner was 80% efficient. There was an 11% incidence of low preload (almost zero) after tensioning. This was caused by an insufficient nut run-down. The residual load can approach zero if the nut is not run down due to oversight, the nut binds on the stud threads, or interferences with the tensioner body.

Turn-of-Nut

The turn-of-nut procedure with lubricated studs produced surprisingly accurate preloads as shown in Figure 5-5. The scatter in preload was essentially the variation in the preload caused by the snug torque which was applied prior to measuring the angle of turn. The 5,000 ft. lb. snug torque is considered high, being equivalent to approximately 30% of the nominal preload. Using an uncontrolled, low run-down torque such as the full effort of a man on a manual wrench may result in lower and more scattered preload.

A turn-of-nut test was performed with the studs and nuts "clean and dry". The turn/preload relationship was linear and the scatter similar to lubricated studs; however, twice the torque was required. The thread flank and nut bearing surfaces were badly damaged during this test, and the nominal preload was never reached. The sounds of the bearing surfaces being destroyed were quite distressing, and it is doubtful that any mechanic would persist in torquing under these conditions.

Grouted Stud

Two mock-ups were tested: one with a grout tube which prevented contact between the concrete and the stud; the other without the grout tube. The effect of the

latter configuration (concrete contacting the stud) on the stretch/load relationship is shown in Figure 5-6. The concrete bond was capable of resisting approximately 100,000 lb. tensile load. There is a distinct change of slope of the stretch versus load plot at 100,000 lb. This load was confirmed on one stud by backing the nut off from the backing plate and monitoring the tensioner load required to pull the nut into contact.

Below 100,000 lb. the stretch-load relationships appear nonlinear, which indicates that the effective stressed length is changing. At a load of 350,000 lb. the bond has a 6% effect on the stretch. The bond exhibited the same characteristics each time the stud was loaded even after a turn-of-nut test during which the stud was observed to turn approximately 15° relative to the concrete.

Determining the Preload in Previously Loaded Studs

Lift-Off Method. A tensioner was used to pull on the stud until the nut lifted free of the joint. This method gave an estimate of preload with ± 6% of the actual load.

Ultrasonic Stretch. The ultrasonic extensometer was used to monitor the slope of ultrasonic stretch versus tensioner load as the lift-off test proceeded (Figure 5-7). The change of slope gave an estimate of preload with ± 6% of the actual preload.

The stretch recovered as the studs were unloaded and was measured ultrasonically. The accuracy of this method was estimated to be ± 2.5%.

Restart Torque, Breakaway Torque. These two methods of measuring existing preload were not indicative of field conditions, since they were performed immediately after make-up. Years of corrosion and exposure to high temperatures would have serious effects on the validity of determining preload by these methods.

Adequacy of Preload. Veneziano (see Section 4, Volume 2) developed a method of calculating the expected range of preload (R_u) developed at assembly. The estimated range was then compared to the design criteria in order to access the adequacy of the preload. Figure 5-8 illustrates the process, showing the acceptable preload range, the estimated preload range, and the action required. The process lends itself to a sequential sampling approach. The first step is to

estimate the preload using installation documentation and appropriate preload models. If the review fails to demonstrate adequate preload, then preload testing must be accomplished to refine the preload estimate and to determine a course of action.

Illustrative Example. As an illustrative example, the expected preload in the RCP clevis studs is evaluated for the four preloading methods: torque, stretch control, hydraulic tensioning, and turn-of-nut. The estimated preloads are evaluated against an appropriate criteria.

Preload Criteria. The preload criteria for this example is established by selecting appropriate criteria from Tables 5-1 and 5-2. The NUREG-0484 criteria, 208 kips, is chosen as the lower limit of acceptable preload. The maximum acceptable preload is set at 644 kips using the AIF/MPC stress corrosion cracking criterion (criterion 4 of Table 5-2).

The nominal preload was taken as the design basis 385 kips. This was the target preload used in calculating the preload control quantities (torque, tension stretch or turn) used at assembly. The acceptable preloads were expressed as a fraction of the nominal preload and are shown as dashed vertical lines on Figure 5-9. The lower limit was 53% of nominal, and the upper limit was 167% of nominal.

Preload Estimates. Preload estimates for the assembly methods are found in Table 5-3. The left side of Table 5-3 shows the information which was available prior to testing. These estimates resulted from considering the preloading process and were used to specify the assembly torque, tensioner load, stretch and angle of turn used in the testing. As an example of how these pre-test estimates were used, consider the tensioner. The left side of Table 5-3 suggests that the residual preload will be 71.5% of the applied tensioner load. The assembly tensioner load should then be specified 29.5% higher than the desired nominal value. This over-tensioning will compensate for tensioner efficiency and other relaxation effects resulting in a preload at the desired nominal level.

The right side of Table 5-3 shows the estimates of the preload mean value and coefficient of variation calculated from the test results. In order to illustrate the test results on Figure 5-9, the mean values are normalized relative

to the pre-test estimates, i.e., each mean is divided by its corresponding pre-test estimated mean. The preload variability is illustrated by the length of the line for each method. The total length of the line is 4.0 times the coefficient of variation or ± 2 coefficients of variation on either side of the mean.

CONCLUSIONS

Design Criteria

The generally observed design criteria of preloading to an extent to preclude joint separation for the worst case loading conditions should be employed.

Load Relief

Significant loading relief is presently available to reduce minimum required preloads. These include removal of conservatisms, use of plant specific seismic loads, and NUREG-0484 load combination. Reduction in the minimum preload required from these sources for the joint evaluated in detail was 54% of the originally specified preload. Further reduction in minimum preload is available by pursuing the elimination of guillotines (leak before break). For the reactor coolant pump clevis joint, the elimination of guillotines would result in an 82% reduction of the originally specified preload.

Acceptable Preload Range

An estimate of the acceptable range of preload was obtained by determining the maximum acceptable preload based on various SSC criteria and comparing these values to the minimum required preloads. Figure 5-3 presents these ranges in terms of percent of yield strength.

Preload Estimation

A method of estimating preloads was proposed and demonstrated. The test results were in close agreement with the estimates (Table 5-3).

Adequacy of Preload

The preload results from the test program were compared to a set of design requirements (Figure 5-9). The stretch, torque, and tensioner assembly methods fall comfortably within the required range at the 95% confidence level. The turn-of-nut

method violates the criteria on the low end. The major factor controlling the accuracy and precision of the turn-of-nut method is the uncertainty of the snug torque.

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11. Aptech Engineering. "Requirements and Guidelines for Evaluating Component Support Materials under Unresolved Safety Issue A-12." EPRI NP-3528, June 1984.

Table 5-1

SUMMARY OF MINIMUM ACCEPTABLE PRELOADS

Load Condition	Load (kips)	% Yield
Design Basis[1]	385	54
Plant Specific SSE[2]	266	37
NUREG-0484[3]	208	29
Elimination of Guillotines (10% Pipe Break)[4]	80	11
No Pipe Breaks[5]	40	5.5

Notes:

1. Dead Weight + Thermal + Generic SSE + Pipe Break
2. Dead Weight + Thermal + Plant Specific SSE + Pipe Break
3. Dead Weight + Thermal + $((\text{Plant Specific SSE})^2 + (\text{Pipe Break})^2)^{1/2}$
4. Dead Weight + Thermal + $((\text{Plant Specific SSE})^2 + (\text{10\% Pipe Break})^2)^{1/2}$
5. Dead Weight + Thermal + Plant Specific SSE

Table 5-2

MAXIMUM ACCEPTABLE PRELOADS

Criteria	Load (kips)	% Yield
1	375	52
2	456	64
3	493	69
4	823	115*

*Criterion 4 results in a value of maximum acceptable preload in excess of yield. For standard engineering practice, this value would be limited to 90% of yield.

Table 5-3

PRELOAD ESTIMATES AND TEST RESULTS

	Pre-Test Estimates		Test Results	
	Mean	Coefficient of Variation	Mean	Coefficient of Variation
Torque	94%	11%	94%	14%
Stretch	100%	1.9%	96%	5%
Tensioner	71.5%	8.6%	77.1%	16.8%
Turn-of-Nut	-	-	68%	14%

Notes: All values expressed as a percentage of the nominal preload.

No estimates were made for turn-of-nut.

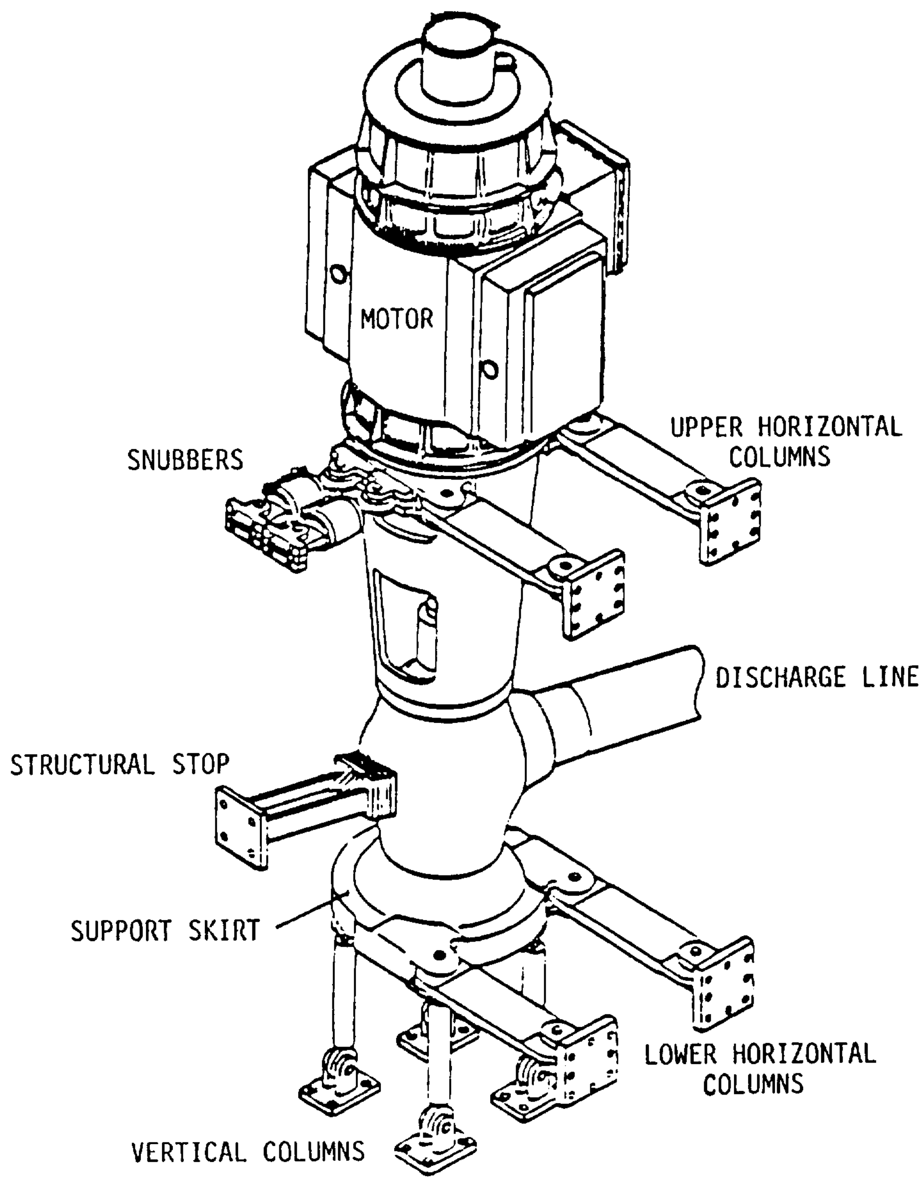

Figure 5-1. Reactor Coolant Pump and Supports

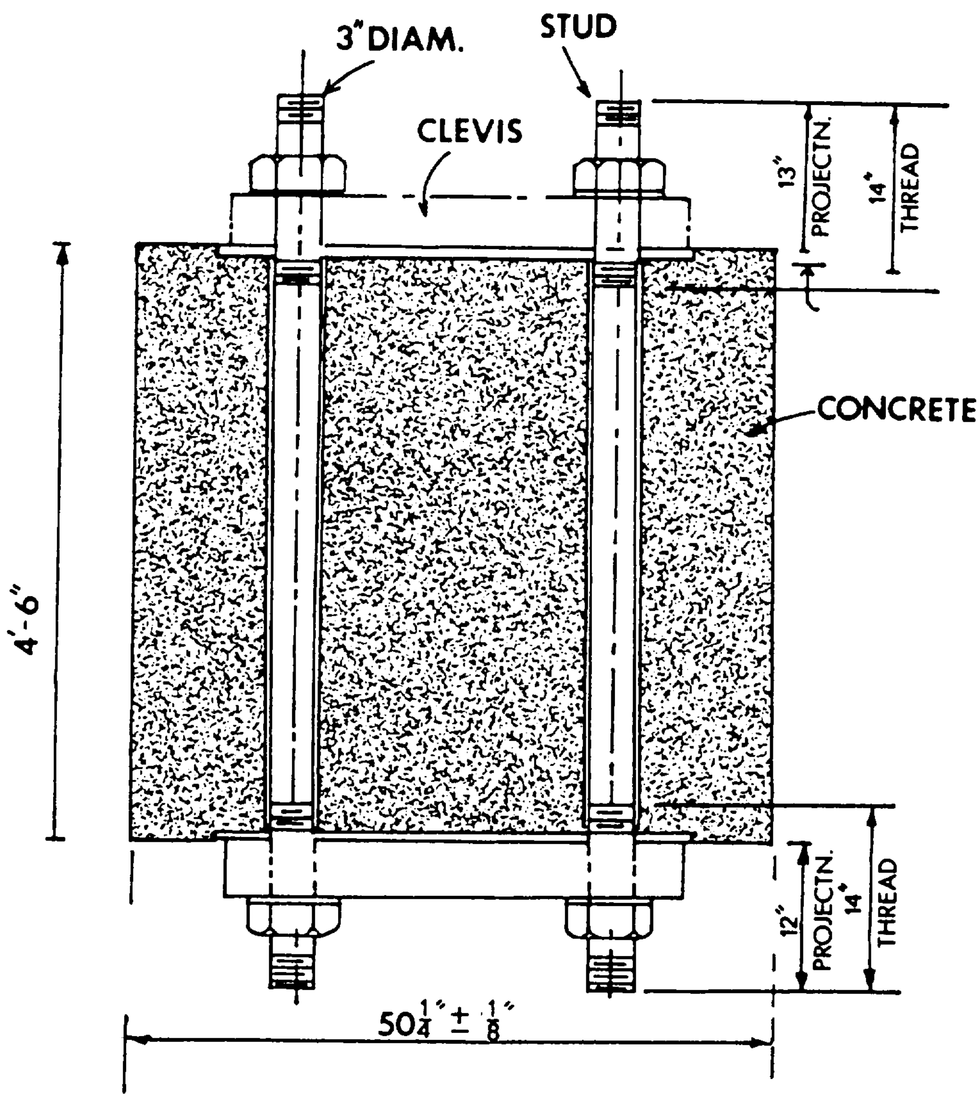

Figure 5-2. Configuration of Support Clevis Test Bed

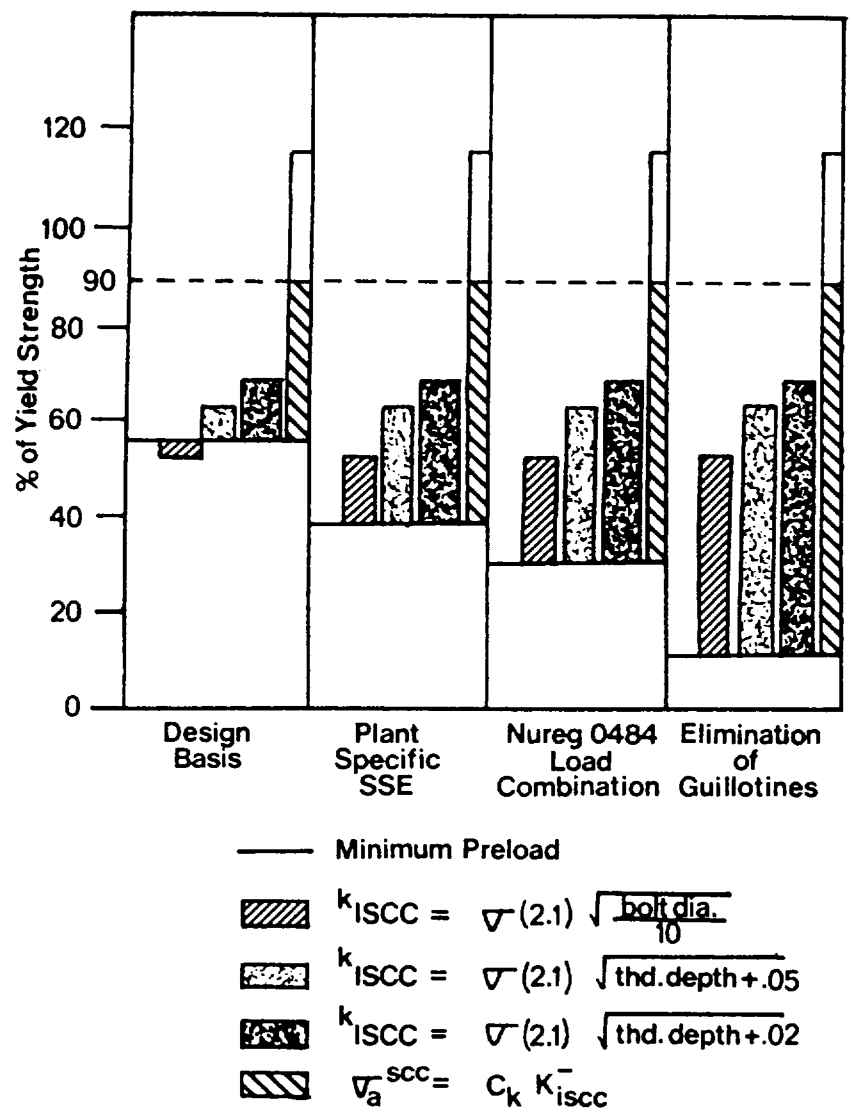

Figure 5-3. Bolt Stress Summary for Heavy Component Structural Joint

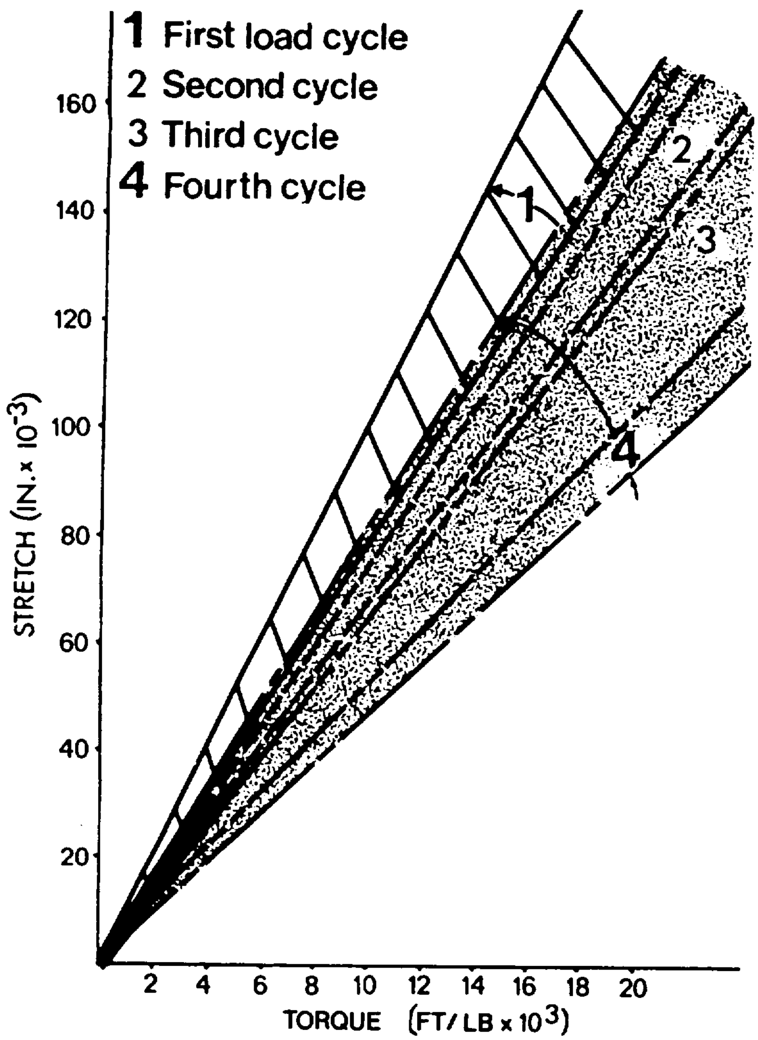

Figure 5-4. Torque Results

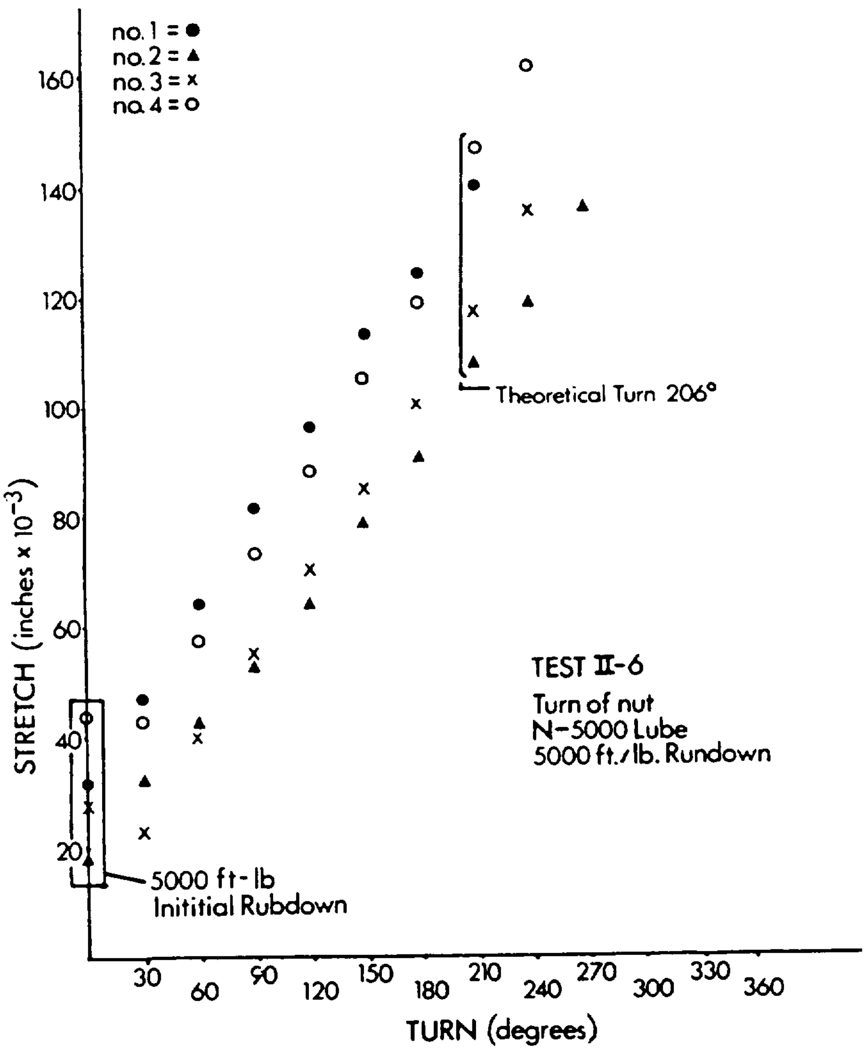

Figure 5-5. Turn-of-Nut Method Test Results

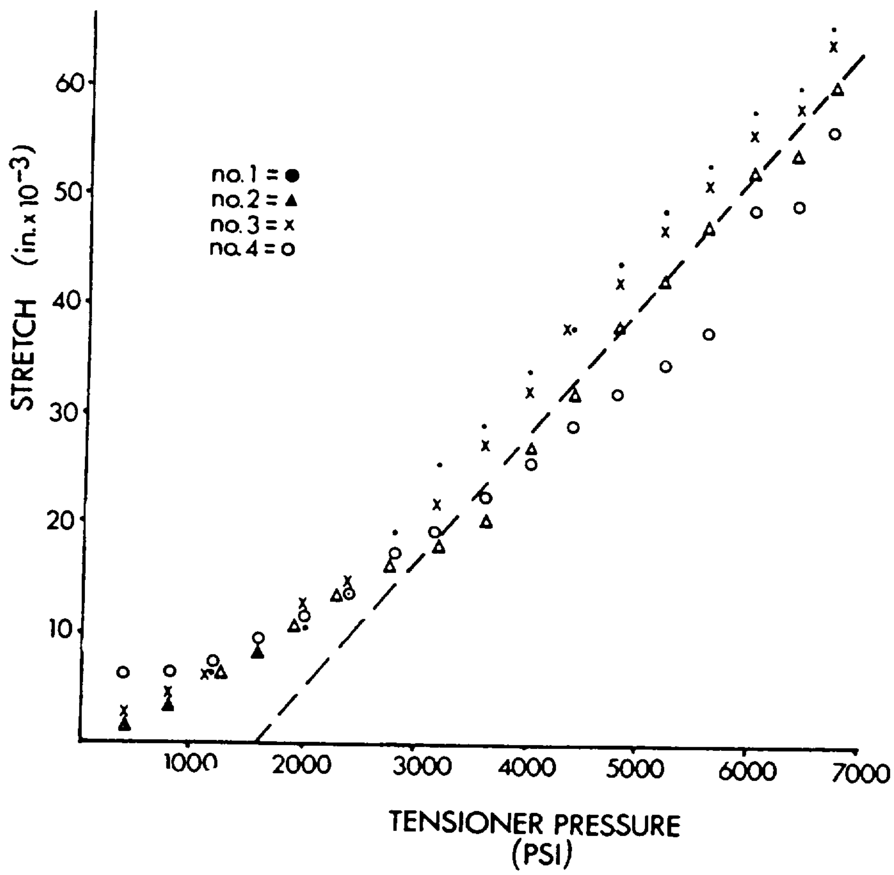

Figure 5-6. Stretch Versus Tensioner Pressure for Grouted Studs

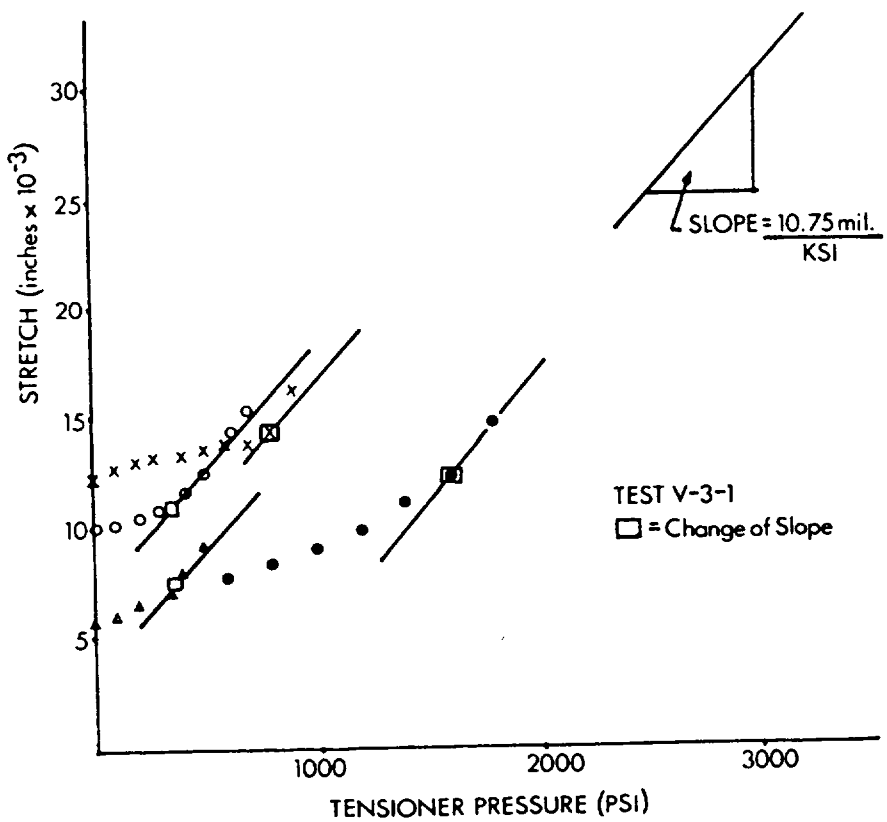

Figure 5-7. Stretch Versus Tensioner Pressure During Liftoff Test

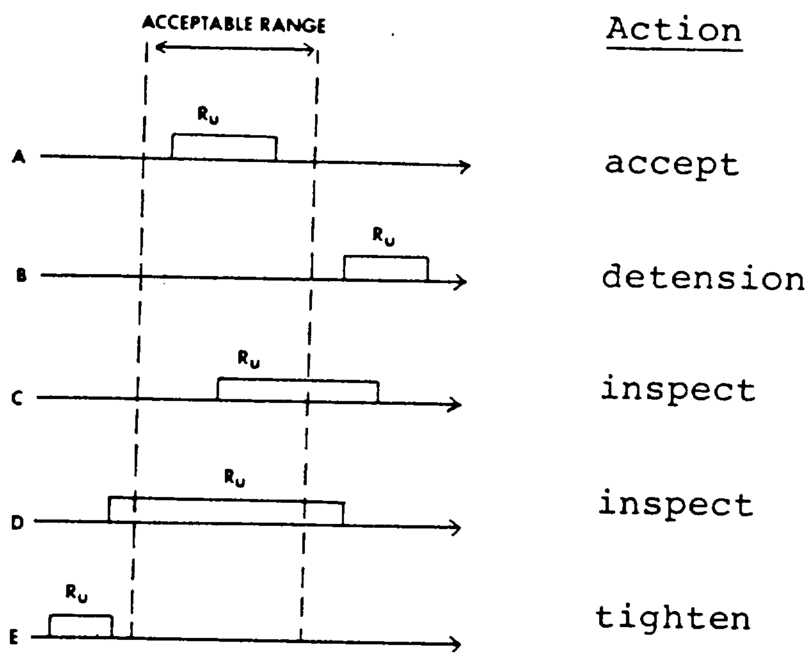

Figure 5-8. Acceptable and Unacceptable Range of Preload Estimates

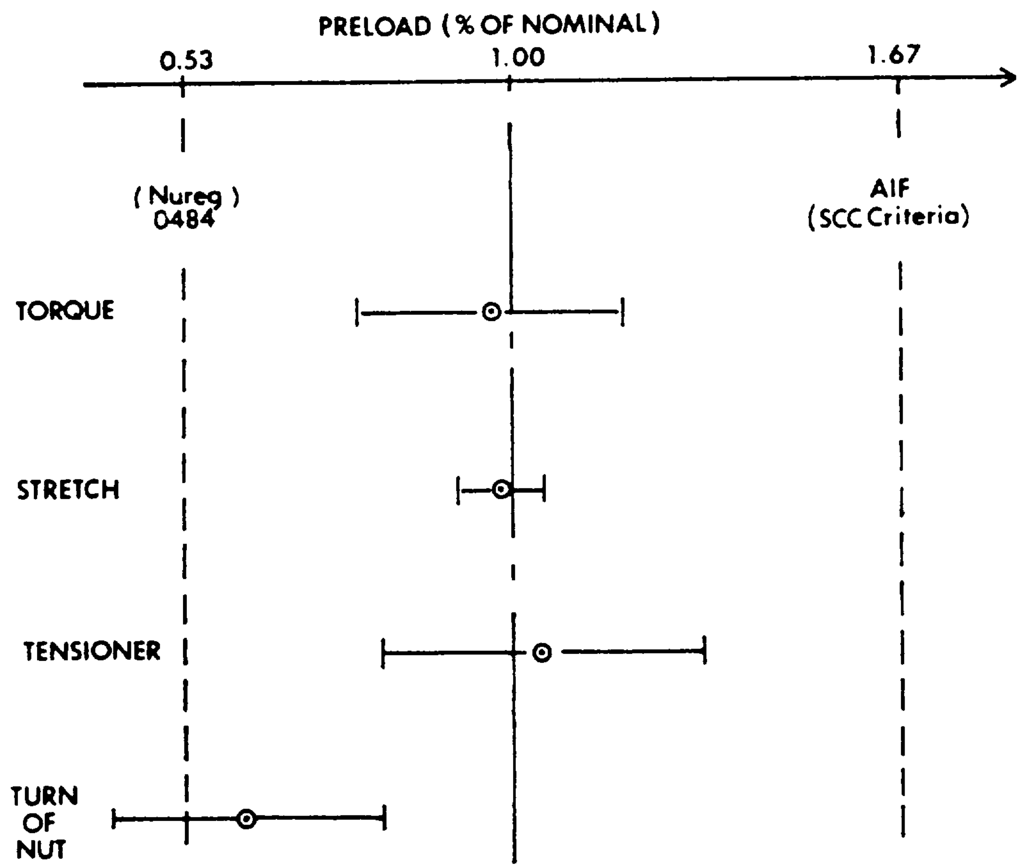

Figure 5-9. Preload Estimates from Test Results and 2X Coefficient of Variation

Section 6

THE BOLTING DATABASE: AN EXAMPLE OF A NUMERIC DATABASE APPLICATION IN THE NUCLEAR POWER INDUSTRY

The AIF/MPC Task Group on Bolting has developed a database termed BOLTS which contains a large body of data on the bolting in nuclear power plants. The data has been installed within a computer database system which permits ready access and study. The types of data and the software available for its access and analysis are described. Examples of applications to resolve issues related to plant operation are given.

INTRODUCTION

Tennessee Valley Authority (TVA) was one of twenty-six utilities that provided input to BOLTS, a database system developed by Materials Research and Computer Simulation under the sponsorship of the Electric Power Research Institute (EPRI). The input included material property data (e.g., yield strength, ultimate tensile strength, chemical composition, hardness, Charpy impact energy, lateral expansion, etc.) obtained from certified material test reports (CMTR) on the support bolting materials. In addition, TVA sent field hardness measurements of support bolts for input into the BOLTS database.

STORING THE BOLTS DATA

The information in the BOLTS database is broken down into two categories: keys and data. Keys are sets of information that help describe and differentiate between different groups of data. Data is the numerical or textual knowledge associated with a particular set of keys. For the BOLTS database, ten keys are used. These denote important metallurgical and engineering features: the source of the bolting data, the plant containing the bolt, the location within the plant, the ASTM/ASME material classification, the AISI classification, the manufacturer, the melting practice used, the failure type (if any failure was noted), a unique heat number, and the data test type performed on the bolt. The data contains the results of Charpy, tensile and hardness tests, chemical analysis and general bolt descriptions, such as installation date, size, and number of bolts. Heat treatment and

miscellaneous information is also included in textual form. The database contents are shown in Table 6-1.

DATABASE ACCESS

Access to the data is by means of a menu-driven user interface. Use of the database is facilitated by a user manual (1), data catalogues, and by an extensive HELP facility.

DATABASE SOFTWARE

In normal database operations, ease of use has primary importance. One of BOLTS strengths is that the database contains an expansive, three-level software interface that buffers the user from the raw data (see Figure 6-1). This software provides for the menu-driven requests, the help facilities, and the many options for extracting, printing, and plotting the data.

In addition, statistical analysis is well supported, permitting correlations and regressions to be developed. Figure 6-2 illustrates a typical application, showing in histogram form a summary of the distribution of all of the Rockwell hardness data contained in the database.

APPLICATION OF THE DATABASE

The database has been accessed by utilities to aid in scoping the bolting issues and in the resolution of various plant-specific problems. For example, a hardness survey of support bolting was conducted by TVA to provide a "random data point" to substantiate conclusions being reached at Consumers Power Company's Midland plant on the material variability of low alloy quenched and tempered bolting. In addition, TVA has been able to resolve questions regarding the integrity of the bolting materials at its Watts Bar and Bellefonte nuclear plants using the bolting data stored in the BOLTS database.

At Watts Bar, the low-alloy quenched and tempered support bolting materials' resistance to stress corrosion cracking was assessed. Random sampling field hardness measurements were taken of the support bolts and the results were sent to MRCS for installation in the database. The bolting hardness data, catalogued and stored in the database, was then analyzed by TVA using the statistical software developed by MRCS for the BOLTS database. Each heat of material was analyzed, and the mean and standard deviation were computed using the BOLT EXTRACT Program. The

plotting capabilities of the BOLT EXTRACT Program were used to construct histograms of each heat of material. Confidence bounds for each heat were calculated and compared to the material specification hardness requirements. If the confidence bounds for a specific heat fell within the material specification hardness requirements, the material was considered to be resistant to stress corrosion cracking and fit for service.

At Bellefonte, a non-conformance report was written addressing the concern of ultra-high strength reactor coolant system support bolting material (150 ksi minimum yield strength, specified) being susceptible to stress corrosion cracking. A decision was made to review the certified material test reports of each heat of material against a screening criteria adopted by the AIF/MPC Task Group on Bolting. A review of the various materials used for support bolting applications identified SA540 Grade B24 Class 1 bolting material as the only material with a specified yield strength of greater than or equal to 150 ksi.

The CMTR review determined if the hardness, yield strength, ultimate tensile strength, and chemical analysis results conformed to the material specification requirements and the mils lateral expansion results exceeded 25 mils.

The BOLT EXTRACT Program of the BOLTS database was used to locate all heats of SA540 Grade B24 Class 1 material. For each heat identified, the hardness, yield strength, ultimate tensile strength, chemical composition and mils lateral expansion results were printed. These results were compared to the material specification requirements for hardness, yield strength, ultimate tensile strength, and chemical composition. The mils lateral expansion results were compared to the 25 mils minimum requirement. The results of the comparisons indicated that the material was resistant to stress corrosion cracking and fit for service.

SUMMARY AND DISCUSSION

The successful application of numeric database techniques to the construction of nuclear power plants has been described. The essential elements are unambiguous identification of data (keys were used in this application), the storage of useful data, and the availability of a suitable software package.

While databases may not be a panacea, they do provide a basis for the establishment of important facts concerning material properties, permitting modeling of power

plant operations, and pointing out potential areas for failure. The relatively low cost of such a technical management tool, when compared to the enormous costs of failure or even unscheduled shutdown, suggest that similar databases should be used to make all important data available to technical personnel. Since key decisions rest on the integrity of the data, only high quality data should be contained within a database. Fortunately, normal database management procedures provide a sophisticated quality assurance scheme to verify the validity of the data. This makes databases superior to individual collections of data.

In our experience, database development is only begun after a serious problem has emerged. This diminishes a database's effectiveness. Instead, the database should be an integral part of a plant's routine operation, where engineers can access information at a moment's notice.

REFERENCES

1. "BOLTS Database User Manual." Materials Research and Computer Simulation, Inc.

Table 6-1

LAYOUT OF BOLTS KEYS AND DATA

Keys

1. Source
2. Location
3. Material
4. Reactor
5. Heat
6. Manufacturer
7. Failure Type
8. Melt Practice
9. Data Type
10. Steel Type

Data Description

Item Size, Diameter, Length Thread Size, Number of Bolts, Years, Preload

- Hardness: Item Number, R_C, BHN
- Charpy: Item Number, Temperature, Energy, LE, % Crystallinity
- Tensile: Item Number, Temperature, YS, TS, RA
- Leeb

Text

- Miscellaneous Information
- Heat Treatment

Chemistry

- Chemistry Content

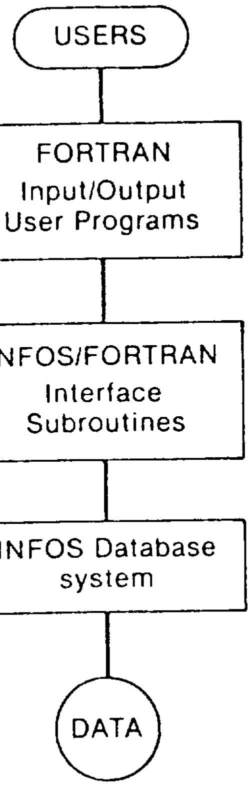

Figure 6-1. Structural Breakdown of the BOLTS Database

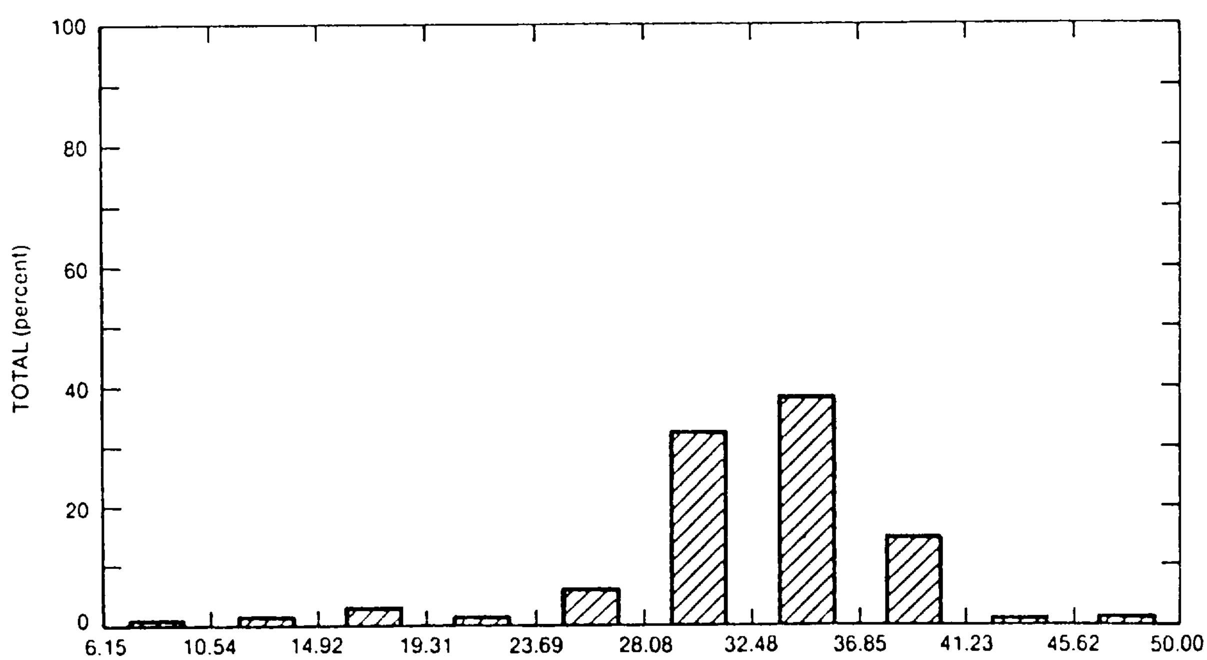

Figure 6-2. Histogram Showing the Distribution of Rockwell C Hardness Over the Database, Produced by the BOLTS EXTRACT Program

Section 7

ASSESSMENT OF FIELD HARDNESS MEASUREMENTS ON LOW ALLOY QUENCHED AND TEMPERED BOLTING MATERIALS AT MIDLAND

BACKGROUND

Failures of structural bolting used in component supports have been reported by several nuclear power plants (1). In most cases, the failure events have been attributed to stress corrosion cracking (SCC); however, there have also been a few minor events reported where bolts have failed during installation by tensile ductile overload related to an understrength material condition. A common feature of the failures by SCC is that either ultra-high strength maraging steels or unintentionally hard low alloy quenched and tempered (LAQT) materials were used in moist environments under high sustained tensile stresses. A key observation is that some materials were above the specified maximum hardness, and it is known that SCC susceptibility of these materials increases with increasing strength. Although LAQT steels are also susceptible to hydrogen embrittlement, especially if electroplated, none of the failures involved plated fasteners; thus hydrogen cracking without an electrolyte is not a contributing factor to the failures.

The variability in strength of certain types of high strength bolting materials has been observed to exceed normal expectations for products fabricated to American Society for Testing and Materials (ASTM) specifications. Because of such behavior, several utilities have studied their procurement practices for safety-related bolting as well as the mechanical behavior and metallurgical condition of actual material received at the plant. The bolting materials under scrutiny are large diameter (i.e., products that are 1 inch or 2.5 cm and greater) and are fabricated from low alloy quenched and tempered (LAQT) steels. These bolting materials are primarily used as threaded fasteners in Class 1 component supports either as structural connection bolting or as embedded anchors.

The information generated by the owners of the affected plants is of the form of hardness measurements made on the ends of individual fasteners. In most cases, the measurements were made in situ on fasteners already installed, although some

hardness information was generated on surplus bolting stored at site warehouses. Because of the desire to obtain field data, the majority of the hardness measurements were made with portable hardness testers.

SCOPE AND OBJECTIVES

The purpose of this assessment is to evaluate the available field hardness information in order to obtain insight into the observed problems associated with LAQT bolting materials and to provide a quantitative basis for possibly exempting material from generic review. A screening procedure for component support bolting has been proposed (2) with bolting materials in the range of 120 ksi to 150 ksi (827 MPa to 1034 MPa) specified minimum yield strength (S_y). Objectives of this investigation are:

1. To assess the proposed screening limit of $S_y \leq 150$ ksi (1034 MPa) as an acceptable cutoff point for the generic issue
2. To establish trends in hardness (strength) in terms of bolting characteristics, such as purchase specification requirements, product size, etc.
3. To identify the important parameters that affect surface hardness variability

Statistical methods of analysis are used to determine the mean and variance of bolting material groups. The degree of variability in surface hardness is equated with SCC susceptibility so that the observed variability, in terms of probability of exceeding some stated hardness limit, can be used to rank bolting materials by their propensity to be out of specification.

It is expected that the results from these assessments will provide the basis for defining the scope of the bolting problems with regard to support bolting and aid in the resolution of bolting integrity issues.

DATA COLLECTION

Data Sources

Midland Field Data. As part of their commitment to the Nuclear Regulatory Commission to review safety-related low alloy, an extensive field testing program was performed by Consumers Power Company (CPCO) on field purchased LAQT bolting materials. Fasteners 0.875 inch (2.2 cm) and greater were tested with a portable hardness tester, specifically an Equotip Model D. The testing program comprised about

a 10% sample of different civil/structural and mechanical applications as summarized in Table 7-1. The governing civil design was according to American Institute of Steel Construction Code, while the mechanical design was according to American Society of Mechanical Engineers (ASME) Code. All applications were related to structural supports or flange bolting in both units with the specific uses either being connection bolts, embedded anchors, through anchors, pins (unthreaded), or threaded hanger rods. The sizes ranged from 0.874 inch (2.2 cm) to 8.25 inches (21 cm) in diameter and lengths ranged from approximately 3 inches (7.6 cm) to 70 inches (178 cm).

At least five hardness measurements were made on the end of each bolt in the sample. At least one measurement was made in each of the three regions on the bolt end; the specific locations were the center, mid radius, and near edge positions on either the bolt head or on the exposed end of studs. The hardness data and corresponding engineering information were maintained on computer files by Science Applications, Inc., (SAI) for statistical analysis and evaluation for CPCO (3). These data were made available to Aptech Engineering Services, Inc. (APTECH) for use in this research project for evaluating trends with respect to size and material specification.

The materials listed in Table 7-1 were supplied to the site by approximately 26 different suppliers under at least 250 purchase orders. The suppliers of bolting to Midland as contained in the database are listed alphabetically in Table 7-2. The chemistries for all materials complied to a LAQT steel with specified minimum yield strengths ranging from 95 ksi (655 MPa) to 130 ksi (987 MPa). Table 7-3 provides a summary of the chemical requirements. The wide cross section of suppliers, sizes, and strengths makes the Midland database a good candidate for assessing the proposed screening procedure limit of 150 ksi (1034 MPa).

Palo Verde Field Data. Because four 1.5-inch (3.8 cm) diameter studs, which were subcomponents within embed plate assemblies, cracked and separated during normal handling in the field. Arizona Public Service Company (APS) performed extensive field hardness testing at Palo Verde to identify the scope of the problem (4). The studs were supplied to ASTM A354-BD, and the embed assemblies were components of pipe whip restraints used for anchoring to the containment concrete structure. The majority of the ASTM A354-BD material was used in these embed plate assemblies;

however, other affected applications included some containment column holddown studs, polar crane girder holddown bolts, and auxiliary feedwater pump anchor studs.

All installed and accessible ASTM A354-BD fasteners, approximately 4500 fasteners, were field hardness tested with an Equotip instrument. One exception was the polar crane bolting where only 32 out of the 288 bolts in Units 1 and 2 were randomly selected and tested.

Other fastener materials, namely ASTM A307, A325, A540, and A490 bolts and ASTM A194, A325, and A563 Grade C nuts, were sampled for hardness testing. In every case, all samples taken met the specification requirements, and no other actions were deemed necessary. The data for these materials were not reported, so that review by APTECH could not be performed.

Watts Bar Field Data. The Electric Power Research Institute (EPRI) Bolts Data Base contains field hardness data from Watts Bar on some support and pressure boundary bolting. The measurements were made by Tennessee Valley Authority (TVA) field personnel with an Equotip tester following similar procedures used at Midland. As shown in Table 7-4, the support bolting included steam generator, pressurizer, and reactor coolant pump connection and anchor bolting in sizes ranging from 1.0 inch (2.5 cm) to 7.5 inches (19.1 cm) in diameter. A total of 355 support bolts/studs were hardness tested.

The pressure boundary bolting data are from reactor coolant pump main flange and reactor pressure vessel head studs. A total of 225 studs were tested. All materials are LAQT steels supplied to ASTM A490, SA193, or A540 specifications with a small number of stud materials being specified as AISI 4142.

Oconee Units 1 and 2. Also contained in the EPRI Bolts Data Base are Equotip hardness measurements made on primary steam generator manway studs at Oconee, which are 2.0 inches (5.1 cm) in diameter and 13 inches (33 cm) long. The bolting material is ASME SA320-L43, another LAQT steel specification similar to ASTM A540. The number of studs in the data base is 224.

Hardness Measurement Technique

The field hardness measurements were made with an Equotip hardness tester manufactured by Proceq SA, Zurich, Switzerland. The hardness numbers from this instrument

are in Leeb-scale units (L-scale). All test data were recorded as L-scale numbers and were later converted to Rockwell-C according to the manufacturer's conversion table. The hardness testing procedure used by CPCO at Midland involved metal removal of a minimum of 1/16 inch (1.6 mm) from the surface by controlled grinding followed by sanding to at least 120 grit surface finish. The grinding and sanding were required to assure the removal of any surface decarburization and to provide a smooth surface for accurate measurements. The hardness data recorded at TVA and APS units were also performed with an Equotip tester following similar procedures.

The testers used by CPCO were calibrated and tested routinely on a test block of known hardness. Test readings fell generally within a tolerance band of ±6 L-scale numbers. This tolerance band converts to approximately ±0.8 R_C. Hardness measurements made on both test blocks as well as actual bolts/studs with Equotip and Wilson testers gave a larger tolerance when the results of the two testing machines were compared. However, the standard deviation of the difference between Equotip and Wilson instruments was only 1.11 R_C suggesting that good accuracy exists between portable and bench mounted instruments when both types are used properly. Field accuracy has been checked by CPCO on a limited basis when bolts tested fell well outside their expected hardness ranges, and in general, Equotip tester results have been verified as being accurate. Because the Equotip tester relies on the rebound velocity of the heat, any adverse conditions, such as nonparallel or rough surfaces, improper restraint of the bolt, or incorrect placement of the head, will tend to give measurement errors to the soft (low) side.

METHODS OF ANALYSIS

Strategy

The evaluation strategy to be applied to the field hardness data involves sorting and analysis to establish out-of-tolerance behavior for structural bolting materials. A flowchart showing the general procedure is given in Figure 7-1. Because the Midland database is well pedigreed in terms of materials, sizes, and suppliers, these data were chosen for full treatment according to Figure 7-1. Sorting the data requires a computerized system where data sets of common characteristics (materials, sizes, and suppliers) can be formed.

The percentage of bolting that is out of tolerance is established by computing the ratio of numbers of bolts falling outside the specification limits for minimum and maximum hardness to the total number of bolts sampled. The percent of out-of-

tolerance is computed for each material, bolt size, and supplier to determine trends, if any exist. Since for small samples, taking simple percentages may lead to incorrect conclusions, statistical tolerance limits for the population are used to compute the probability of falling outside the specification requirements based on 95% confidence.

For example, it is possible to determine the probability (P) of exceeding the upper hardness limit, H_u, with a stated confidence of 95% from the following:

$$P\ \{P\ \{h > H_u\} > X\} = 0.95 \qquad (7\text{-}1)$$

In Eq. 7-1, X is the computed probability of occurrence for all past and future hardness tests for the given population and is determined by solving Eq. 7-1 for X for the given sample statistical parameters, namely, the sample mean, standard deviation, and sample size. A discussion of this approach follows below.

Statistical Methods

Population Tolerance Limits. The normal distribution statistic was used to estimate the percent of hardness measurements in each population which would be expected to be above and below the specified hardness limits for each diameter and material. In applying the normal distribution, it is assumed that a continuous distribution of surface hardness exists within any given bolt as well as from bolt to bolt. Furthermore, it is assumed that this distribution can be developed from sampling bolt heads and stud ends and that the variability within any given bolt is no worse than the variability observed within the given lot (or stratum) of bolts (a stratum was defined by SAI as a group of bolts where the bolt size and material specification were the same and of similar chemistries but may be comprised of multiple heats). The test for normality was positive for the CPCO bolts (3), so use of the normal distribution to represent the probability density function for hardness is justified. Following the approach for determining population tolerance limits (6), this analysis involved calculation of a K-factor from the given hardness limits as:

$$K_\ell = (\overline{x} - H_\ell)/S \qquad (7\text{-}2)$$

$$K_u = (H_u - \overline{x})/S \qquad (7\text{-}3)$$

where

K_ℓ = K-factor bounding the lower hardness limit

K_u = K-factor bounding the upper hardness limit

H_ℓ = Lower hardness limit

H_u = Upper hardness limit

$\overline{x}$ = Sample mean

S = Sample standard deviation

These one-sided K-factors were then used to calculate the percent population out-of-tolerances above and below the hardness limits according to this sequence of equations:

$$K = \frac{z_p + (z_p^2 - ab)^{1/2}}{a} \tag{7-4}$$

$$a = 1 - \frac{z_\gamma^2}{2(n - 1)} \tag{7-5}$$

$$b = z_p^2 - \frac{z_\gamma^2}{n} \tag{7-6}$$

$$P \left\{ \frac{H - \mu}{\sigma} \leq z_p \right\} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z_p} e^{-z^2/2}\, dz \tag{7-7}$$

where z_p and z_γ are the normal deviates corresponding to the desired probability level and the desired confidence level, and where μ is the mean hardness, σ is the standard deviation, and H represents either the upper or lower hardness limit. Figure 7-2 illustrates the use of population tolerance limits to estimate out-of-tolerance probabilities.

The K-factors resulting from these calculations are only approximate but are considered close enough to make an engineering judgement for the comparison purposes. This judgement is based on a comparison of the calculations from Eqs. 7-3 through 7-5 with the exact K-factors published in Ref. (6).

Out-of-Tolerance Limits for Populations. As an alternate means for establishing out-of-tolerance probabilities where finite populations are sampled, the hypergeometric probability distribution was used to calculate the probability of finding N_s rejects on a sample size n. The equation for this distribution is:

$$P\left\{\frac{N_s}{n}\right\} = \frac{\binom{N_p}{N_s}\binom{N_8}{n - N_s}}{\binom{N}{n}} = \frac{\dfrac{N_p!}{N_s!(N_p - N_s)!}\;\dfrac{N_q!}{(N - N_s)!\,[N_q - (n - N_s)]!}}{\dfrac{N!}{n!(N - n)!}} \qquad (7\text{-}8)$$

where $P\{N_s/n\}$ is the probability that a sample of n bolts will contain N_s out-of-tolerance bolts based on hardness. Also, in Eq. 7-8, N is the population size and N_q is the number of bolts that are within the specification in the population. Since one is interested in the number of bolts that fall outside the specification in the populations, Eq. 7-8 was solved iteratively for N_p for each material and supplier. Several computer counting exercises were made where the bolts with any single measurement above or below the hardness specification were totalled by material and by supplier. These computer data sortings gave values of N_s and n that were used in Eq. 7-8 for determining the out-of-tolerance probability.

Regression Analysis. Standard least squares regression analysis was used to establish hardness trends and to identify outliers in the data. Predictive models that relate hardness with bolt size and material specification were formulated on three individual bases: no weighting of data, 1/n weighting, and $1/\sigma$ weighting.

Regression coefficients were computed and tested for statistical significance with regard to establishing hardness trends by material and by sizes.

Analysis of Midland Field Data

Data Sorting and Organization. The hypothesis is made that hardness behavior is governed by material specification, product size, and supplier. For each variable, the statistical approach outlined in the previous subsection is used to verify or reject this hypothesis. The large size of the data base, consisting of three measurements made on each of 6,303 bolts (18,909 measurements), necessitated extensive computer rearrangement of the original data files obtained from SAI. First, the data were arranged by material and bolt diameter. Then histograms were

constructed using frequency counts of increments divided into a single Integer Rockwell-C hardness unit. These were scanned for obvious deviations from normality which were not expected, since prior work by SAI established that most of the stratums chosen in their work could be approximated by a normal distribution based on testing with a Kalmogorov-Smirnov goodness-of-fit test for normality.

After satisfying ourselves that the assumption of normality was not unreasonable, means and standard deviations were computed for each material and bolt size. The hardness means and standard deviations for such material were tested for correlation to bolt diameters by regression analysis. Additionally, the standard deviations were used to test for variability between materials.

Hardness Behavior by Normal Distribution Statistics

Hardness Distribution Overview. A summary of the total bolt populations at Midland by materials and the number of bolts sampled is in Table 7-5. The population of bolts under scrutiny by CPCO was 65,053 products which encompassed all of the field purchased LAQT bolting materials at Units 1 and 2. The majority of fasteners were ASME SA193-B7, which comprised approximately 70% of the total population.

It is our basic premise in this analysis that the sample strata formed by segregation of materials and sizes is from a large population which is normally distributed. The resulting K-factors and out-of-tolerances above and below the stated lower and upper hardness limits are summarized in Table 7-6. It should be noted that ASME SA193-B7 bolting does not have a hardness requirement. The hardness limits given in Table 7-6 are based on engineering judgement taking into account the material thickness and specified minimum strength requirements.

With the exception of three sizes of ASTM A540-B3-5 material, all computed mean hardness values fell within the required specification. The standard deviation for the bolting ranged from less than 1 R_C to as large as 7 R_C. The greatest variability in hardness was observed with ASTM A354-BD material, whereas, the least scatter in hardness was observed in various grades of ASTM A540.

The estimated probabilities of surface hardness falling outside the desired range are shown in the last three columns of Table 7-6. The material exhibiting the largest out-of-tolerance is ASTM A540-B23-5. This observation is surprising since

this specification also exhibits a small standard deviation. Provided it is accepted that the data are accurate, the three sizes that exhibit poor compliance are 1.75 inches (4.4 cm), 5.5 inches (14 cm), and 7 inches (17.8 cm), where the out-of-tolerance probabilities are 86% (low), 95% (high), and 85% (high), respectively. However, since the mean hardness also falls outside the range, one must suspect that the bolting was either mis-specified or the vendor supplied higher strength material to satisfy a lower strength requirement. From a design verification viewpoint, the only size that would require additional review and disposition would be the 1.75-inch (4.4 cm) material because the mean hardness falls 2 R_C points below the minimum limit. The corrective actions and final disposition for these materials are not known; however, CPCO/Bechtel was able to resolve many of these problems without a significant effort.

The greatest hardness variability that has resulted in high probabilities in exceeding the upper hardness limits is observed with ASTM A354-BD and A490 bolting. For example, in the case of 2.5-inch (6.4 cm) diameter bolting, both ASTM A354-BD and A490 showed a greater than 46% chance that the surface hardness will exceed 38 R_C. The highest recorded hardness among these bolts ranged between 45 R_C and 47 R_C. One possible explanation why ASTM A490 bolting may exceed maximum hardness limits is that tensile test results can be used to accept material in the event that there is controversy over low or high readings of hardness tests. This exemption is not allowed for ASTM A354 bolting; however, the low sampling rate for hardness when lots are small may also lead to hardness falling outside the specified range.

The material specifications which demonstrated the least tendency to be overly hard are ASTM A540-B23-4, A540-B23-3, and SA193-B7. Charpy V-notch lateral expansion requirements for ASTM A540 bolting may significantly contribute to limiting the within-heat variability in strength, thus reducing the scatter in hardness. For ASME SA193-B7 bolting, this material specification has the lowest S_y requirements of the group making it less likely to be overly hard.

Hardness Behavior by Size. Regression analysis was used to explore the question of whether the mean Rockwell-C hardness values are related to bolt size. The use of mean hardness values causes ASTM A540-B23-4, A540-B23-5, and A490 to be dropped from statistical testing because of insufficient data. Another criterion used in evaluation is to delete those means where the hardness specification limits change.

As a result, only ASTM A354-BD, A540-B23-3, and SA193-B7 meet the criterion for testing by this method. Semi-logarithmic plots of the mean data versus nominal bolt diameters are shown in Figures 7-3 through 7-5 for the above three materials. Only data points with the same specification limits are connected in the graphs. The model which was tested is of the form:

$$h = A \log (D) + b \tag{7-9}$$

where h is the hardness (R_C) and D is the nominal bolt diameter (inches).

The weighted linear regression program used is the Statistical Analysis System Code (7). If the residuals indicated an outlier or model mis-specification, adjustments were made for final statistical testing. A description of the regression analyses and results is given in Appendix B of this section.

The mean Rockwell-C hardness values for ASTM A540-B23-3 were found to be correlated with bolt diameters after two outliers were deleted from the analysis. On the basis of better distributed residuals, it was concluded that the correlation based on the weighted 1/n was the most satisfactory relationship explaining 94.4% of the variability in Rockwell-C hardness, with a probability of only 0.0001 of there being no relationship. The parameter n is the number of observations. Additionally, it was the smallest mean square error (MSE). As the plot in Figure 7-3 shows, Rockwell-C hardness increases with bolt diameter.

For ASTM SA193-B7, the analysis results were quite different. No correlation is observed, and this may be confirmed by examination of Figure 7-4. Hence, there is no significant relationship between Rockwell-C hardness and bolt diameter as determined by regression analysis with either no weighting, 1/n weighting, or $1/\sigma$ weighting.

The relationship between mean Rockwell-C hardness values and diameter for ASTM A354-BD also proved to be significant, but less so than that shown by ASTM A540-B23-3. Although the correlation weighted by 1/n has the smallest R^2, 0.521, its MSE is significantly lower than for the case of no weight and $1/\sigma$ weighting. Therefore, 1/n as a weighting factor has the better predictive capability (i.e., smaller predicted measured residuals). In any case, the relationship is statistically significant indicating, again, an increase in mean Rockwell-C hardness with diameter. It should be noted that an R^2 of 0.521 explains only about 52% of the

observed variability in hardness explained by the variable diameter. The inclusion of another variable in the model might well produce different conclusions.

The standard deviations for each of the three materials evaluated above are also plotted in Figures 7-3 through 7-5. These show no discernible relationship with bolt diameter as well as the other materials not plotted. However, it is possible to compare variabilities between five of the six materials based on their standard deviations. A plot of standard deviations versus probability of occurrence based on median ranks (Figure 7-6) discloses that the distributions are approximately log normal. One outlier for ASTM A540-B23-5 was not used in the calculations to derive the means and standard deviations for these distributions which are summarized in Table 7-6.

It is hypothesized that if the mean standard deviation of any distribution is significantly different at the 95% confidence from any other mean standard deviation, then the variabilities of the two distributions are different. A t-test where variances cannot be assumed equal was used (7) in hypothesis testing for significant differences. It was determined at the 95% confidence level that:

- ASTM A354-BD and SA193-B7 are significantly higher in variability than ASTM A540-B23-3, A540-B23-4, and A540-B23-5.
- ASTM A354-BD and SA193-B7 are not significantly different in variability.
- ASTM A540-B23-3, A540-B23-4 and A540-B23-5 are not significantly different in variability.

These statistical findings are visibly noted in the standard deviation plots shown earlier in Figures 7-3 through 7-5. Additional data analysis by material specification is presented next where the out-of-tolerance behavior is investigated.

Hardness Behavior by Specification. Hardness specification limits were also used to derive out-of-tolerance populations for each material and size. The fraction of population out-of-tolerances high and out-of-tolerances low were calculated as indicated in the Background subsection. These represent bolt populations which would be considered to be out-of-tolerance assuming the Midland sample measurements can form a large population of bolts with hardnesses normally distributed.

Comparisons between out-of-tolerance populations for materials and sizes (Table 7-6) are difficult because not all materials have the same size representation.

Another complication within a materials grouping is that hardness specifications change for the larger sizes. One method of accounting for the latter is to segregate not only by material but also when hardness limits change within a material grouping and account for them separately. A suitable listing of bolting materials is thereby produced in Table 7-7. In this table, ASTM A540-B23-5 measurements (for only 7-inch or 17.8-cm diameter bolts) resulted in the highest total out-of-tolerance population with 85% of an estimated large population having out-of-tolerance measurements. A ranking ordered by total out-of-tolerances with sizes included in the sample is shown in Table 7-8. The specifications marked with an asterisk have a different hardness limit requirement and are therefore treated separately.

The three material specifications exhibiting the largest out-of-tolerance behavior are ASTM A490, A540-B23-5, and A354-BD. These materials exhibit greater than 50% probability of falling outside the specified hardness limits. In contrast, ASTM A540-B23-4, A540-B23-3, and SA193-B7 would be predicted to have the lowest out-of-tolerance hardness measurements. If the materials are grouped without regard to size or hardness limit requirements, the out-of-tolerance behavior for each is as shown in Table 7-9. Although the out-of-tolerance rates improved (i.e., averaged out), the ranking of materials remains the same with ASTM A490, A540-B23-5, and A354-BD having the highest probability of out-of-tolerance hardness behavior. As discussed earlier, the ASTM A540-B23-5 bolting, particularly the 7-inch (17.8 cm) diameter material, appears to be mis-specified or mis-supplied because the mean hardness exceeds the upper limit. If some sizes of ASTM A540-B23-5 are truly mis-specified, then the expected behavior of this material would be similar to the other grades of ASTM A540 material, leaving only ASTM A490 and A354-BD as being distinctly different from the other specifications.

The total out-of-tolerance populations from Table 7-6 are plotted in Figure 7-7. On a per bolt size basis, the highest out-of-tolerance bolt populations again consist of three materials (i.e., ASTM A540-B23-5, A490, and A354-BD). Any statement on the relationship between bolt diameter and total population out-of-tolerance should be tempered by observing that the sample size in each diameter is small ranging from one to six. If populations with 50% exceedance rates are ranked, six of nine diameters are 2.5 inches (6.4 cm) or greater. Hence, larger diameter bolts of these three worst materials are more likely to have larger numbers of out-of-tolerance measurements. In contrast, if bolt populations with 10% and less exceedance rates are ranked, seven out of eleven bolt diameter are 2 inches (5.1 cm) and less. These results suggest bolting of smaller sizes have better within-tolerance

behavior than bolting greater than, say, 2.5 inches (6.4 cm). Again, the best materials with the lowest out-of-tolerance populations are predicted from previous rankings of ASTM A540-B23-4, A540-B23-3, and SA193-B7.

Out-of-Tolerance Behavior by Bolt Numbers

Another method of estimating the population out-of-tolerance behavior is to first count those bolts in the sample exceeding the specification limits and then to predict the rejection rates expected in the total population at a 95% confidence level by the hypergeometric distribution. The results of this method were consistent with the previous results based on the normal distribution where again ASTM A540-B23-5, A354-BD, and A490 were ranked the highest in out-of-tolerance behavior. These three materials again exhibited greater than 50% probabilities in their respective populations for exceeding the upper/lower specification limits.

Out-of-Tolerance Behavior of Vendors

The trends in hardness variability as they relate to suppliers of the product was investigated; however, since the definition of the supplier could include companies that actually fabricate the bolts to just a retailer that acts as a warehouse for supplying steel products, it will be difficult to draw any conclusions with regard to the root cause of bolting not meeting specification requirements unless one or two suppliers are associated with the majority poor bolting products. No attempt was made to determine the actual suppliers of the steel or the heat treatment company, etc., among bolts exhibiting large variability. Such an effort was judged too large for the project scope, although some information on this subject may exist at CPCO.

The out-of-tolerance behavior for each supplier was evaluated by sorting those bolts in the sample based on hardness measurements falling above or below the specification limits. The 95% confidence limits of these populations was predicted from the hypergeometric distribution, as described in the previous subsection. A summary of these results is given in Table 7-10 for the 26 suppliers of Midland bolting. A supplier code number was assigned to each supplier in decreasing order of number of bolts supplied. The total out-of-tolerance is shown in Table 7-10 based on two different methods: one method based on the number of measurements falling outside the limits to the number of bolts samples, and a second time with the hypergeometric distribution with a stated confidence of 95%.

From the data summary, the first five suppliers produced approximately 80% of the field purchased bolting. Furthermore, Supplier 1 had contributed approximately 25% of the field purchased bolting to Midland, with over 16,000 bolts/studs shipped. On average, the out-of-tolerance rates of the larger suppliers were better than the suppliers of smaller quantities of bolts. Specifically, vendors supplying numbers under about 1,000 units have the highest out-of-tolerance rates, although some exceptions are observed. Caution must be observed in interpreting Table 7-10 in that some suppliers of bolts with low numbers were inadequately sampled, and the low sample numbers will conservatively bias the statistics (i.e., larger rates) at 95% confidence.

Only two suppliers exhibited out-of-tolerance rates based on statistics less than 10%, Suppliers 10 and 21. The remaining suppliers exhibited out-of-tolerance rates from 16% to 100%. However, Suppliers 1 through 5, where 80% of the products were obtained, had an aggregate out-of-tolerance rate of 20.6%. The last three suppliers in the list given in Table 7-10 were grouped together because individual totals for products could not be ascertained from the data base. This was because these vendors had supplied threaded rods that were later cut to length for embed anchors, and the actual numbers of anchors for these vendors were not listed. The total percentage of bolts/studs obtained from Suppliers 24, 25 and 26 is not known exactly but is probably less than 6% of the total population.

The vendors with greater than 50% out-of-tolerance rates were Supplier Codes 12, 14, 15, 17, 18, 19, 20 and 23; however, five of these had potential of small sample bias leaving Suppliers 14, 17 and 23 with the highest out-of-tolerance hardness measurements. It should be noted that Supplier 22 only had two products represented in the data base, and both had exceeded the upper hardness limit requirement. These two fasteners were 5.5-inch (14-cm) diameter recess pins fabricated to ASTM A540-B23-5.

IMPLICATION OF FINDINGS

A major observation of the Midland data is that field hardness testing of bolting will undoubtedly produce results that will question the compliance of bolting to the stated hardness requirements, if one equates the out-of-tolerance rates calculated herein to out-of-specification rates. Strict interpretation of the ASTM standards would imply any hardness measurement result falling outside the hardness limits would cause the lot of bolts to be classified not in compliance with the

specification. Hence, any utility intending to perform field hardness testing should be prepared to disposition material for noncompliance with the standard by suitable plant-specific strategies.

The observation that only two out of the 26 vendors supplied bolting with calculated out-of-tolerance rates of less than 10% was particularly surprising, since it was thought that a sharper distinction between high hardness versus normal hardness behavior would be seen when the data were segregated by suppliers. Such data segregation would help identify underlying characteristics, such as different procurement practices, good versus bad manufacturers, time periods of purchases, etc.

However, aside for the possible trend with numbers of bolts supplied, there was no distinction among the suppliers with relatively high out-of-tolerance rate behavior. Hence, it would seem prudent for purchasers of bolting, especially for critical bolting applications, to use receipt inspection as a means of screening material prior to acceptance into site warehouses. These results also suggest an inadequacy of the specifications evaluated to produce bolting whose hardness will lie within the stated requirements. In general, the mean hardness fell within the requirements, but some 1σ and most 2σ scatter bands exceed either the lower or upper limits of the specifications. Hence, the manufacturing and lot acceptance sampling requirements of these specifications cannot support strict interpretation of mechanical hardness testing requirements. For example, the scatter observed in hardness for ASTM A354-BD bolts should be expected since only one bolt for lot sizes up to 800 bolts is all that is required to be mechanically tested.

Although a major conclusion from this investigation is that variability of bolting materials can be large and that there is high probability that the upper and lower hardness limits could be violated, the actual consequence of impact of such an event is most likely not serious. Since SCC of fasteners will not be a problem unless surface hardness significantly exceeds the specified upper hardness limit, the likelihood of SCC susceptibility was investigated by viewing the trend of hardness out-of-tolerance probabilities as the upper hardness limit was varied from 38 R_C to 45 R_C. A hardness level of 41 R_C and lower has been judged to be acceptable for mitigating SCC concerns in structural bolting applications (8). Hardness in excess of 41 R_C could still be acceptable for service provided that it can be demonstrated that failure will not occur under the long-term and short-term loading conditions.

The probability of exceeding a given hardness level for each material is shown in Figure 7-8. These results are based on the population tolerance limits using the normal distribution and 95% confidence level. The probability is observed to decrease rapidly as the hardness limit changes from 38 R_C to 45 R_C. Only two materials exhibited high probabilities over the range, namely, ASTM A490 and A354-BD. At 41 R_C, ASTM 490 and A354-BD show approximately a 15% probability of exceeding this level. All the other materials fall at or below 5% probability exceedance levels at 41 R_C. Hence, ASTM A490 and A354-BD bolting tend to be hard relative to their specification requirements.

On a total population basis, the exceedance probabilities of Figure 7-8 are not as bad when numbers of bolts exceeding a given hardness level are compared to the total number supplied. Because ASTM A490 and A354-BD at Midland do not comprise a large percentage of bolting used, the total fractions exceeding a given hardness level are very low. The estimated numbers and population percentages are given in Table 7-11. At 38 R_C, 3,095 out of 65,053 bolts would be predicted to exceed 38 R_C based on the probabilities given in Figure 7-8. This number corresponds to only 4.8% of the bolting at Midland. A 1.1% rate is calculated for 41 R_C suggesting only a very small percentage of the bolting would be potentially susceptible to SCC. If the bolting materials and frequency of use at Midland is typical of other plants, a generic concern for structural LAQT bolting does not seem justified because of the small percentage of bolts expected to exceed 41 R_C. Furthermore, at hardness levels in excess of 41 R_C, much smaller exceedance rates (i.e., less than 1%) are calculated. Of course, plant-specific issues will remain when problems in fastener integrity exist. Based on the experiences at Midland and other plants, ASTM A490 and A354-BD bolting would be most prone to SCC because these specifications show the most variability in hardness.

SUMMARY AND CONCLUSIONS

Evaluation of field hardness testing data at Midland Units 1 and 2 suggest that bolting material specification requirements on hardness are easily exceeded when larger samples than those required by the specification are taken. Of the six bolting specifications evaluated (namely, ASTM A490, A354-BD, A540-B23, Classes 3, 4 and 5, and ASME SA193-B7), ASTM A490, A354-BD and A540-B23-5 exhibited the highest probability for hardness measurements to fall outside their respective limits. It is speculated, however, that some sizes of ASTM A540-B23-5 were either mis-specified or improperly supplied because sample means also fell outside the

hardness limit range, and the observed variability of ASTM A540 was much less than either ASTM A490 and A354-BD.

The variability in hardness of ASME SA193-B7 is comparable to ASTM A354-BD, and this variability in hardness is that which causes these materials to exceed their limits. Unlike ASTM A490 and A354-BD, ASME SA193-B7 and ASTM A540 do not have the tendency to exceed upper hardness limit requirements where SCC is a concern.

There is a trend between hardness and bolt diameter for ASTM A540-B23-3 and A354-BD where hardness is observed to increase with increasing bolt size. No such trend was observed for ASME SA193-B7, and there were insufficient data for the other materials for testing this hypothesis. No trend with bolt size was observed for variance in the data.

Although some vendors were clearly better than others with regard to out-of-tolerance behavior, there was no clear distinction between groups of suppliers to suggest good versus bad procurement sources. Because the observed population out-of-tolerance behavior is insensitive to supplier, a receipt inspection program for material acceptance prior to storage and installation would be effective for identifying bolting material problems associated with out-of-specification strengths. Without receipt inspection, more stringent requirements at the fabrication level (i.e., additional testing or increased sampling frequencies) would be needed.

Based on the review of hardness limits, the out-of-tolerance probability for each material, and SCC susceptibility of structural components, the probability of exceeding the hardness levels which could lead to SCC failure is low for all bolting applications. The highest probabilities for SCC exist for ASTM A490 and A354-BD materials. The failures of ASTM A354-BD bolting at Midland and Palo Verde are consistent with these results. In addition, it is estimated that the number of bolts at Midland that would have a susceptible hardness for SCC is less than 1% of the total bolt population. Hence, a generic concern for all LAQT materials does not seem warranted based on the likelihood of material falling above a critical hardness level for SCC.

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Table 7-1

SUMMARY OF MIDLAND UNITS 1 AND 2 FIELD DATA

Plant Application	Material Specification	Size	Length[1] Code	Total Number	Number Tested
Connection Bolts (Civil)	SA193-B7	1-1/4"	A	90	0
	A354-BD	1-1/8" to 2-1/2"	A-D	1,944	397
	A540-B23-3	7/8" to 2-1/2"	A-C	14,639	1,211
PW Restraint Pins (Civil)	A540-B23-3	2-1/4" to 6-1/2"	A,B	38	36
	A540-B23-5	4" to 8-1/4"	B,C	168	123
Embedded Anchors (Civil)	A354-BD	2-1/4" to 3-1/2"	D	634	613
	A490	1-1/2" to 2-1/2"	D	361	221
	A540-B23-3	2-1/2"	D	539	48
Through Anchors (Civil)	SA193-B7	7/8" to 2"	C,D	158	46[2]
	A354-BD	1-1/4" to 2-1/2"	C,D	1,075	225
	A540-B23-4	1-1/2" to 3-1/2"	D	86	82
	A490	1-1/2"	D	103	63
RPV Shear Pins (Civil)	A354-BD	2"	B	100	50
Pipe Support Hangers (Mechanical)	SA193-B7	7/8" to 2-1/2"	A,B	7,260	787
Anchor Bolts (Mechanical)	SA193-B7	7/8" to 1-3/4"	B,C	7,121	752
	A540-B23-5	1-1/2" to 1-3/4"	D	48	39
Pipe Flanges (Mechanical)	SA193-B7	7/8" to 1-5/8"	A,B	30,679	1,654
U-Bolts	A540-B23-4	2-1/2"	D	10	0
Total				65,053	6,349

Notes:

1. Length Code - A: <6", B: 6" to 12", C: 12" to 24", D: >24"
2. These data were not included in the evaluation because they were missing in the data base.

Table 7-2

LISTING OF BOLT SUPPLIERS TO MIDLAND UNITS 1 AND 2

Acimet Manufacturing Company

Bergen Paterson Company

Billings Machine and Tool Company

Bunker Ramo-Amphenol Company

Capital Pipe & Steel Company

Cardinal Industries

Chicago Bridge & Iron Company

Chicago Tube & Iron Company

Cleveland City Forge

Coast Industrial Supply Company

Haven Busch Company

Inryco, Inc.

Liberty Equipment Company

North Central Fasteners Company

NPS Industries

Power Engineering Products Company

Pressure Vessel Nuclear Company

REC Corporation

Steam Boiler & Tank Works

Schreiber Manufacturing Company

Southern Bolt & Fastener Company

Tally Fasteners Company

U.S. Fastener Corporation

Vitco Nuclear Products Company

Wiltse & Company

Table 7-3

CHEMICAL COMPOSITION FOR FOUR COMMON LAQT BOLTING STEELS

Material Specif.	AISI Equivalent	Chemical Composition									
		C	Mn	Si	Cr	Ni	Mo	V	P(max)	S(max)	B(min)
SA193-B7	4100 Series	0.37-0.49	0.65-1.10	0.15-0.35	0.75-1.20	-	0.15-0.25	-	0.035	0.040	-
A354-BD	4000 Series										
A490:											
Type 1	4000 Series	0.30-0.53	-	-	-	-	-	-	0.040	0.040	-
Type 2	4000 Series	0.15-0.34	0.70 min	-	-	-	-	-	0.040	0.050	0.0005
Type 3*	4000 Series	0.20-0.53	0.40 min	-	0.45 min	0.20 min	0.15 min	-	0.040	0.050	-
A540-B23	E-4340H	0.37-0.44	0.60-0.95	0.15-0.35	0.65-0.85	1.55-2.0	0.20-0.30	-	0.025	0.025	-

*Nickel and chrome requirements for Type 3 bolts are either nickel or chrome.

Table 7-4

SUMMARY OF WATTS BAR FIELD DATA

Plant Application	Material Specification	Size	Length	Number Tested
SG Supports	SA193-B7	1-1/4" to 1-7/8"	5" to 7-1/2"	53
	A490	1-3/8" to 2-1/4"	5-1/2" to 6-1/2"	20
	A540-B23	2" to 2-1/4"	37" to 58"	82
	AISI 4142	1-1/4"	5"	20
SG Manway Pins	A490	1-1/2"	15-1/2"	8
RCP and SG Column	A540-B23	3-1/2"	58"	30
RCP Supports	A540-B23	2-1/2" to 7-1/2"	41" to 113"	72
RCP Bonnet	A540-B24	4-1/2"	30-1/2"	105
RPV Head	A540-B24	7"	65"	120
Pressurizer Supports	A490	1" to 1-1/2"	2-1/2" to 23-1/2"	70

Table 7-5

TOTAL BOLT POPULATION AT MIDLAND AND BOLTS SAMPLED

Material Specification	Midland Population, Bolts	Bolts Sampled	Hardness Data Points
A540-B23-3	15,216	1,295	3,885
A540-B23-4	96	82	246
A540-B23-5	216	162	486
A490	464	284	852
SA193-B7	45,308	3,195	9,585
A354-BD	3,753	1,285	3,855
Total	65,053	6,303	18,909

Table 7-6

NORMAL DISTRIBUTION STATISTICS FOR BOLTING MATERIALS SEGREGATED BY MATERIAL AND SIZE

Material I.D.	Bolt Diameter (Inch)	No. of Sample	Hardness Data: Mean	Hardness Data: Standard Dev.	Hardness Data: Low Value	Hardness Data: High Value	Hardness Data: Lower Limit	Hardness Data: Upper Limit	K-Values: Low	K-Values: High	Probability: Low	Probability: High	Probability: Total
540-B23-3	0.875	237	32.77	1.642	29	37	31	39	-1.077	3.796	0.156	0.000	0.157
	1.000	1197	32.59	2.415	22	45	31	39	-0.658	2.655	0.264	0.005	0.268
	1.125	444	32.39	1.081	29	37	31	39	-1.289	6.109	0.108	0.000	0.108
	1.250	462	33.40	1.393	29	37	31	39	-1.723	4.019	0.048	0.000	0.048
	1.375	150	38.36	0.762	37	40	31	39	-9.656	0.840	0.000	0.223	0.223
	1.500	465	33.95	3.092	11	40	31	39	-0.955	1.632	0.182	0.058	0.240
	1.750	267	35.34	2.773	28	45	31	39	-1.564	1.321	0.068	0.105	0.174
	2.000	150	37.00	0.976	34	39	31	39	-6.146	2.049	0.000	0.027	0.027
	2.250	72	35.14	2.815	26	40	31	39	-1.470	1.372	0.092	0.108	0.200
	2.500	306	35.35	1.464	31	39	31	39	-2.973	2.491	0.002	0.008	0.010
	3.000	27	36.37	0.926	35	38	31	39	-5.799	2.840	0.000	0.007	0.007
	4.000	60	38.32	1.610	35	43	32	40	-3.923	1.045	0.000	0.181	0.181
	6.500	48	35.27	1.267	32	37	33	42	-1.792	5.310	0.055	0.000	0.055
540-B23-4	1.375	108	32.96	0.995	29	35	28	37	-4.990	4.059	0.000	0.000	0.000
	1.500	24	31.58	0.717	30	33	28	37	-4.996	7.552	0.000	0.000	0.000
	3.000	24	31.63	1.469	29	34	28	37	-2.468	3.659	0.017	0.001	0.018
	3.500	90	31.64	1.968	28	36	29	38	-1.344	3.230	0.111	0.001	0.112
540-B23-5	1.500	24	25.46	0.509	25	26	24	33	-2.865	14.817	0.007	0.000	0.007
	1.750	93	22.34	1.691	18	26	24	33	0.979	6.303	0.861	0.000	0.861
	4.000	6	31.67	1.633	30	34	24	33	-4.695	0.816	0.000	0.339	0.339
	5.500	54	35.85	1.917	31	40	24	33	-6.182	1.487	0.000	0.951	0.951
	7.000	165	36.01	2.101	28	40	25	34	-5.241	0.958	0.000	0.850	0.850
	8.250	144	31.89	1.809	27	36	27	34	-2.702	1.167	0.005	0.141	0.146
A490	1.500	276	33.59	4.952	13	42	33	38	-0.119	0.891	0.473	0.203	0.676
	2.500	576	37.69	3.235	27	45	33	38	-1.451	0.094	0.081	0.476	0.557
SA193-B7	0.375	948	28.32	2.961	20	38	26	36	-0.783	2.594	0.226	0.006	0.232
	1.000	1605	29.54	3.662	19	41	26	36	-0.968	1.764	0.173	0.042	0.215
	1.125	1488	30.33	3.313	20	41	26	36	-1.307	1.711	0.101	0.047	0.148
	1.250	2241	32.15	3.200	23	42	26	36	-1.921	1.203	0.029	0.119	0.148

Table 7-6 (Continued)

Material I.D.	Bolt Diameter (Inch)	No. of Sample	Hardness Data: Mean	Standard Dev.	Low Value	High Value	Lower Limit	Upper Limit	K-Values: Low	K-Values: High	Probability: Low	Probability: High	Probability: Total
SA193-B7	1.375	690	30.85	2.843	23	39	36	36	-1.705	1.813	0.049	0.039	0.088
	1.500	1356	31.66	3.786	21	47	26	36	-1.494	1.147	0.072	0.132	0.204
	1.625	318	28.91	2.241	21	35	26	36	-1.300	3.163	0.108	0.001	0.109
	1.750	453	29.36	2.299	23	37	26	36	-1.462	2.889	0.080	0.003	0.083
	1.875	150	26.54	1.661	22	30	26	36	-0.325	5.694	0.399	0.000	0.399
	2.000	144	32.81	2.442	23	39	26	36	-2.787	1.308	0.004	0.112	0.117
	2.250	150	27.15	2.227	22	33	26	36	-0.515	3.976	0.329	0.000	0.329
	2.500	42	29.07	3.543	23	38	26	36	-0.867	1.955	0.237	0.041	0.278
A354-BD	1.125	159	33.67	1.508	29	37	33	38	-0.442	2.873	0.355	0.003	0.358
	1.250	177	33.03	7.206	11	41	33	38	-0.004	0.690	0.523	0.267	0.791
	1.500	324	35.35	1.969	31	41	33	38	-1.192	1.349	0.129	0.099	0.228
	1.750	87	34.10	1.905	28	38	33	38	-0.579	2.046	0.314	0.029	0.344
	2.000	486	36.42	3.142	25	41	33	38	-1.89	0.502	0.149	0.322	0.471
	2.250	303	35.32	3.089	24	43	33	38	-0.750	0.869	0.243	0.208	0.451
	2.500	1773	37.54	4.020	23	47	33	38	-1.130	0.113	0.135	0.463	0.597
	3.000	402	31.47	4.629	22	45	31	38	-0.100	1.412	0.476	0.088	0.564
	3.500	144	35.14	5.002	25	47	31	38	-0.828	0.572	0.227	0.309	0.537

Table 7-7

POPULATION TOTAL OUT-OF-TOLERANCE BY MATERIALS AND HARDNESS LIMITS

Material I.D.	Bolt Diameter (Inch)	No. of Sample	Hardness Data: Mean	Hardness Data: Standard Dev.	Hardness Data: Low Value	Hardness Data: High Value	Hardness Data: Lower Limit	Hardness Data: Upper Limit	K-Values: Low	K-Values: High	Probability: Low	Probability: High	Probability: Total
540-B23-3	3.000	3777	33.74	2.637	11	45	31	39	-1.040	1.994	0.153	0.024	0.177
540-B23-A	4.000	60	38.32	1.610	35	43	32	40	-3.923	1.045	0.000	0.181	0.181
540-B23-B	6.500	48	35.27	1.267	32	37	33	42	-1.792	5.310	0.055	0.000	0.055
540-B23-4	3.000	156	32.54	1.215	29	35	28	37	-3.742	3.663	0.000	0.000	0.000
540-B23-C	3.500	90	31.64	1.968	28	36	29	38	-1.344	3.230	0.111	0.001	0.112
540-B23-5	5.500	177	27.20	6.263	18	40	24	33	-0.511	0.925	0.328	0.197	0.526
540-B23-D	7.000	163	36.01	2.101	28	40	25	34	-5.241	-0.958	0.000	0.850	0.850
540-B23-E	8.250	144	31.89	1.809	27	36	27	34	-2.702	1.167	0.005	0.141	0.146
A490	2.500	852	36.36	4.324	13	45	33	38	-0.778	0.378	0.228	0.364	0.592
SA193-B7	2.500	9585	30.48	3.551	19	47	26	36	-1.261	1.555	0.106	0.062	0.167
A354-BD	2.500	3309	36.44	4.403	11	47	33	38	-0.851	0.385	0.202	0.356	0.558
A354-BD-F	3.500	546	32.43	4.995	22	47	31	38	-0.287	1.114	0.401	0.143	0.543

Notes:

1. Materials A540-B23-A and A540-B23-B are the same material as A540-B23-3 but have different hardness limits.
2. Material A540-B23-C is the same as A540-B23-4 but has a different hardness limit.
3. Materials A540-B23-D and A540-B23-E are the same material as A540-B23-5 but have different hardness limits.
4. Material A354-BD-F is the same as A354-BD but has different hardness limits.

Table 7-8

RANKING OF OUT-OF-TOLERANCE POPULATIONS BY SPECIFICATION

Material Specification	Applicable Diameters in Sample (Inch)	Number in Sample	Out-of-Tolerance %		
			Low	High	Total
A540-B23-5*	7.0	163	0.0	85.0	85.0
A490	1.5 and 2.5	852	22.8	36.4	59.2
A354-BD	1.125 to 2.5	3,309	20.2	35.6	55.8
A354-BD*	3.0 and 3.5	144	40.1	14.3	54.3
A540-B23-5	1.5, 1.75, 4.0, 5.5	177	32.8	19.7	52.6
A540-B23-5*	4.0	60	0.0	18.1	18.1
A540-B23-3	0.875 to 3.0	3,777	15.3	2.4	17.7
SA193-B7	0.875 to 1.5	9,585	10.6	6.2	16.7
A540-B23-5*	8.25	144	0.5	14.1	14.6
A540-B23-4*	3.5	90	11.1	0.1	11.2
A540-B23-3*	6.5	48	5.5	0.0	5.5
A540-B23-4*	1.375, 1.5, 3.0	156	0.0	0.0	0.0

*These specifications have changing hardness requirements with diameter. Those noted by * have different limits than those not noted within the same specification.

Table 7-9

MATERIAL OUT-OF-TOLERANCE POPULATION RANKED BY AVERAGES
(Size and Hardness Limits)

Material Specification	Number of Size	Fraction of Population Out-of-Tolerance
A490	2	0.617
A540-B23-5	6	0.526
A354-BD	9	0.482
SA193-B7	12	0.196
A540-B23-3	13	0.131
A540-B23-4	4	0.033

Table 7-10

SUMMARY OF OUT-OF-TOLERANCE BEHAVIOR BY SUPPLIER

Supplier Code	Total Bolts Supplied	Percent of Population	Total Sampled	Percent Sampled	Based on Percentage Sampled	Quantities Supplied at 15% Confidence
1	16,028	24.6	1,108	6.9	15.0	17.6
2	10,418	16.0	385	3.7	16.9	21.1
3	9,869	15.2	891	9.0	11.1	15.5
4	8,780	13.5	638	7.3	20.1	23.8
5	5,872	9.0	1,299	22.1	28.3	31.3
6	2,818	4.3	329	11.7	27.7	32.6
7	1,334	2.1	112	8.4	26.8	39.1
8	1,076	1.7	89	8.3	11.2	22.0
9	684	1.1	70	10.2	28.6	44.7
10	658	1.0	139	21.1	4.3	9.9
11	605	0.9	43	7.1	7.0	23.1*
12	604	0.9	57	9.4	52.6	73.3*
13	507	0.8	323	63.7	42.7	47.7
14	384	0.6	192	50.0	51.6	58.6
15	308	0.5	7	0.2	85.7	100.0*
16	279	0.4	69	24.7	31.9	47.7
17	193	0.3	190	98.4	82.1	82.9
18	164	0.3	23	14.0	47.8	76.8*
19	162	0.2	10	6.2	20.8	75.3*
20	100	0.2	7	7.0	0.0	68.0*
21	96	0.1	82	85.4	2.4	7.3
22	16	-	0	0.0	-	-
23	2	-	1	100.0	100.0	100.0
24			155	-	54.2	-
25			73	-	6.8	-
26			10	-	80.0	-

* Possible small sample number bias.

Table 7-11

ESTIMATED BOLT NUMBERS AND POPULATION PERCENTAGE FOR EXCEEDING A GIVEN HARDNESS LEVEL

Hardness Level, H (R_C)	A490	A354-BD	A540-B23-5	A540-B23-3	SA193-B7	A540-B23-4	Total Number	Total Population Fraction (%)
38	169	1,200	29	881	816	0	3,095	4.76
39	130	916	21	398	408	0	1,873	2.88
40	97	672	15	156	181	0	1,121	1.72
41	70	473	11	57	91	0	702	1.08
42	48	323	7	14	45	0	437	0.67
43	32	210	5	7	20	0	274	0.42
44	20	131	3	4	10	0	168	0.26
45	12	79	2	2	5	0	100	0.15

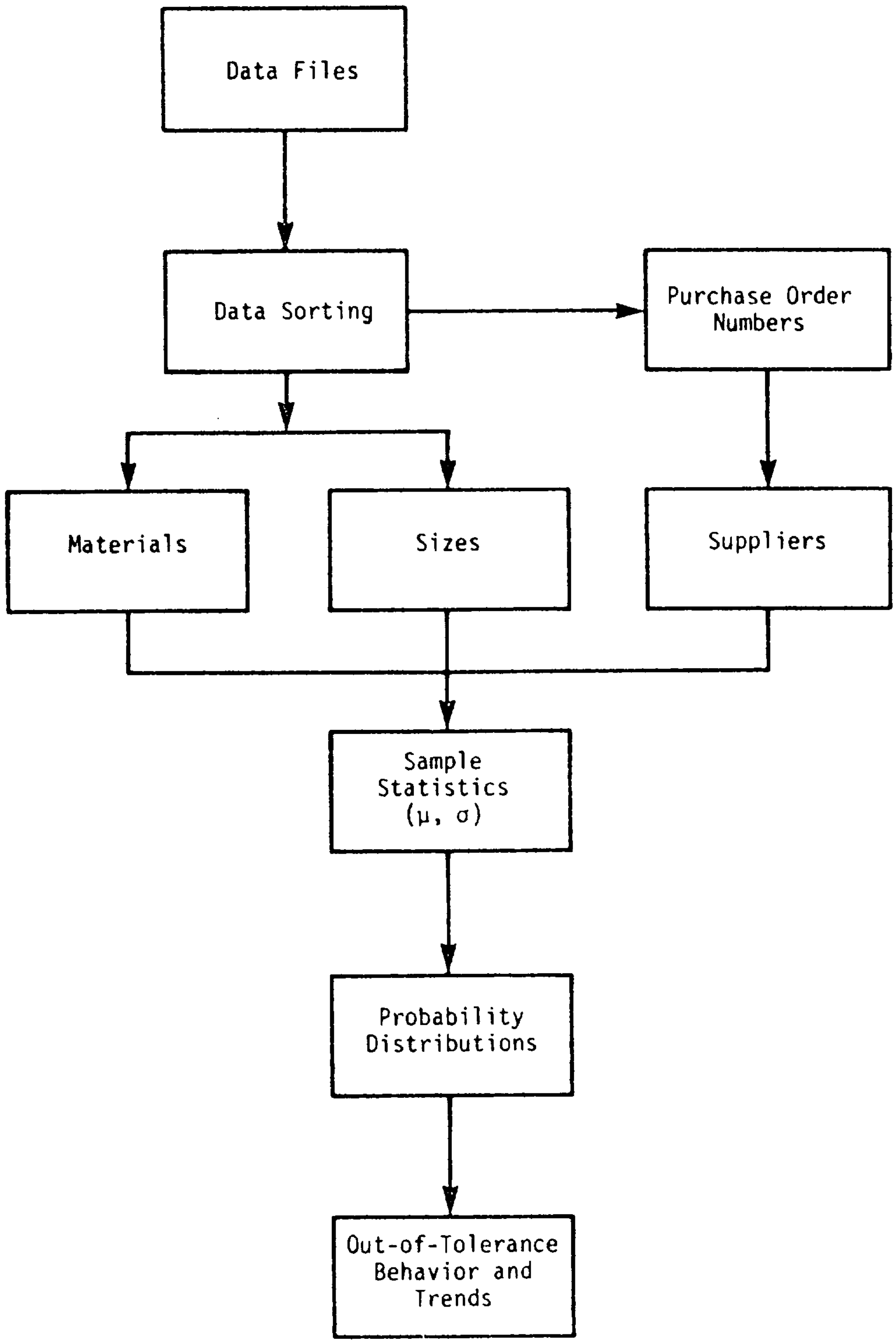


Figure 7-1. Data Analysis Flowchart

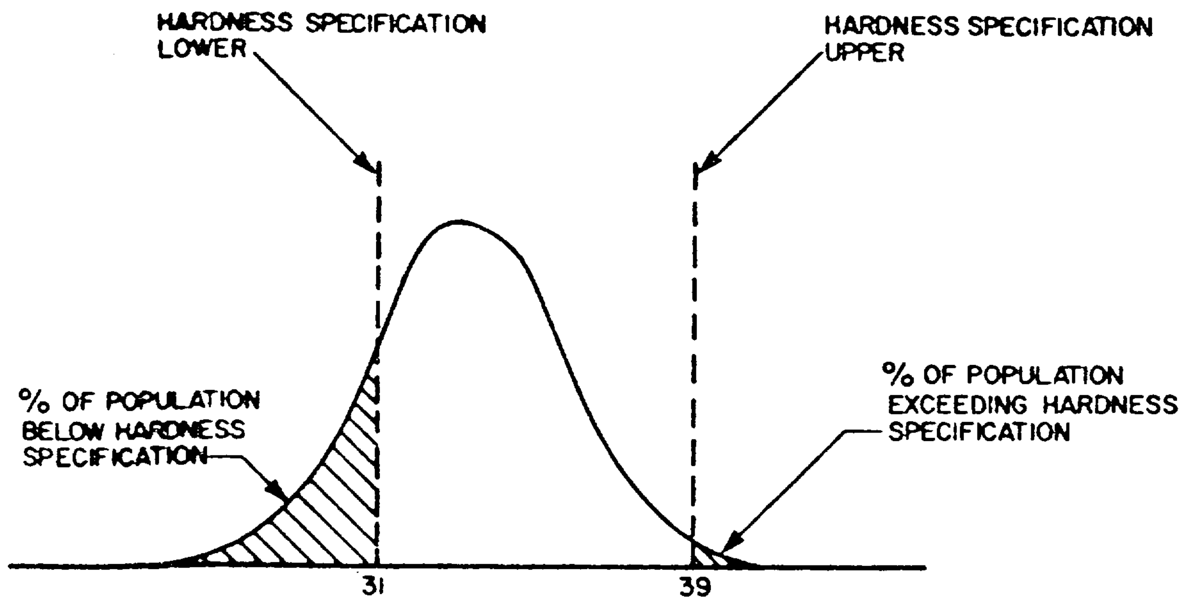


Figure 7-2. Estimation of Population Tolerance Limits Using K-Factors

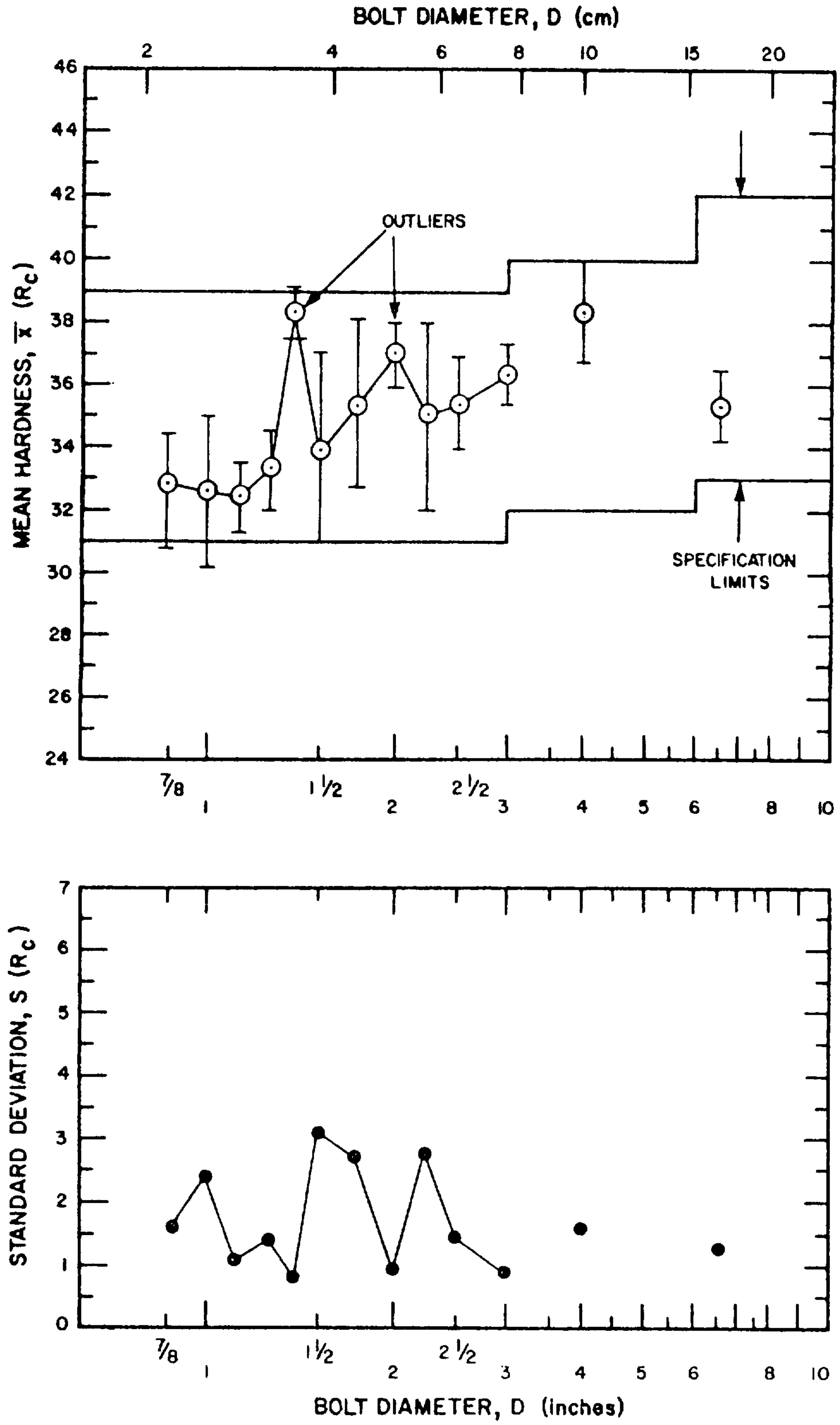


Figure 7-3. Mean Hardness and Standard Deviation for ASTM A540-B23-3 Bolts at Midland Units

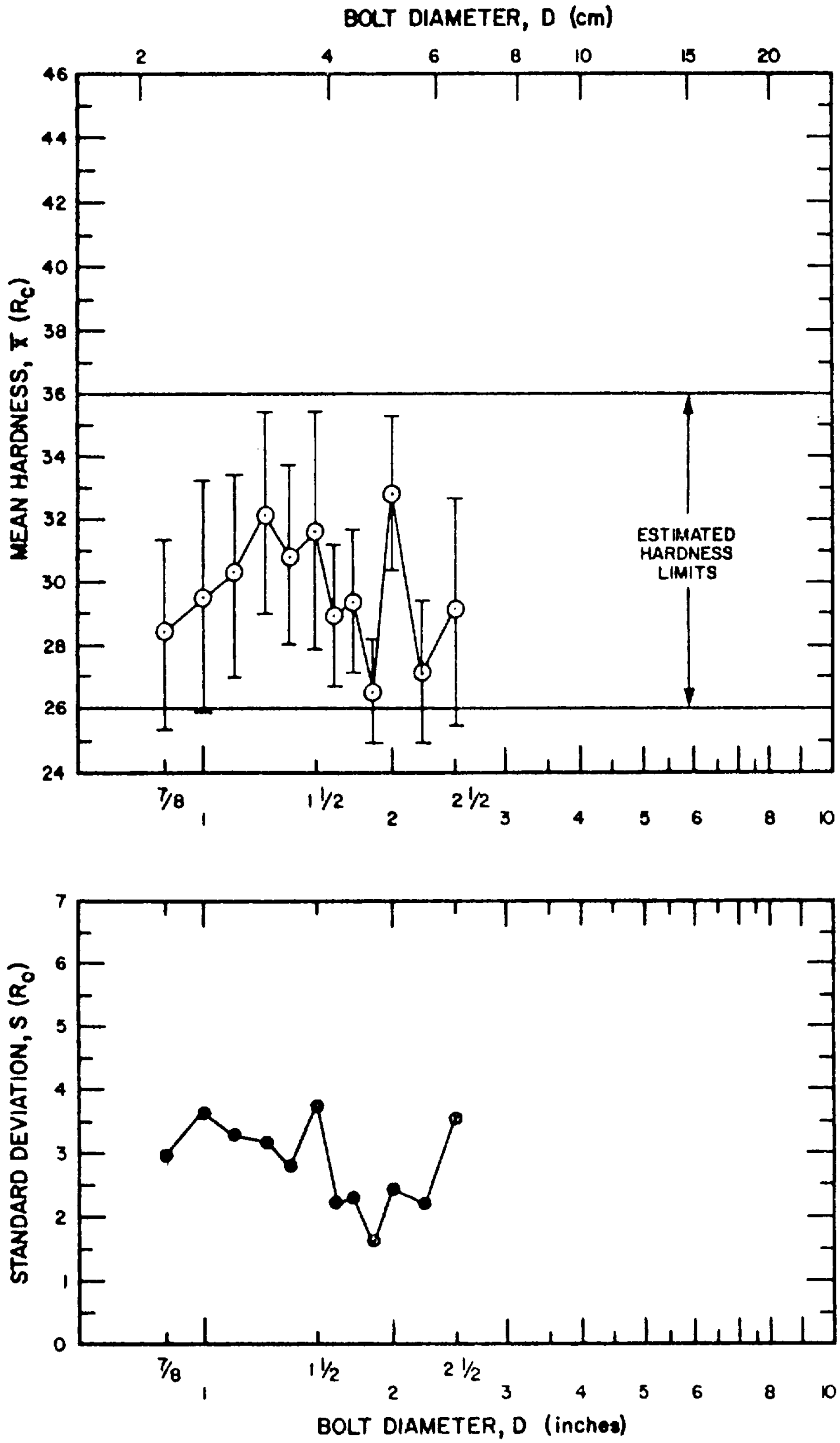


Figure 7-4. Mean Hardness and Standard Deviation for ASME SA193-B7 Bolts at Midland

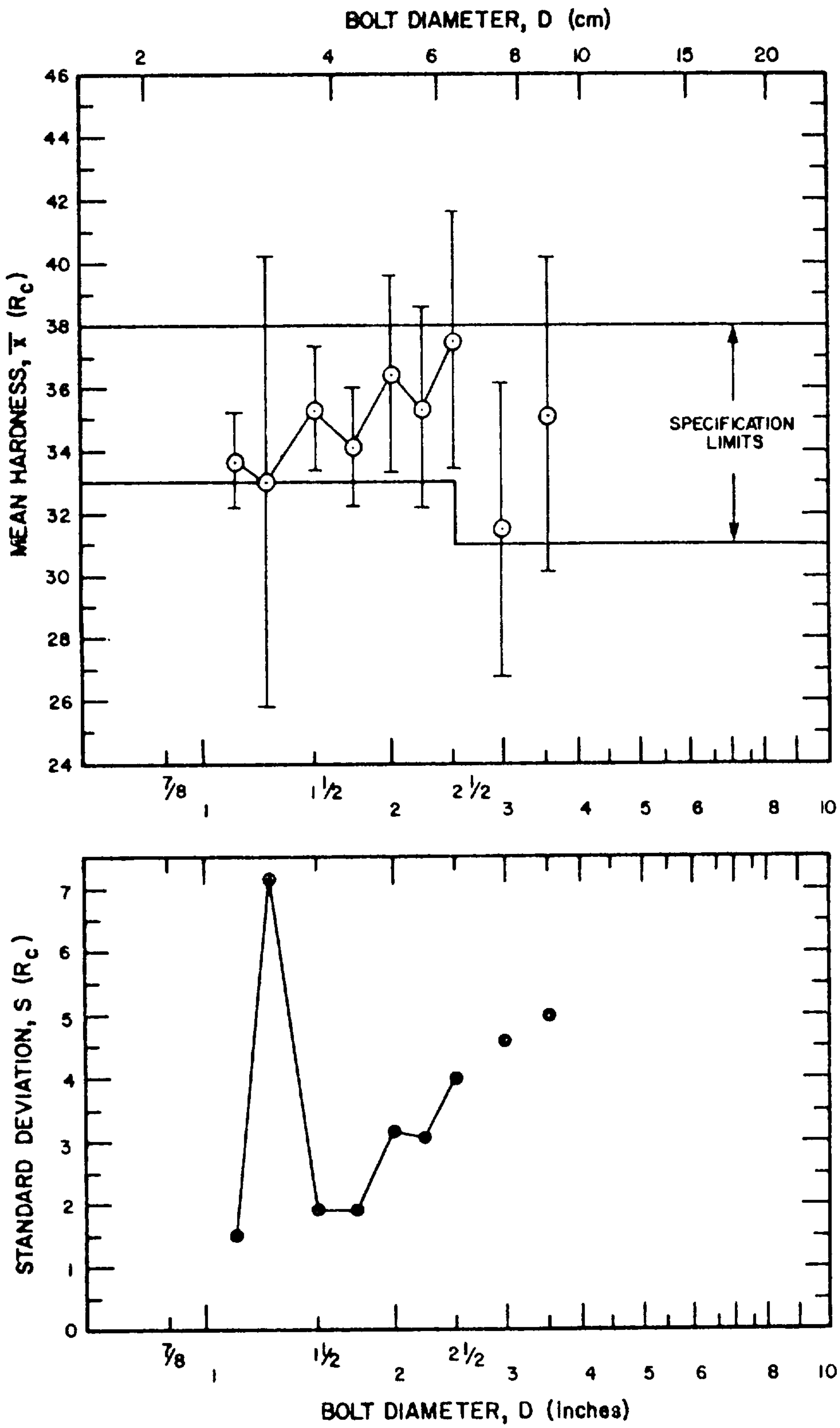


Figure 7-5. Mean Hardness and Standard Deviation for ASTM A354-BD Bolts/Studs at Midland

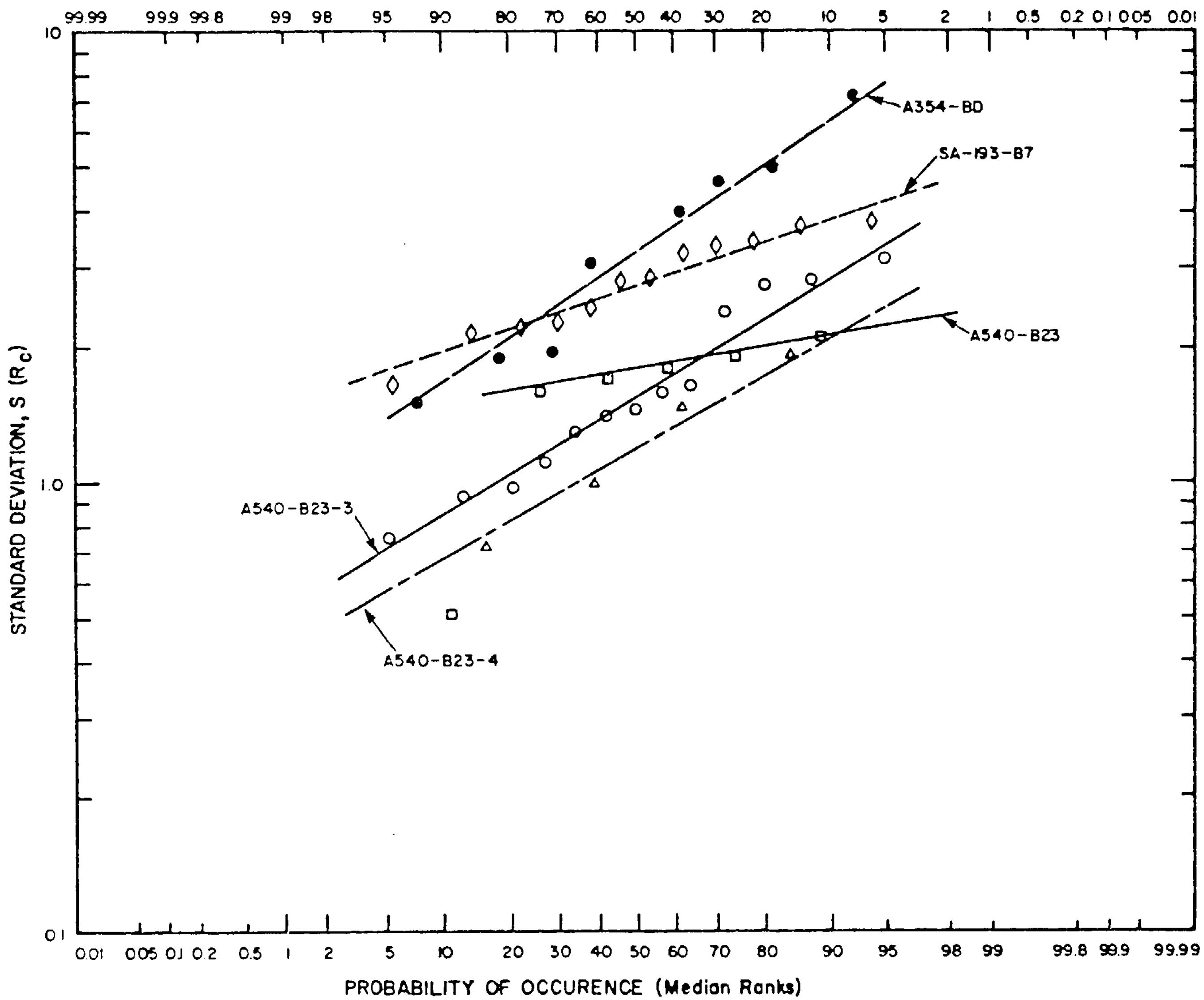


Figure 7-6. Log-Normal Standard Deviation Plots

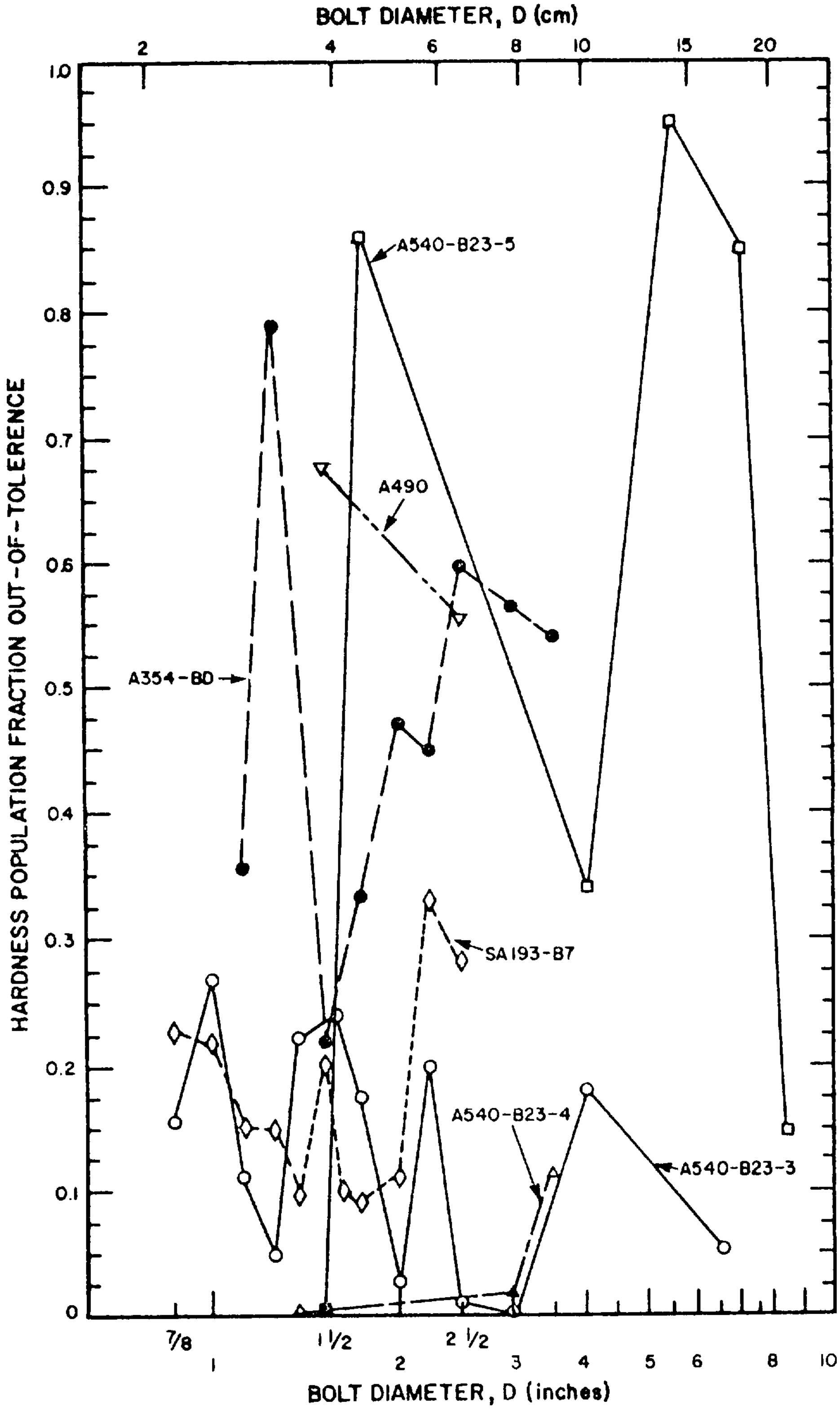


Figure 7-7. Out-of-Tolerance Behavior by Material and Bolt Size

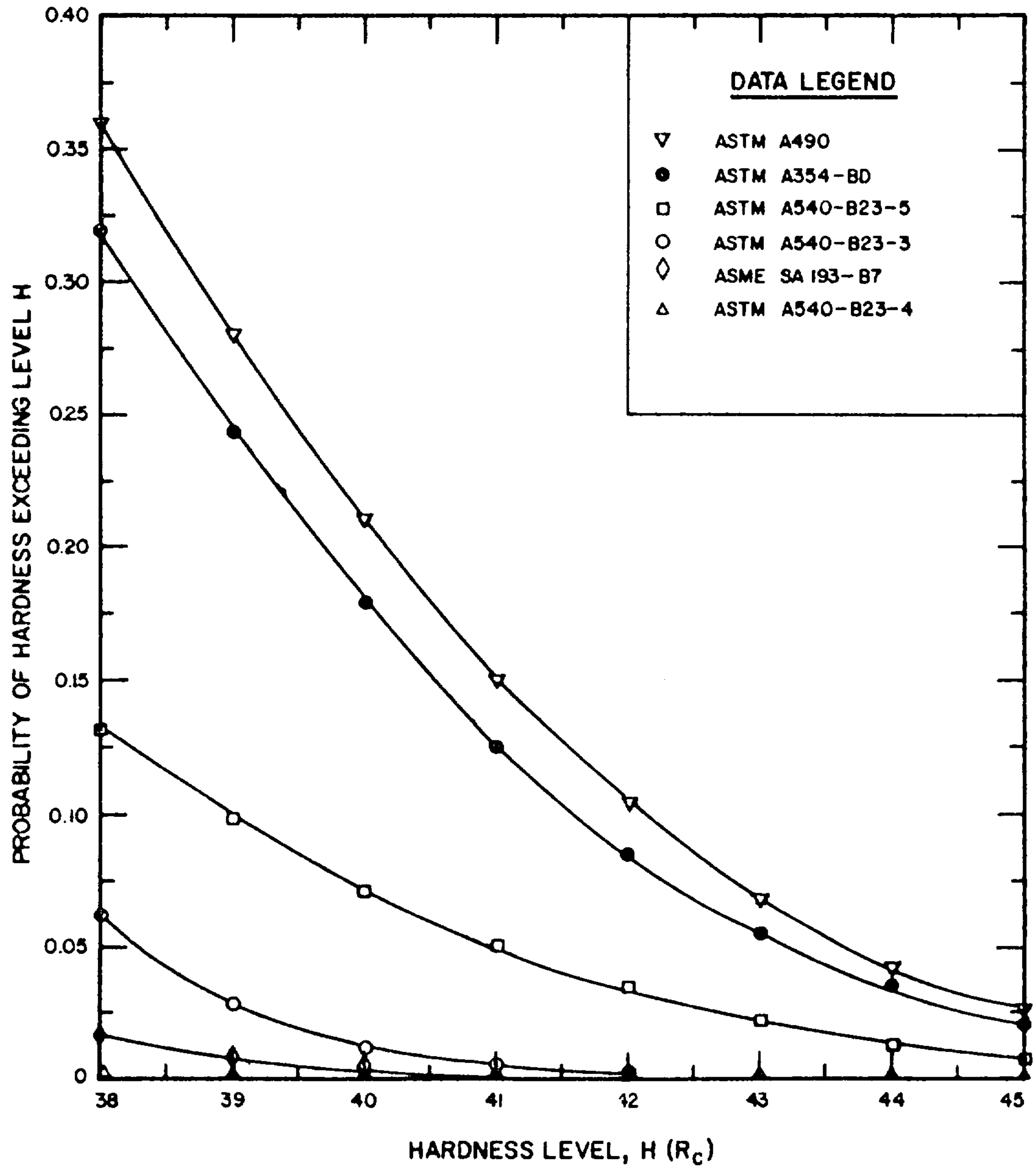


Figure 7-8. Probability of Exceeding Hardness Levels at 95% Confidence for Six Bolting Materials

Appendix 7A

SUMMARY OF MINIMUM STRENGTH AND HARDNESS REQUIREMENTS FOR LOW ALLOY QUENCHED AND TEMPERED BOLTING MATERIALS

The table which follows contains a summary of specified minimum strength and hardness limit requirements for bolting materials specifications that could yield LAQT products. Contained in this table are the requirements for the materials used at Midland, Watts Bar, Palo Verde, and Oconee units, as well as other similar bolting materials.

Table 7A-1

SUMMARY OF HARDNESS REQUIREMENTS PER SPECIFICATION FOR CANDIDATE LAQT STEELS

ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	Specified Min. Strength (ksi)		Specified Hardness	
			σ_y	σ_{uts}	Minimum	Maximum
A7-66	(See Note 1)	--	--	--	--	--
A36-771	(See Note 1)	--	--	--	--	--
A125-73	(See Note 2)	--	--	--	NS	477BHN
SA155-75	CMSH-80[3]	≤ 2-1/2" Thick Over 2-1/2" to 4"	60 55	80-100 75-95	NS NS	NS NS
A182-78/SA182-78	F1	All	40	70	143BHN	192BHN
	F2	All	40	70	143BHN	192BHN
	F11	All	40	70	143BHN	207BHN
	F12	All	40	70	143BHN	207BHN
	F21	All	45	75	156BHN	207BHN
	F22	All	45	75	156BHN	207BHN
	F22a	All	30	60	NS	170BHN
A193-78a/SA193-78a	B7	≤ 2-1/2" Diam. Over 2-1/2" to 4" Over 4" to 7"	105 95 75	125 115 100	NS NS NS	NS NS NS
	B7M	≤ 2-1/2" Diam.	80	100	201BHN or 94HRB	235BHN or 99HRB

Table 7A-1 (Continued)

ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	Specified Min. Strength (ksi) σ_y	Specified Min. Strength (ksi) σ_{uts}	Specified Hardness Minimum	Specified Hardness Maximum
A193-78a/SA193-78a	B16	< 2-1/4" Diam. Over 2-1/2" to 4" Over 4" to 7"	105 95 85	125 110 100	NS NS NS	NS NS NS
A194-80a/SA194-80a	4	All	--	--	248BHN or 24HRC	352BHN or 38HRC
	7	All	--	--	248BHN or 24HRC	352BHN or 38HRC
	7M	All	--	--	159BHN	237BHN or 22HRC
A234-80/SA234-78	WP1	All	30	55	NS	197BHN
	WP12	All	30	60	NS	197BHN
	WP11	All	30	60	NS	197BHN
	WP22	All	30	60	NS	197BHN
	WPR	All	46	63	NS	217BHN
A304-79	(See Note 4)	--	--	--	--	--
A320-80b/SA320-78[5]	L1 L7,L7A,L7B,L7C	≤ 1" Diameter ≤ 2-1/2" Diam.	105 105	125 125	NS NS	NS NS
	L7M	≤ 2-1/2" Diam.	80	100	201BHN or 94HRB	235BHN or 99HRB
	L43	≤ 4" Diameter	105	125	NS	NS
A322-80	(See Note 4)	--	--	--	--	--

Table 7A-1 (Continued)

			Specified Min. Strength (ksi)		Specified Hardness	
ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	σ_y	σ_{uts}	Minimum	Maximum
A325-78a/SA325-78a	2,3 (See Note 6)	1/2" to 1" Diameter	81	105	248BHN or 24HRC	331BHN or 35HRC
		1-1/8" to 1-1/2" Diam.	81	105	223BHN or 19HRC	293BHN or 31HRC
A331-74	(See Note 4)	--	--	--	--	--
A333-79	8	--	75	100	NS	NS
A354-78a/SA354-78a	BC (See Note 6)	1/4" to 2-1/2" Diam.	109	125	255BHN or 26HRC	331BHN or 36HRC
		Over 2-1/2" Diameter	99	115	235BHN or 22HRC	311BHN or 33HRC
	BD	1/4" to 2-1/2" Diam.	130	150	311BHN or 33HRC	352BHN or 38HRC
		Over 2-1/2" Diameter	115	140	293BHN or 31HRC	352BHN or 38HRC
A434-76	BB	1-1/2" Diam. and Less	90	110	(See Note 4)	
		Over 1-1/2" to 2-1/2"	80	105		
		Over 2-1/2" to 4"	75	100		
		Over 4" to 7"	75	95		
		Over 7" to 9-1/2"	65	90		
	BC	1-1/2" Diam. and Less	110	130	(See Note 4)	
		Over 1-1/2" to 2-1/2"	105	125		
		Over 2-1/2" to 4"	95	115		
		Over 4" to 7"	85	110		
		Over 7" to 9-1/2"	80	105		
	BD	1-1/2" Diam. and Less	130	155	(See Note 4)	
		Over 1-1/2" to 2-1/2"	120	150		
		Over 2-1/2" to 4"	110	140		
		Over 4" to 7"	105	135		
		Over 7" to 9-1/2"	100	130		

Table 7A-1 (Continued)

ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	Specified Min. Strength (ksi) σ_y	Specified Min. Strength (ksi) σ_{uts}	Specified Hardness Minimum	Specified Hardness Maximum
A487-80	1Q,2Q	--	65	90-115	NS	NS
	4Q,11Q,12Q,13Q	--	85	105-130	NS	NS
	4QA	--	95	115	NS	NS
	6Q	--	95	120	NS	NS
	7Q	2-1/2" Maximum	100	115	NS	NS
	8Q,9Q	--	85	105	NS	NS
	10Q	--	100	125	NS	NS
	14Q	--	95	120-145	NS	NS
A490-80a	All Grades (See Note 7)	1/2" to 1-1/2" Diam.	130	150-170	311BHN or 33HRC	352BHN or 38HRC
A514-77	All Grades	To 34" Thick[8]	100	110-130	235BHN	293BHN
	--	Over 3/4" to 2-1/2"	100	110-130	NS	NS
	--	Over 2-1/2" to 6"	90	100-130	NS	NS
A519-80	(See Note 4)	--	--	--	--	--
A521-76	CG	≤4" Solid Dia. or Thick or≤ 2" Bored Wall Thick	55	90	NS	NS
		>4" to 7" (Solid) or >2" to 3-1/2" (Bored)	50	85	NS	NS
		>7" to 10" (Solid) or >3-1/2" to 5" (Bored)	50	85	NS	NS
		>4" to 10" (Bored)	48	82	NS	NS

Table 7A-1 (Continued)

ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	Specified Min. Strength (ksi) σ_y	σ_{uts}	Specified Hardness Minimum	Maximum
A521-76	AD	≤7" Solid Dia. or Thick or ≤3-1/2" Bored Wall Th.	70	95	NS	NS
		>7" to 10" (Solid) or >3-1/2" to 10" (Wall)	65	90	NS	NS
	AE	≤7" Solid Dia. or Thick or ≤3-1/2" Bored Wall Th.	80	105	NS	NS
		>7" to 10" (Solid) or >3-1/2" to 5" (Bored)	75	100	NS	NS
		>10" to 20" (Solid) or >5" to 8" (Bored)	70	95	NS	NS
	AF	≤4" Solid Dia. or Thick or ≤2 Bored Wall Thick	105	125	NS	NS
		>4" to 7" (Solid) or >2" to 3-1/2" (Bored)	95	115	NS	NS
		>7" to 10" (Solid) or >31/2" to 5" (Bored)	85	110	NS	NS
	AG	≤4" Solid Dia. or Thick or ≤2" Bored Wall Thick	120	145	NS	NS
		>4" to 7" (Solid) or >2" to 3-1/2" (Bored)	115	140	NS	NS
		>7" to 10" (Solid) or >3-1/2" to 5" (Bored)	110	135	NS	NS
	AH	≤4" Solid Dia. or Thick or ≤2" Bored Wall Thick	140	170	NS	NS

Table 7A-1 (Continued)

ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	Specified Min. Strength (ksi) σ_y	σ_{uts}	Specified Hardness Minimum	Maximum
A521-76	AH	>4" to 7" (Solid) or >2" to 3-1/2" (Bored)	135	165	NS	NS
		>7" to 10" (Solid) or >3-1/2" to 5" (Bored)	130	160	NS	NS
SA537-78	2	≤ 2-1/2" Thick	60	80-100	NS	NS
		Over 2-1/2" to 4"	55	75-95	NS	NS
A540-77a/SA540-77a	B21,CL5	≤ 2" Thick	105	120	241BHN	285BHN
		Over 2" to 6"	100	115	248BHN	302BHN
		Over 6" to 8"	100	115	255BHN	311BHN
	B21,CL4	≤ 3" Thick	120	135	269BHN	331BHN
		Over 3" to 6"	120	135	277BHN	352BHN
	B21,CL3	≤ 3" Thick	130	145	293BHN	352BHN
		Over 3" to 6"	130	145	302BHN	375BHN
	B21,CL2	≤ 4" Thick	140	155	311BHN	401BHN
	B21,CL1	≤ 4" Thick	150	165	321BHN	429BHN
	B22,CL5	≤ 2" Thick	105	120	248BHN	293BHN
		Over 2" to 4"	100	115	255BHN	302BHN
	B22,CL4	≤ 1" Thick	120	135	269BHN	341BHN
		Over 1" to 4"	120	135	277BHN	363BHN
	B22,CL3	< 2" Thick	130	145	293BHN	363BHN
		Over 2" to 4"	130	145	302BHN	375BHN
	B22,CL2	≤ 3" Thick	140	155	311BHN	401BHN
	B22,CL1	≤ 1-1/2" Thick	150	165	321BHN	401BHN

Table 7A-1 (Continued)

			Specified Min. Strength (ksi)		Specified Hardness	
ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	σ_y	σ_{uts}	Minimum	Maximum
A540-77a/SA540-77a	B23,CL5	≤ 6" Thick	105	120	248BHN	311BHN
		Over 6" to 8"	100	115	255BHN	321BHN
		Over 8" to 9-1/2"	100	115	262BHN	321BHN
	B23,CL4	≤ 3" Thick	120	135	269BHN	341BHN
		Over 3" to 6"	120	135	277BHN	352BHN
		Over 6" to 9-1/2"	120	135	285BHN	363BHN
	B23,CL3	≤ 3" Thick	130	145	293BHN	363BHN
		Over 3" to 6"	130	145	302BHN	375BHN
		Over 6" to 9-1/2"	130	145	311BHN	388BHN
	B23,CL2	≤ 3" Thick	140	155	311BHN	388BHN
		Over 3" to 6"	140	155	311BHN	401BHN
		Over 6" to 9-1/2"	140	155	321BHN	415BHN
	B23,CL1	≤ 3" Thick	150	165	321BHN	415BHN
		Over 3" to 6"	150	165	331BHN	429BHN
		Over 6" to 8"	150	165	341BHN	444BHN
	B24,CL5	≤ 6" Thick	105	120	248BHN	311BHN
		Over 6" to 8"	100	115	255BHN	321BHN
		Over 8" to 9-1/2"	100	115	262BHN	321BHN
	B24,CL4	≤ 3" Thick	120	135	269BHN	341BHN
		Over 3" to 6"	120	135	277BHN	352BHN
		Over 6" to 8"	120	135	285BHN	363BHN
	B24,CL3	≤ 3" Thick	130	145	293BHN	363BHN
		Over 3" to 8"	130	145	302BHN	388BHN
		Over 8" to 9-1/2"	130	145	311BHN	388BHN
	B24,CL2	≤ 7" Thick	140	155	311BHN	401BHN
		Over 7" to 9-1/2"	140	155	321BHN	415BHN

Table 7A-1 (Continued)

ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	Specified Min. Strength (ksi) σ_y	Specified Min. Strength (ksi) σ_{uts}	Specified Hardness Minimum	Specified Hardness Maximum
A540-77a/SA540-77a	B24,CL1	≤ 6" Thick	150	165	321BHN	415BHN
		Over 6" to 8"	150	165	331BHN	429BHN
	B24V,CL3	≤ 4" Thick	130	145	293BHN	363BHN
		Over 4" to 8"	130	145	302BHN	375BHN
		Over 8" to 11"	130	145	311BHN	388BHN
	B24V,CL2	≤ 4" Thick	140	155	311BHN	388BHN
		Over 4" to 8"	140	155	311BHN	401BHN
		Over 8" to 11"	140	155	321BHN	415BHN
	B24V,CL1	≤ 4" Thick	150	165	321BHN	415BHN
		Over 4" to 8"	150	165	331BHN	429BHN
		Over 8" to 11"	150	165	331BHN	444BHN
A563-78a	DH3	1/4" to 4" Size	NS	NS	248BHN or 24HRC	352BHN or 38HRC
	C3	1/4" to 4" Size	NS	NS	143BHN or 78HRB	352BHN or 38HRC
A574-80	(See Table 2)	≤ 1/2" Diameter	153	180	39HRC	45HRC
		≥ 5/8" Diameter	153	170	36HRC	45HRC
A668-79a	F,FH	≤ 4" Thick	55	90	187BHN	235BHN
		Over 4" to 7"	50	85	174BHN	217BHN
		Over 7" to 10"	50	85	174BHN	217BHN
		Over 10" to 20"	48	82	174BHN	217BHN
	J,JH	≤ 7" Thick	70	95	197BHN	255BHN
		Over 7" to 10"	65	90	187BHN	235BHN
	K,KH	≤ 7" Thick	80	105	212BHN	269BHN
		Over 7" to 10"	75	100	207BHN	269BHN

Table 7A-1 (Continued)

ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	Specified Min. Strength (ksi) σ_y	Specified Min. Strength (ksi) σ_{uts}	Specified Hardness Minimum	Specified Hardness Maximum
A668-79a	L,LH	≤ 4" Thick	105	125	255BHN	321BHN
		Over 4" to 7"	95	115	235BHN	302BHN
		Over 7" to 10"	85	110	223BHN	293BHN
	M,MH	≤ 4" Thick	120	145	293BHN	352BHN
		Over 4" to 7"	115	140	285BHN	341BHN
		Over 7" to 10"	110	135	269BHN	331BHN
	N,NH	≤ 4" Thick	140	170	331BHN	401BHN
		Over 4" to 7"	135	165	331BHN	401BHN
		Over 7" to 10"	130	160	321BHN	388BHN
A687-79	All Grades	--	105	150(max)	NS	NS
A739-76/SA739-76	B11	--	45	70-95	NS	NS
	B22	--	45	75-95	NS	NS
F568-79	8.8	--	660 MPa (95.7 ksi)	830 MPa (120 ksi)	23HRC or 255VHN	34HRC or 336VHN
	8.8.3	--	660 MPa (95.7 ksi)	830 MPa (120 ksi)	23HRC or 255VHN	34HRC or 336VHN
	9.8	--	720 MPa (104 ksi)	900 MPa (131 ksi)	27HRC or 280VHN	36HRC or 360VHN
	10.9	--	940 MPa (136 ksi)	1040 MPa (151 ksi)	33HRC or 327VHN	39HRC or 382VHN
	10.9.3	--	940 MPa (136 ksi)	1040 MPa (151 ksi)	33HRC or 327VHN	39HRC or 382VHN
	12.9	--	1100 MPa (160 ksi)	1220 MPa (177 ksi)	38HRC or 372VHN	44HRC or 434VHN

Table 7A-1 (Continued)

(Definitions and Notes)

Definitions		
BHN	-	Brinell Hardness Number
HRC	-	Hardness Rockwell-C Scale
HRB	-	Hardness Rockwell-B Scale
VHN	-	Vickers Hardness Number

Notes:

1. Bolts or nuts when included with material purchased can be supplied to A325.

2. When hardness limits are specified, the total range or spread may not be less than 0.15 mm difference in indentation diameters (see Table 1 in A125). The specified or indicated minimum hardness must be sufficient to develop the required strength to withstand the solid stresses of the spring design.

3. Same material grade as A537 Class 2.

4. Maximum surface Brinell hardness, if specified by purchaser as a supplementary requirement, shall be agreed upon between the manufacturer and the purchaser.

5. SA320-78 is identical to A320-76 except for the deletion of Grade L1.

6. Bolts shall not exceed maximum hardness specified. Bolts less than 3 diameters in length shall have a hardness value not less than the minimum nor more than the maximum in hardness limits, as hardness is the only requirement.

7. Bolts less than 3 diameters in length shall have hardness values not less than the minimum nor more than the maximum hardness limits specified, as hardness is the only requirement.

8. For plates 3/8 inches and under in thickness, a Brinell hardness test may be used instead of tension testing each plate.

Appendix 7B

LINEAR REGRESSION METHODOLOGY

In the weighted least squares problem, the errors may have different variances but are uncorrelated. Cases with large weight have small variance and are more important in the regression problem. So, when the means of a number of unequal observations are used in the regression, the variance is normally weighted by 1/n, where n is equal to the number of observations used to calculate each mean. A weight of $1/\sigma$ has also been used for this purpose.

The results of linear regression for a model in the following form are given in Tables B-1 through B-3:

$$h = a + bD$$

where

h = Rockwell C hardness

D = Nominal bolt diameter

a,b = Constants

The tables contain regression coefficients (R^2), number of observations (h), weights, F-test for probability of a greater F in test for significance of the model, residual count in terms of plus or minus residuals, and mean square error derived from the fit of the model. The correlation coefficient is defined as:

$$R^2 = \frac{\text{Model Sum of Squares}}{\text{Model Sum of Squares + Error Sum of Squares}}$$

It is interpreted as the fraction of variability about the dependent variable, which may be explained by the variability in independent variables. For the model of ASTM A540-B23-3, with a weight factor of 1/n, the R^2 is 0.944. This model explains 94.4% of the variability of Rockwell C hardness, which is explained by the variable diameter.

Table 7B-1

LINEAR REGRESSION STATISTICS FOR ASTM A540-B23-3

R^2	a	b	n	Weight	Pr > F	Residuals	Mean Square Error
0.090	3.198	32.7	9	None	0.0001	3+, 6-	0.4655
0.944	3.199	32.8	9	1/n	0.0001	3+, 6-	0.0291
0.928	3.298	32.6	9	1/σ	0.0001	5+, 4-	0.3605

Table 7B-2

LINEAR REGRESSION STATISTICS FOR ASTM SA193-B7

R^2	a	b	n	Weight	Pr > F	Residuals	Mean Square Error
0.028	-1.000	30.1	12	None	0.601	5+, 6-	1.9966
0.011	-0.828	29.7	12	1/n	0.742	7+, 5-	0.1342
0.046	-1.423	30.1	12	1/σ	0.502	7+, 5-	1.2855

Table 7B-3

LINEAR REGRESSION STATISTICS FOR ASTM A354-BD

R^2	a	b	n	Weight	Pr > F	Residuals	Mean Square Error
0.701	4.416	32.7	7	None	0.019	4+, 3-	0.9425
0.521	3.113	32.9	7	1/n	0.067	4+, 3-	0.0566
0.625	3.680	33.1	7	1/σ	0.034	4+, 3-	0.5695

Section 8

GOOD BOLTING PRACTICES

As a part of the EPRI Generic Bolted Joint Integrity Program, two reference manuals for nuclear power plant maintenance personnel were developed. Both manuals were written by Mr. John H. Bickford of Raymond Engineering Inc. and Mr. Michael E. Looram of Looram Engineering, and are being published separately from this report. The first of these manuals is entitled "Good Bolting Practices: Large Bolt Manual", while the second is entitled "Good Bolting Practices: Small Bolt Manual". Both manuals are intended for rapid-access field or office use by utility staff who must disassemble and assemble bolted joints in nuclear power plants. Bolting practices are described which should help these people to identify, understand, and solve or minimize bolted joint problems, such as leaks, vibration loosening, fatigue, and stress corrosion cracking.

The manuals describe the problem-reducing steps in order of increasing complexity and cost, since the authors recognized that the options available to maintenance personnel are generally limited. Redesign of equipment is not usually an option, and the cost of using state-of-the-art bolting tools and instruments on any joints other than those most critical to safety is often prohibitive. Therefore, the basic concept is to try the simple remedies first, with more complex and expensive steps to follow, as needed. The remedies are all based upon field experience, rather than on theory, although theoretical justification is generally available, if necessary.

The manuals are not intended for use by designers; therefore, the theories behind the recommended procedures are not discussed at any length. The encyclopedia format for the manuals is intended to make the topics easy to locate. Topics are listed alphabetically and identified by legends that are printed in bold face. Each topic is described briefly, with typical data if pertinent, and with cross references to related topics, also in bold-faced type.

Section 9

BOLTING RULES OF THE ASME BOILER & PRESSURE VESSEL CODE

INTRODUCTION

The provisions of the ASME Boiler and Pressure Vessel Code for the design and construction of bolted joints are often difficult to interpret. There are relatively few bolting rules, and they are scattered throughout the Code among voluminous rules for welding and other fabrication methods. The following example illustrates some of the confusion which exists concerning bolting rules.

Many believe that the room temperature stress in an SA193 B7 bolt should not exceed 25,000 psi, since this is the allowable stress tabulated in Table UCS-23 of Section VIII of the Code. In fact, however, when a B7 bolt is used in a gasketed joint, considerably higher stress is often required at assembly in order to produce a leak-free joint. This example is further discussed later in this section.

Experienced personnel have learned to utilize and interpret the Code rules on bolting. This report will attempt to catalog the bolting rules and comment on rules where appropriate.

OBJECTIVE

The objectives of this report are:

- To review Section III, Division 1; Section VIII, Division 1; and Section XI of the Code, collect all Class I, II and III bolting provisions and publish them in a single reference booklet, with the source for each entry given.
- Explanation of the Code requirements will be given where necessary.
- Conflicting requirements and ambiguities will be noted.
- No attempt will be made to change or extend any portion of the Code.

Organization

The rules relating to bolting for each section are grouped into the following categories:

- Scope
  - --Description of components covered by that section of the code
  - --Responsibilities
  - --Jurisdiction
  - --Exemptions
- Materials
  - --Material specifications
  - --Testing requirements
  - --Certifications
  - --Exemptions
- Design
  - --Design approach
  - --Loads
  - --Allowables
  - --Assembly
- Testing
  - --Hydrostatic
  - --System pressure test

1983 ASME BOILER AND PRESSURE VESSEL CODE, SECTION VIII, DIVISION 1

Scope (U-1)

The scope of this division, ASME VIII Division 1 (hereinafter referred to as the Code), is defined in detail in U-1 of the INTRODUCTION. Specifically, this division is divided into: (a) three Subsections, (b) Mandatory Appendices and (c) Nonmandatory Appendices. Subsection A consists of Part UG and covers general requirements applicable to all pressure vessel. Subsection B covers specific requirements that are applicable to welded (Part UW), forged (Part UF) and brazed (Part UB) pressure vessels. Subsection C covers specific requirements applicable to the several classes of materials used in pressure vessel construction. It consists of parts UCS, UNF, UHA, UCI, UCL, UCD, UHT, ULW and ULT dealing with carbon and low alloy steels, nonferrous metals, high-alloy steels, cast iron, clad and lined material, cast ductile iron, ferritic steel with properties enhanced by

heat treatment, layer construction, and low temperature materials, respectively. Subsection C also contains tables of maximum allowable stress values for the various classes of materials. The Mandatory Appendices address specific subjects not covered elsewhere in the Code; the Nonmandatory Appendices provide information and suggested good practices.

Materials (UG-4)

Materials for bolts and studs must conform to one of the specifications given in Section II and are limited to these which are permitted in the applicable part of Subsection C. When provisions of the Code exceed or supplement the requirements of the material specification of Section II, the material (bolting) shall be ordered in accordance with the material specification and the special provisions of the Code (UG-93(c)).

Bolts and Studs (UG-12). UG-12 expands upon the requirements of UG-4 and gives design details for the threaded and unthreaded portions of studs.

Allowable Stress Values (UG-23). This specifies the tables of maximum allowable stress values for various types of materials; for example, maximum allowable stress values for carbon and low-alloy steel bolting are given in Table UCS-23 which is included in Subsection C. See UNF-12 for some special requirements which apply to nonferrous bolting materials.

Low Temperature Operation. Each of the various parts of Subsection C state when (or if) bolting must past impact tests as prescribed in UG-84; the requirements of the various Parts are summarized below (the applicable Code paragraph should be referred to for specific requirements and exemptions).

1. Part UCS: According to UCS-65 and UCS-66, impact testing is required when the operating temperature is below -20°F.

2. Part UNF: According to UNF-65, no impact tests are required for wrought aluminum alloys when they are used down to -452°F, or for copper and copper alloys and nickel and nickel alloys when they are used down to -325°F.

3. Part UHA: According to UHA-51, no impact tests are required for Types 304, 304L and 347 stainless steel and for 36% nickel steel when they are used at temperatures of -425°F and higher and for all other Table UHA-23 materials operating at temperatures of -325°F and higher. Certain requirements are modified in UHA-51(b).

4. Parts UCI and UCD: According to UCI-12 and UCD-12, the requirements for bolts, nuts and washers are the same as for carbon and low-alloy

steels per UCS-10 and UCS-11. Although it is not stated, the intent of Parts UCL and ULW should be similar.

Impact Test Criteria (UG-84). For bolting, impact testing shall be in accordance with an approved material specification as described in Par. 2 above, except as otherwise modified by UG-84. According to Table UG84-1, for bolting having a specified minimum tensile strength of 95,000 psi and over, the minimum lateral expansion for 3 specimens shall be 0.015 inch; however, for bolts in diameters of 2 inches and under, the Charpy V-notch impact requirements of SA-320 may be applied.

Marking (UG-94). Bolts shall be marked (identified) in accordance with the approved Section II material specification.

Inspection (UG-93).

1. All materials shall be examined for the purpose of detecting, as far as possible, defects which would affect the safety of the vessel.

2. All materials that are to be tested in accordance with the requirements of UG-94 shall be inspected for surface cracks (UG-93(D)(2)).

Responsibilities (U-2(b)).

- Quality Control System in accordance with Appendix 10 of the Code.

- Traceability to the material specification in accordance with UG-93.

Design

General. In the Code, bolts (staybolts, as referred to in UG-47 and elsewhere in the Code are beyond the scope of this discussion) are used principally for:

1. Unstayed flat heads and covers as illustrated in Details (j), (k), (o) and (p) of Fig. UG-34.

2. Circular, spherically dished heads with bolting flanges such as described in 1-6 of Mandatory Appendix 1.

3. Studded connections such as Detail (p) of Fig. UW-16.1.4.1.

4. Bolted flange connections with ring type gaskets as described in Appendix 2; this appendix covers both conventional, raised face flanges and reverse, raised face flanges (2-13).

5. Supported and unsupported tubesheets with a bolting flange as illustrated in Fig. UW-13.2 sketches (h) through (l) or Fig. UW-13.3 sketch (c).

6. ANSI and API flanges and flanged fittings as described in UG-44.

7. Flat face flanges with metal-to-metal contact outside the bolt circle as described in Nonmandatory Appendix Y.

Design Requirements (Appendix 2). Rules for the design of bolted flange connections with gaskets that are entirely within the bolt circle and with no contact outside this circle are contained in Appendix 2. These rules are used to calculate both flange stresses and the amount of bolting required. Appendix 2 is also used for figuring the amount of bolting required. Appendix 2 is also used for figuring the amount of bolting required for unstayed flat heads and covers of the types depicted by Details (j) and (k) of Fig. UG-34 and spherically dished covers with bolting flanges and ring gaskets as illustrated in Fig. 1-6. According to Appendix 2, the minimum load required to seat a gasket is:

$$W_{m2} = 3.14bGy \qquad (9\text{-}1)$$

and the minimum total bolt load required at the operating condition for a tight joint is:

$$W_{m1} = 0.785G^2P + (2bx3.14GmP) \qquad (9\text{-}2)$$

where

G = Diameter at location of the gasket load reaction

b = Effective gasket width

y = Gasket unit seating load

P = Design pressure

m = Gasket factor related to the minimum required load on the gasket for a tight joint at the design pressure

The significance of Formula (9-2) is that when the design pressure "P" is applied, a load equal to $0.785G^2P$ is removed from the gasket leaving a residual load of 2bx3.14GmP on the gasket, which is required for a tight joint at the design pressure.

The total required (minimum) cross-sectional area of the bolts is the greater of W_{m1}/S_b and W_{m2}/S_a where:

S_a = Allowable bolt stress at atmospheric temperature

S_b = Allowable bolt stress at design temperature

A detailed discussion of bolting will be found in 2-5 of Mandatory Appendix 2. Paragraph 2-2(e) recommends that bolts and studs have a nominal diameter of not less than 1/2 inch but requires that ferrous bolting material for bolts or studs smaller than 1/2 inch be of alloy steel.

Design Requirements (Appendix Y). Appendix Y is a Nonmandatory Appendix which covers flat face flanges with metal-to-metal contact outside the bolt circle. Since the use of such flanges is generally limited to special applications, the appendix should be referred to for flange- and bolting-design rules. Particular attention is called to the discussion on bolting in Y-1, Y-4, Y-8 and Y-9.

Design Requirements (Miscellaneous). The Code does not provide rules for bolted flanges using full-face gaskets, accordingly, U-2(g) applies. The design of clamp connections including the bolting is covered in Appendix Z, "Design Rules for Clamp Connections".

Paragraph 2-1 states in part: "These rules are not to be used for the determination of the thickness of supported or unsupported tubesheets integral with a bolting flange....". Paragraph 2-5, however, provides rules for the design of bolting for flange pairs used to contain a tubesheet of a heat exchanger or any similar design where the flanges and/or gaskets may not be the same.

Bolt Preload (Appendix S)

The rules in Appendix 2 apply only to the design of bolted flange connections with gaskets that are entirely within the circle enclosed by the bolts and with no contact outside this circle. The Appendix covers both the design of the flange and associated bolting. Although the application of the rules leads to the minimum amount of bolting required (A_m), Appendix 2 provides no guidelines with respect to a suggested preload, nor does it limit the bolt assembly (preload) stress. It can be shown that the bolt assembly stress will often have to exceed the so-called "maximum allowable stress" for the joint to be tight at the design pressure or to pass a hydrostatic test. Assume that the amount of bolting required is governed by Formula 2 above and that the total cross-sectional area of the bolts provided just equals the total required area $A_m = W_{m1}/S_b$; bolts stressed to their allowable

stress will develop a total load equal to W_{m1}. It may be deduced from Formula 2 that the residual load on the gasket at the design pressure is just equal to the load required for a tight joint, i.e., 2bx3.14GmP. In actuality, if the bolt assembly stress equals S_b, the actual bolt stress after the design pressure has been applied will usually be less than W_{m1} (and the residual load on the gasket will be less than 2bx3.14GmP) due to the pressure causing additional rotation of the flanges. Accordingly, the assembly will leak at the design pressure. For the case just cited, the assembly bolt stress must exceed 1 1/2 time W_{m1} or 1 1/2 times the allowable bolt stress to pass a pressure test which is 1 1/2 times the design pressure.

Appendix S, "Design Considerations for Bolted Flange Connections", recognizes the above and states in part: "In any event, it is evident that an initial bolt stress higher than the design value may and, in some cases, must be developed in the tightening operation, and it is the intent of this Division that such a practice is permissible....". Appendix S approves the use of simple wrenching without verification of the actual bolt stress and states that on this basis the probable bolt stress is S = 45,000/d, where S is the bolt stress and d is the nominal diameter of the bolt.

Appendix Y which applies to flat face flanges with metal-to-metal contact outside the bolt circle adopts the same philosophy as Appendix S (simple wrenching without verification) except in special cases as described in Y-8.

1983 ASME BOILER AND PRESSURE VESSEL CODE, SECTION III, DIVISION 1, SUBSECTION NC (SUMMER 1985 SI ADDENDA)

Scope (NC 1100)

This subsection contains rules for the design, fabrication and testing for Class 2 construction. The types of components covered are pressure retaining components such as vessels, pumps, valves, and tanks. NC 1100 (c) acknowledges that the subsection may not have rules for all construction details; the Owner and the N Certificate Holder are responsible to provide details of construction consistent with the rules of NC.

Jurisdiction (NC 1131). The Design Specification is required to define the boundary of the component. The boundary is the face of the first flange in bolted connections; when connected to piping the bolts are considered part of the piping.

Materials (NC 2000)

Bolting Materials (NC 2128).

- Materials for bolting must be in accordance with the specifications of Table 7.3.
- Nuts must conform to SA194 of the "a" specification listed in Table I-7.3.
- Washers are optional; if used, washers must be of wrought material which is compatible with the nut material.

Material Certification (NC 2130).

- Certified Material Test Reports (CMTR) is required for all pressure retaining material.
- Manufacturer's Certificate of Compliance is acceptable for bolting smaller than M24 (one inch diameter).

Material Marking (NC 2150). All material must be marked in accordance with NCA 3866.6, so that parts are identifiable at all times.

Test Coupon (NC-2224.3). This paragraph specifies the test coupon for bolting.

Impact Tests (NC 2310). Charpy V-notch tests are required on all pressure retaining material. The tests are performed in accordance with NC 2330.

Exemptions. NC 2311 (e)(2) exempts bolting smaller than M24 (1 inch diameter). There are also other exemptions based on the component pipe size and wall thickness.

Charpy V-Notch Tests (NC 2332.3).

- Must be performed at the lowest service metal temperature.
- Tests must meet the requirements of Table NC 2332.3-1, (0.65 mm lateral expansion for bolting).

Sampling (NC 2345).

- Sample frequency is based on lot size by weight of material.
- Retests are specified in NC 2352.

Examinations. Studs and bolts must meet the requirements of SA-614. Examinations are performed in accordance with Paragraph of SA-614.

Design (NC 3000)

The design rules of NC address flanged joints, pumps and valves. The flange design rules are very similar to those of Section VIII. NC has some additional rules concerning fatigue, bending, and service conditions. The pump and valve design rules are an adaptation of the flange design rules.

Bolting Dimensional Specifications. Table NC 3132-1 lists the acceptable ANSI B18 standards for bolting.

Bolted Flanges (NC 3262).

- Flange dimensions of ANSI B16.5 tables 13-33 are acceptable and may be used at the rated temperature and pressure.
- There is an exception taken to using ANSI threaded and socket weld flanges at the ANSI ratings.
- ANSI slip-on flanges are subjected to a set of additional criteria (NC-3262.2).
- Flanges not conforming to ANSI B16.5 must be designed in accordance with Appendix XI or by rules of Appendices II, XIII, XIV.

Appendix XI Rules for Bolted Flange Connections for Class 2 and 3 Components. Appendix XI gives rules for design of bolted gasketed joints with the gasket entirely within the bolt circle (RF flanges). Appendix XI is identical to Appendix 2 of Section VIII in regard to design rules for selecting, sizing and preloading bolts. The comments on Section VIII Appendix 2 therefore apply to Appendix XI.

Appendix XII Design Considerations for Bolted Flange Connections.

- Appendix XII is identical to Appendix S of Section VIII. Appendix XII is a mandatory appendix; whereas Appendix S is nonmandatory. The discussion of Appendix S therefore applies to Appendix XII.
- NC allows tightening bolts to stress levels in excess of design allowables provided precautions are taken to ensure against flange or gasket damage.

Appendices II, XIII, and XIV. Flanges may be designed to these appendices.

- Appendix II covers design by experimental stress analysis. Bolting is not specifically mentioned in this appendix.

- Appendix XIII covers design based on stress analysis for vessels designed in accordance with NC 3200. This is an alternate design approach which uses a more detailed stress analysis. The analysis requires the calculation of principal stresses, and considers bending, stress concentrations, and thermally-induced bolt stresses. The results of the analysis are in the form of stress intensities which are compared to allowable stress intensities, such as S_m.

Appendix XIII Design of Bolting (XIII 1180).

- The sizing of the bolts is done the same as Appendix XI. The only variation being that the stress intensity allowables S_m of Table I-1.3 are used as the bolt allowable stress.
- For comparison an SA 193 B7 stud less than 2 1/2 inch diameter, Appendix XI stress allowable at 100°F is 25,000 psi (Table I-7.3). The Appendix XII stress intensity for the same stud is 35,000 psi (Table I-1.3).

Allowable Service Stress (XIII 1182). Appendix XIII, like Appendix XII, recognizes that bolt stress may exceed the design allowable stress (S_m). Appendix XIII deals with this issue by placing limits on the bolt service stress. The service stress is calculated by considering the effect of bolt preload, internal pressure and differential thermal expansion on bolt stress.

- The maximum service stress based on the bolt cross section (neglecting stress concentrations) will be less than $2S_m$.
- When bending is included (again neglecting stress concentrations) the bolts stress based on average section area will be less than $3S_m$.
- When bolts are tightened by methods which introduce torsional stress, such as torque, the service stress will be calculated as a stress intensity rather than an average stress and then compared as above to the $2S_m$ or $3S_m$ allowable.

Appendix XIV. Appendix XIV describes fatigue-analysis requirements. Fatigue analysis is required if the conditions of NC 3219 are not met. NC 3219 contains a series of screening rules intended to characterize the cyclic loading of the vessel. Bolts are evaluated for fatigue service using Paragraph XIV 1220 and the requirements imposed by XIV 1322, 1323, 1324.

Attachments NC 3264. Attachments to the outside of the vessel using stud bolts must be analyzed for fatigue in accordance with Appendices XIII and XIV, unless the fatigue analysis is judged unnecessary by considering the screening criteria of NC 3219.

Flat, Unstayed Heads (NC 3325.2). The thickness of this type of head is calculated using a bolt load (the greater of W_{m1} or W_{m2}) from Appendix XI 3223.

Bolted, Flange and Studded Connections (NC 3362).

- Recommends ANSI B16.5, MSS SP-42 or API 605 for connections to external piping.
- Paragraph (b) gives an equation for calculating the length of engagement of tapped holes:

$$\text{Depth} = 0.75\, d_s \times \frac{\left(\begin{array}{c}\text{Maximum Allowable Stress Value of}\\ \text{Stud Material at Design Temperature}\end{array}\right)}{\left(\begin{array}{c}\text{Maximum Allowable Stress Value of}\\ \text{Tapped Material at Design Temperature}\end{array}\right)}$$

  where d_s = the stud diameter

- The thread engagement need not exceed 1.5 times the stud diameter.

Pumps (NC-3434).

- (NC-3434.1) Bolting for radially-split configurations with the bolts arranged axisymmetrically is designed using Appendix XI.
- (NC-3434.2) Bolting for axially-split pumps is designed by NC-3441.7 for type G pumps.
- The analysis is an adaptation of the Appendix XI approach for RF flanges:

  --W_{m1} and W_{m2} loads are calculated

  --Gasket m and y factors are used

  --Bending and shear stresses are calculated for the bolting and the pump case.

- The formula for calculating the bending, shear and combined stress in the bolts is detailed. This is unusual for the Code. Normally the assumptions required to calculate the bending in a bolt are not prescribed but are left to the analyst.

Reciprocating Pumps (NC-3450).

- Liquid end pressure retaining bolting must be analyzed for fatigue (NC-3454.4). Any analysis method may be used which has been demonstrated to be satisfactory for the specified design.
- Axisymmetric bolting arrangements involving the pressure boundary are designed using Appendix XI (NC-3454.7).

Relief Valves (NC-3591.1). The body-to-bonnet (yoke) bolting must be designed to resist the hydrostatic end force of the rated maximum secondary Design Pressure, combined with the total spring load to full lift. With these loads applied, sufficient compression must be maintained on the joint. Bolt stress must be less than allowables of Table I-7.3.

Piping (NC-3600).

- Bolting standards must comply with standards listed in Table NC-3132-1. Bolting to be in accordance with ANSI B16.5 (NC-3647.6).
- Bolts or studs shall extend completely through the nut.
- Studs shall be threaded for the full length or machined to the root diameter with suitable transitions to the threaded portion of the stud (NC-3647.6[6]).

Flange Joints (NC-3658.1). Flange and bolt design use methods of Appendix XI. The design pressure is replaced by the flange design pressure P_{FD}

$$P_{FD} = P + P_{eq}$$

where P is the service design pressure, and P_{eq} is the equivalent pressure to account for the moments applied to the flange joint during the design condition. The flange and bolting may also be designed using Appendix XIII.

Testing

NC-6111 exempts bolts, nuts and washers from pressure tests. NC-6220 requires a hydrostatic test on an installed system to a pressure of 1.25 times the design pressure.

1983 ASME BOILER AND PRESSURE VESSEL CODE, SECTION III, DIVISION I, SUBSECTION ND

Scope (ND-1100)

This subsection contains rules for the design and fabrication and testing of Class 3 construction.

Materials (ND-2000)

The material requirements for ND are identical to those of subsection NC. The paragraph numbering also corresponds almost exactly with the "C" being replaced by "D". The only difference between NC and ND is that ND is a little less stringent

on the Charpy impact requirements. Table ND-2333-1 allows lateral expansion of 40 to 50 mm, depending on nominal diameter, whereas Subsection NC, Table NC-2332.3-1 requires 65 mm on all sizes.

Flange Bolting Rules

The flange bolting rules are similar to NC.

- ANSI B16.5, API 605, MSS SP-42 or flanges designed to Appendix XI are acceptable per NC-3352.
- Appendices II, XIII and XIV are not mentioned as alternate design procedures.

Testing

The same requirements exist as for NC components.

- Hydrotest at 1.25 times system pressure.

1983 ASME BOILER AND PRESSURE VESSEL CODE, SECTION XI (SUMMER 1985 ADDENDA)

Scope

The rules of Section XI constitute requirements to maintain a nuclear power plant and to return it to service following an outage. The rules require mandatory examinations, testing and inspections, and levy requirements in the following areas: (1) areas to be inspected, (2) accessibility requirements, (3) examination methods, (4) evaluation standards, and (5) repair requirements.

Jurisdiction (IWA-1200). Subsection XI covers individual components and complete power plants that have met the requirements of the Construction Code, commencing at the time that the Construction Code requirements have been met.

Class 1 Components (IWB-1100)

This subsection provides rules and requirements for inservice inspection, repair, and replacement of Class 1 pressure retaining components and their integral attachments.

Exemptions (IWB-1220). The following components are exempted from volumetric and surface examination:

1. Components of such a size that a postulated rupture is within the capacity of the makeup system.

2. Piping of NPS 1 and smaller.

3. Reactor vessel head connections and associated piping, NPS 2 and smaller, made inaccessible by control rod drive penetrations.

Examination and Inspection (IWB-2000)

All examinations required by this article must be completed before plant startup. Shop and field examination may serve in lieu of pre-service examination if they are done under conditions, with equipment and techniques equivalent to those that are expected to be employed in subsequent inservice inspections. If a component is replaced, added or altered, it must be inspected.

Evaluation Standards

Examination and Pressure Test Requirements (IWB-2500). This subsection specifies the parts, requirements, the examination method and the frequency of examination.

There are two examination categories for bolting: B-G-1 for bolting greater than 2" diameter, and B-G-2 for bolting less than 2" diameter.

There are three examination methods prescribed for bolting in this subsection:

1. Surface Examination - The acceptance standard for this type inspection is in preparation. IWA-2220 states that a surface examination is conducted by either magnetic particle or liquid penetrant method.

2. Volumetric Examination - The volumetric examination may be conducted using either radiographix or ultrasonic techniques in accordance with IWA-2230. IWB-3515 details the acceptance criteria for volumetric examination:

   --This subsection applies to bolting greater than 2" diameter (B-G-1 examination category).

   --Allowable surface flaws are 1/4" in non-axial direction and 1" in the axial direction.

   --Allowable non-axial flaws are specified by Table IWB-3515-1.

   --The allowable flaw in a tapped hole shall not exceed 0.2 inch in a plane normal to the bolt axis as measured radially from the root of a thread.

3. Visual, VT-1 (IWB-3517) - This section covers B-G-1 bolting (greater than 2" diameter) and B-G-2 bolting (less than 2" diameter). The examination as described in IWA-2211 is visual, looking for cracks, wear, corrosion, or physical damage on the surface. This inspection may be conducted when access is sufficient to place the eye within

24" from the surface and not less than 30° to the surface. Lighting shall be sufficient to resolve a 1/32" black line on an 18% neutral gray card. IWB-3517 states that the following conditions require correction prior to service:

--Cracks which exceed the allowables in IWB-3515

--Deformed or sheared threads in the thread engagement

--Corrosion-induced decrease in thickness of 5%, or greater

--Bending or twisting of fastener which impairs assembly or disassembly

--Missing or loose fastener, nut or washer

--Fractured fastener or nut

--Degradation of coating on fastener

--Evidence of leakage near bolting

Corrective Actions

If any of the above conditions are found prior to service, the corrective actions are specified by IWB-3122. The acceptable corrective actions are supplemental examination (IWB-3122.2), repair (IWB-3122.3) or replacement (IWB-3122.4).

When unacceptable conditions are found during inservice inspection, the corrective actions are governed by IWB-3142. These actions are the same as the preservice corrective actions, with the addition of an acceptance by analytical evaluation (IWB-3142.4). This last course of action allows continued service if the analysis shows that the component is acceptable for service with the defect, provided that the component be examined in accordance with IWB-2420 to determine that the defect has increased in size for three successive inspection periods.

Repair (IWB-4000). No repair procedures are authorized for bolting.

Replacement (IWB-7320). Bolt size and torquing loads shall be in accordance with the rules of Section III, Appendix E, unless mating parts built to other requirements make this impractical. Materials for replacement are specified by IWA-7200:

- Must meet the requirements of the Construction Code to which the original component or part was constructed.
- If no Construction Code existed, replacements must meet the original design, fabrication and inspection requirements.

- Replacements may meet all or portions of later Code additions, provided that function and performance of the part is unchanged and that the change is reconciled with the Owner's Specification through Stress Analysis Report, Design Report or other suitable method.

Replacement Because of Failure (IWA-7220). If a part or component is replaced because of failure, a failure analysis is required to consider the suitability of the replacement. If the failure was caused by a deficiency in the specification of the original part, the specification for the replacement should make appropriate remedial provisions.

System Pressure Test (IWB-5000)

This subsection specifies that pressure retaining components be tested and inspected in accordance with IWA-5000. Components are subjected to system pressure test during which a VT-2 visual examination is performed to detect leakage (IWA-5211, and IWA-5240). If leakage is detected at a bolted connection, the bolting shall be removed and a VT-3 visual examination be performed for corrosion. The results of the examination are evaluated in accordance with IWA-3100 (IWA-5250). The VT-3 examination is specified in IWA-2213; its purpose is to determine the general structural and mechanical condition of the bolting, in this case corrosion, wear, erosion or loss of integrity. IWA-3100 refers to IWB-3000 for evaluation of defects found during pressure tests.

Class 2 Components (IWC-1000)

This subsection provides for inspection, repair and replacement of Class 2 pressure retaining components and their integral attachments.

Exempt Components (IWC-1220).

- Component connections smaller than 4" nominal pipe size (NPS 4) in vessels, piping, pump, valves, etc., in all systems except high pressure safety injection systems of PWR plants.
- Component connections smaller than NPS 1-1/2 in safety injection systems of PWR plants.

Examination and Pressure Test Requirements (IWC-2500)

- There are no requirements for examining bolts less than 2" diameter.
- For pressure retaining bolting greater than 2.0" diameter, volumetric examination in accordance with IWC-3513 is required. This requirement is found in Table IWC-2500-1.

- Examinations may be performed on bolting in place under load or at disassembly. Where a group of similar joints exists, examination of one joint in the group meets the requirement.

Evaluation Standards for Volumetric Examinations

- Standards for examination, Category C-D, Pressure Retaining Bolting (greater than 2" diameter) (IWC-3513).
- Allowable planar indication sizes are given in Table IWC-3513-1.
- Surface indication allowables are found in IWC-3513.2. Permissible surface indications are:

  --Non-axial $\leq$ 1/4 inch length

  --Axial $\leq$ 1 inch length

Corrective Actions

Repair (IWC-4000). No repair practices or procedures stated for bolting.

Replacements. Replacements are made in accordance with IWC-7000. Bolt size and torquing loads shall be in accordance with the rules of Section III, Appendix E, unless mating parts built to other requirements make this impractical. Materials for replacement (IWA-7200):

- Must meet the requirements of the Construction Code to which the original component or part was constructed.
- If no Construction Code existed, replacements must meet the original design, fabrication and inspection requirements.
- Replacements may meet all or portions of later Code additions, provided that function and performance of the part is unchanged and that the change is reconciled with the Owner's Specification through Stress Analysis Report, Design Report or other suitable method.

Replacements Because of Failure (IWA-7220). If a part or component is replaced because of failure, a failure analysis is required to consider the suitability of the replacement. If the failure was caused by a deficiency in the specification of the original part, the specification for the replacement should make appropriate remedial provisions.

Pressure Tests (IWC-5000)

The pressure retaining components are subjected to the prescribed pressure tests. The pressure retaining boundary is visually inspected (VT-2) in accordance with Table IWC-2500-1.

1983 ASME BOILER AND PRESSURE VESSEL CODE, SECTION III, DIVISION 1, SUBSECTION NF (SUMMER 1985 ADDENDA)

Scope (NF-1110)

This subsection covers supports for components which are intended to conform to the requirements for Classes 1, 2, 3 and MC construction as set forth in Subsections NB, NC, ND and NE. Component supports are metal elements which transmit loads between nuclear power plant components and the building structure; they carry weight of components or provide structural stability. The supports may be of the plate shell type such as vessel skirts, or of the linear variety such as a clevis and pin arrangement. Hangers are considered structural supports in accordance with NCA-3240.

Boundaries of Jurisdiction (NF-1130). Rules for determining an appropriate interface between NF components and other elements such as pressure retaining, intervening and building structure are detailed in NF-1130. There are 13 sketches and explanations covering the many possible combinations. Jurisdictional boundaries may be summarized as follows:

- If the bolted joint has at least one NF component, the connection is governed by NF.
- If the joint has no NF components (i.e., a joint between an intervening element and building structure), NF is not applicable.
- In a joint between an NF support and building structure using embedded studs, the following jurisdiction applies:

  --Non-integral support to building structure Fig. NF-1131-1 (f). The connection is governed by NF; therefore, the studs would be NF.

  --Integral support to building structure Fig. NF-1131-1 (m). The boundary is at the surface of the building structure (NF-1132.7). The design rules for the studs are undefined, since they cross the jurisdictional boundary.

Not Covered by NF.

- Intervening elements in the load path as well as the building structure: The owner is responsible for assuring the adequacy of the building structure and the intervening elements (NF-1111).
- Dynamic loads: A structural element, the sole function of which is to carry dynamic loads caused by a postulated loss of pressure retaining integrity, i.e., pipe whip restraints.
- Deterioration which may result from erosion, corrosion, or radiation effects.

Materials (NF-2000)

Permitted Material (NF-2121). Materials must conform to the requirements of the specifications listed in Appendix I. Bolting requirements for all classes of construction are found in Tables I-1.3, I-13.1, I-13.3, I-3.1, I-3.2.

Test Coupon (NF-2224 [b]). Specifies the location of a test coupon from nut, stud, or bolt.

Impact Testing (NF-2311).

- Design specification (NCA-3250) states whether impact testing is required for all classes of supports.
- Bolting including studs, nuts and bolts less than M24 (1.0" diameter) are exempted from impact tests for all classes of construction.
- Other exemptions are given based on class of support, material, thickness and lowest service temperature.

Impact Test Criteria (NF-2333). For bolting, three specimens must meet the lateral expansion values of Table NF-2333-1 (0.65 mm for bolts over 25 mm diameter).

Sampling Frequency (NF-2345). One sample is required per lot. The lot size is based on diameter and weight.

Required Examinations (NF-2581.1). All Class 1 bolting must be visually examined in accordance with NF-2582. Diameters greater than M48 (approximately 2.0") require magnetic particle or liquid penetrant inspection per NF-2583. This inspection is performed on the finished bolting material or on the material stock of approximately the finished diameter after heading. Linear indications greater than 25 mm long are unacceptable. Sizes greater than M100 (4") also require ultrasonic inspection over the entire volume prior to threading per NF-2584.

Inspection.

Visual Examination (NF-2582). This applies to Class 1, 2, 3 and MC Construction. Threads, shanks and heads of final machined parts shall be visually examined for discontinuities such as laps, seams or cracks that would be detrimental to the intended service.

Weld Repair (NF-2586). Weld repair is not permitted for threaded fasteners.

Documentation (NF-2610). Quality system in accordance with NCA-3800 is required. Small products (bolting less than M48) require only a Certificate of Compliance when no impact testing is required. When impact tests are required, the material shall be furnished with Certified Material Test Reports.

Design (NF-3000)

General Design Requirements (NF-3100). The following loadings shall be designed for:

- Weight of piping and components and contents under normal operating or test conditions, including loads due to static and dynamic head and fluid flow effects.
- Weight of piping or component supports.
- Superimposed loads and reactions induced by supported system components.
- Dynamic loads including earthquake.
- Thermal expansion effects.
- Anchor and support movement effects.
- Environmental loads such as wind and snow.

Design Loadings (NF-3112). The design loadings, design temperature and the service conditions are established in the Design Specification in accordance with NCA-2142. Component supports are designed by different methods, depending on the type of support and the class of component being supported. The Maximum Shear Stress Theory is used for design by analysis of plate and shell type component supports such as cylindrical skirts. The Maximum Stress Theory is used for linear supports. Component standard supports can be designed by Load Rating (prototype testing) or Experimental Stress Analysis.

Design Requirements (NF-3324.6). This section covers joints which are subjected to tensile, shear loads and a combination of tensile and shear loads. All classes of joints must be designed in accordance with this section. For Class 1 joints, additional consideration must be given to fatigue loading.

Tension Joints (NF-3324.6[1]). For joints carrying tensile loads, the allowable bolt stress (F_{tb}) is specified as:

$$F_{tb} = \frac{S_u}{2.0} \quad \text{for ferritic steel}$$

$$F_{tb} = \frac{S_u}{3.33} \quad \text{for austenitic steel}$$

The computed tensile stress in the bolt (F_{tb}) is based on the following:

- The tensile area of the bolt cross section.
- The applied load is the sum of the external load, plus any tension resulting from prying action.
- Preload stress in the bolts is not considered.
- The computed stress must be less than the allowable stress for a satisfactory design.

Shear Joints (NF-3324.6[2]). The allowable shear stress for bolts in a bearing type shear joint is given as:

$$F_{vb} = \frac{0.62\ S_u}{3} \quad \text{for ferritic steel}$$

$$F_{vb} = \frac{0.62\ S_u}{5} \quad \text{for austenitic steel}$$

where F_{vb} is the allowable shear stress. The nominal bolt diameter or the root diameter is used in the calculation depending on whether or not the thread area is excluded from the shear plane.

S_u = Ultimate Strength at Temperature

In this type of joint the bolts bear across the thickness of the plates, with the bolts carrying the load in shear.

Bearing Allowables (NF-3324.6). The allowable bearing stress on the projected area of the bolts in a bearing type connection is:

$$F_p = \frac{L\ S_u}{2d} - 1.5\ S_u$$

where L is the distance from center of bolt hole to edge, and F_p is the bearing stress allowable. The bearing area is calculated as the projected bolt diameter times the length of the bolt in bearing. Other rules of NF-3324.6 are:

- Minimum and maximum distance from center of bolt hole to nearest edge are specified.
- Minimum hole spacing is specified.
- For SA-307 bolts with long grids (greater than 5 diameters), the number of bolts must be increased by 1% for each additional 1.6 mm in the grip.
- Anchor bolts shall be designed to provide resistance to all conditions of tension and shear at the bases of any columns, including the net tensile components of any bending moments which may result from fixation or partial fixation of columns.

Combined Tensile and Shear Joint (NF-3324.5[3]). The equation below using the calculated tensile and shearing stress must be satisfied.

$$\left(\frac{f_t}{F_{tb}}\right)^2 + \left(\frac{f_v}{F_{vb}}\right)^2 \leq 1.0$$

where f_t is the computed tensile stress, f_v is the computed shear stress, $F_{tb}$is the allowable tensile stress at temperature, and F_{vb} is the allowable shear stress at temperature.

Friction Joints (NF-3324.6[3][b]). Friction joints rely on the high clamping force of the bolts to develop frictional resistance at the mating surfaces of the joint. These frictional forces transmit the external loads across the joint. The slip resistance of the joint P_s is calculated as follows:

$$P_s = m\ n\ T_i\ K_s$$

where P_s is the maximum slip resistance of the joint, m is the number of shear planes per bolt, n is the number of bolts in the joint, T_i in the initial clamping force per bolt, and K_s is the slip coefficient for a particular surface condition taken from Table NF-3324.6[a][4]-1.

If the joint clamping force will be reduced by direct tension load on the joint, reduce T_i by an equivalent amount. SA-307 or austenitic steel bolting shall not be used for friction type joints.

NF-3225.2 lists stress limit factors (K_{bo}) which range from 1.0 for Service Level A to 1.25 for Test Loading. The stress in a component must not exceed the allowables of NF-3324.6 times the stress limit factor for the appropriate loading condition. This product must not exceed the yield strength at temperature. These multiplying factors are not applicable for friction type joints.

Design by Load Rating (NF-3281). When bolted assemblies are tested to establish a load rating, the bolted joints in the test sample shall be made up using the lowest strength bolt material and minimum edge distance allowed by specification.

The NF joint design rules are straightforward and very similar to the AISC rules. The NF rules are clear and specific for tensile and shear joints in which:

- All joint members are metal.
- One or more of the members are NF.

The joint design for an integral NF support attached to a building structure with embedded studs is not adequately covered by NF.

The jurisdictional boundary for this joint is at the surface of the building structure (NF-1132.7). This boundary puts the studs in the interface. It is not clear whether the studs are structure or NF. A common sense approach would be to design the studs to the more stringent requirements (in this case, NF). Even if the studs were designated NF, there are no rules in NF for the design of the embedment.

Fatigue Analysis. High cycle fatigue analysis is required per NF-3143 for Linear Supports for Class 1 construction. NF-3330 prescribes the rules for high cycle fatigue design:

- If the members are subjected to repeated variation of live load, the range of stress and the number of stress cycles must be considered in the design analysis (NF-3332.1).
- Properly tightened ASTM A325 or ASTM A490 bolts do not require a fatigue analysis (NF-3332.5).
- The maximum stress including the effects of prying action shall not exceed the allowables of NF-3332.4 subject to the following conditions:

  --Joints subject to 20,000 to 500,000 cycles of direct tension may be designed for the stress produced by summing the applied axial load and the prying load, provided the prying load does not exceed 10% of the external load.

- --If the prying load exceeds 10% of the external load, then the allowable stress of NF-3324.6 is reduced to 40% applicable to the external load alone.
- --Joints subject to greater than 500,000 cycles are designed as above with the prying load limited to 5% of the external load. If the prying load exceeds this 5% value, then the allowable is reduced by 50%.
- --The use of threaded fasteners in tensile fatigue loadings is not recommended.
- --Shear joints subject to fatigue loading shall be designed as bearing type connections with regard to the fatigue strength of the fastener.

Preload

The design of NF supports (NF-3000) considers bolt preload only in the case of the friction joint (NF-3324.6[3][b]). The preloads are essential in a friction joint to maintain the contact forces between the plies of joined material.

The phrase "properly tightened ASTM A325 or ASTM A490 bolts" is used in NF-3332.5. Bolts tightened to these specifications are tightened to a minimum preload of 70% of the tensile strength. This is the only reference to preload in NF-3000, and it pertains to fatigue considerations of Class 1 joints.

Preload is mentioned in NF-4725 as being an acceptable locking mechanism. The preload must be 20% above the maximum load on the fastener for the specified loading condition but is limited to 70% of the tensile strength of the fastener. This preload upper limit of 70% is in conflict with the ASTM A325 and A490 specification which uses 70% of tensile as the minimum acceptable preload.

Joint Assembly (NF-4700)

Section NF-4700 details the requirements for bolted construction. It covers many details of the bolted parts which are similarly addressed by the AISC specification. Briefly listing the items considered:

NF-4711 - Threads engaged the full length of the load carrying nut.

NF-4712 - Thread lubricant to be suitable for the service conditions and the surfaces clean before application.

NF-4721 - Guidance is given on the use of oversized and slotted holes, and hardened washers over these holes.

NF-4722 - The use of beveled washers is recommended for slopes of more than 1:20.

NF-4723 - Contact surfaces of joint materials shall be free of chips, scale and deleterious material.

NF-4724 - Hardened washer is required under the turned element when calibrated torque wrench is used.

Bolt tension is to be achieved by tightening to a torque not less than given in the design specification.

Turn-of-nut method is allowed.

Allows control of bolt tension by load indicating washers or by direct extension indicators.

Hardened washers are required when using indicating washers, or when joint material is less than 275 MPa yield strength.

NF-4725 - Locking devices to prevent loosening are required.

Sufficient fastener preload can be considered as a locking device.

Threaded assemblies shall be tested for dynamic loading conditions specified in the Design Specification.

The established preload shall be verified on the assembly by properly calibrated torque wrenches, hydraulic tensioners, direct extension indicators, turn-of-nut method or by ultrasonic method. The results of the test, required preload and specified thread lubricant shall be provided in the Design Report.

1983 ASME BOILER AND PRESSURE VESSEL CODE, SECTION III, DIVISION 1, SUBSECTION NB, CLASS 1 COMPONENTS (SUMMER 1983 ADDENDA)

Scope (NB-1100)

Subsection NB contains rules for the material, design, fabrication, examination, testing overpressure relief, marking, stamping, and preparation of reports on Class 1 components.

Jurisdiction (NB-1130). Class 1 components are those components which are contained in the reactor coolant pressure boundary. They include reactor vessel, piping, pumps and valves. The Design Specification is required to define the Class 1 components. NCA-2000, system safety criteria, and regulatory guides are used by the Owner in classifying components. NB-1131 defines the component boundary as the first circumferential joint in a welded connection, the face of the first flange in a bolted connection, or the first thread in a threaded joint.

Materials (NB-2000)

Materials for bolting must conform to the requirements of one of the specifications listed in Table I-1.3. Material for nuts shall conform to SA-194 or one of the specifications of Table I-1.3.

Washers are optional; when used, they shall be of wrought material compatible with the nuts used.

Material Certification (NB-2130). A Certified Material Test Report (CMTR) is required for all pressure retaining material except as specified in NCA-3867.4(b).

Material Identification (NC-2150). All materials must be marked in accordance with NCA-3866.6 so that parts may be identified at all times.

Heat Treatment (NB-2170). Paragraphs NB-2170 through NB-2300 contain requirements for heat treating quenched and tempered materials. The requirements include:

- Surveying the heat treating oven
- Oven loading
- Location, form and heat treatment of tensile and impact specimen

Test Coupon (NB-2224). For Bolting Materials NB-2224(b) specifies that the test coupon be taken in accordance with the applicable material specification and with the mid-length of the specimen at least one diameter or thickness from the heat treated end.

Impact Tests (NB-2310). Charpy V-notch tests are required for all pressure retaining bolting with nominal diameter greater than 1.0". The Charpy V-notch tests are performed in accordance with SA370. Paragraph NB-2322.1 describes the impact specimen preparation, and NB-2322.2 describes the orientation of the specimen for the test.

Three specimens at temperature no higher than the preload temperature or the lowest service temperature shall meet the lateral expansion requirements of Table NB-2333-1.

Sampling (NB-2345). Sampling is required from each heat of material. Retests are specified in NB-2350.

Examinations (NB-2541). Bar material used for bolting is examined in accordance with NB-2550 which invokes the requirements of SA614 paragraphs RU, RZ, and either RW or RX.

Quality System (NB-2600). Material Manufacturers and Material Suppliers shall have a Quality System Program or an Identification and Verification Program which meets the requirements of NCA-3800. Small parts (bolting of nominal diameter less than 1.0") may be supplied with a Certificate of Compliance.

Design (NB-3000). Component design rules are given in Section NB-3000. The design approach is described as "design by analysis". This approach requires the calculation of principal stresses, the use of stress concentrations and consideration of the operating and assembly loadings. The component must be evaluated for fatigue, or the designer must establish that the component is not subject to significant fatigue loading.

Design by analysis is the only acceptable design method for Class 1 components. The "design by rule" methods used for Class 2 and Section VIII components are not acceptable for Class 1 components. In many cases "design by rule" is used to size the components, and then the appropriate rules of NB-3000 are used to analyze and validate the configuration. The design rules of NB-3000 are grouped according to type of component:

- Vessels - NB-3300
- Pumps - NB-3400
- Valves - NB-3500
- Piping - NB-3600

General Design (NB-3100). Section NB-3100 covers a general design practice including the following.

Loading Conditions (NB-3111). This specifies the load conditions which must be considered in the design analysis including: pressure, impact, weight of components, wind, snow, vibration, earthquake, reaction loads, temperature, and superimposed loads.

Design Loads (NB-3112). The design loadings shall be established in accordance with NCA-2142. Design service limits are required in the Design Specifi-

cation (NB-3113). The service limits for the design loads are defined in NCA-2142.2. A brief discussion of service levels follows:

> Level A - Service limits which must be satisfied for all loading conditions identified in the design specification to which the component may be subjected during its life. These are generally the normal operating conditions for the component.
>
> Level B - Limits which must be withstood by the component without damage which would require repair. These limits are sometimes referred to as Upset conditions. Examples of conditions which might cause these limits are: (1) Operation Based Earthquake (OBE), which is a seismic event usually on the order of one-half the Safe Shutdown Earthquake (SSE) - the component is designed to operate through this event; and (2) transient conditions, such as power level changes on the order of 10% to 20%. The duration of Level B conditions must be included in the Design Specification.
>
> Level C - Limits which are sometimes referred to as Emergency conditions. The components must withstand these loads, but large deformations in areas of discontinuity are acceptable. Removal and/or repair of the component is permissible. These limits must not cause more than 25 stress cycles having an S_a of greater than that for 10^6 cycles on the appropriate fatigue diagram.
>
> Level D - Limits are sometimes referred to as Faulted conditions, which permit gross general deformation with a loss of dimensional stability. The component may require repair or removal from service after the event. Some of the events which can impose Level D limits are SSE, pipe break, or a combination of these events.

General Design Rules (NB-3130). These design practices are applicable to all components. The various subsections give design details which are specific to the particular component. When a conflict arises between NB-3130 and a subarticle for a particular component, the subarticle governs.

Standard Products (NB-3132). Table NB-3132-1 is a list of acceptable standard products such as ANSI B16.5 flanges and ANSI B18.2.1 Bolts and Screws. Compliance with these standards does not replace or eliminate the need for stress analysis when called for by the subarticle. The subarticle may accept the component without stress analysis as in the case of paragraph NB-3647.1, which accepts ANSI B16.5 flanges without stress analysis provided that the component is used at or below its rated temperature and pressure.

Leak Tightness (NB-3134). Where system leak tightness greater than that required or demonstrated by hydrostatic test is required, this requirement shall be set forth in the Design Specification.

Design by Analysis (NB-3200). The design approach of Section III, Subsection NB requires:

- An evaluation of stress concentrations which exist at discontinuities
- Calculation of stresses at operating conditions
- Fatigue considerations
- Thermal stresses

The underlying design philosophy of Section III is that the component may be subjected to cyclic loads and that superior reliability is required due to the nature of the contained fluids and the fact that periodic inspections may be difficult and often impossible (1).

Design in accordance with Subsection NB relies heavily on stress analysis. Margins of safety are assessed by comparing calculated stress to a predicted failure using the maximum shear theory of failure. The basis of comparison is the equivalent stress intensity.

Design Criteria (NB-3210). The allowable stress intensities (S_m) for various materials are given in Table I-1.0. The calculated stress intensities are compared against the stress intensity or some multiple of the stress intensity to show the acceptability of the design.

The Code has always considered both the yield strength and ultimate tensile strength in assigning allowable stresses. In Section III these allowables are based on 2/3 of yield strength and 1/3 ultimate strength. These allowables are up from the 5/8 yield and 1/4 ultimate used for Section VIII (2).

Protection against non-ductile fracture is required. Appendix G and the Welding Research Council Bulletin 175 are cited as acceptable methods for preventing non-ductile failure. These articles use linear elastic fracture mechanics, material impact properties and a postulated flaw size to predict the adequacy of the bolting to resist fracture when the component is subjected to Level C and D service limits.

Stress Analysis. Terms relating to stress analysis are given in paragraphs NB-3213.1 to NB-3213.34. A brief description of the important terms follows:

Stress Intensity - The difference between the algebraically largest and smallest principal stress at a point.

Local Structural Discontinuity - A material or geometric discontinuity which affects the stress distribution, e.g., a fillet or a thread root.

Normal Stress - The component of stress normal to the plane of reference.

Average Stress - The uniform distribution of normal stress across a section.

Shear Stress - The component of stress tangent to the plane of reference.

Bending Stress - The variable component of normal stress across a section.

Primary Stress - A stress developed by an imposed loading. These stresses are not self-limiting.

Secondary Stress - A normal or shear stress which is developed as the result of a constraint of adjacent material or self-constraint of the structure. General thermal stress is an example of a secondary stress.

Thermal Stress - A self-balancing stress produced by a non-uniform distribution of temperature or differing coefficients of thermal expansion.

Peak Stress - An increment of stress which is additive to primary and secondary stress caused by local discontinuities or local thermal stress including the effect of stress concentrations.

Total Stress - The sum of primary, secondary, and peak stress.

Operational Cycle - Initiation and establishment of new conditions followed by a return to the conditions that prevailed at the beginning of the cycle.

Stress Analysis (NB-3214). A detailed stress analysis of all major structural components shall be prepared in sufficient detail to show that the stress limitations of NB-3220 and NB-3230 is satisfied when the component is subjected to loadings of NB-3110.

Calculation of Stress Intensity (NB-3215). The stress intensity at a point of interest on the structure is calculated as follows:

1. Set up an orthogonal coordinate system; for bolting, the directions of interest will be along the axis of the bolt and tangential.

2. Calculate the stress components (both normal and shear) in each direction for each type of loading. The stresses for bolting will usually be axial tension, bending, and shear stress.

3. Assign each set of stress values to one or a group of the following categories:

   Primary Membrane Stress P_m (NB-3213.8)

Primary Bending Stress	P_b	(NB-3213.7)
Secondary Stress	Q	(NB-3213.9)
Peak Stress	F	(NB-3213.11)
Expansion Stress	P_e	(NB-3213.20)

For example, the stresses in the bolting of a raised face gasketed joint would be categorized as follows (3): (a) axial tension, P_m, due to assembly preload and hydrostatic end load; (b) bending, P_b, due to flange rotation; (c) thermal stress, Q, due to thermal gradient and dissimilar materials; and (d) peak stress, F, considering stress concentration due to thread roots, thread runout and shank to bolt head fillet.

4. Translate the stress components for the t, l, and r directions into principal stresses, σ_1, σ_2, and σ_3. In many pressure component calculations, the t, l and r directions may be so chosen that the shear stress components are zero, and σ_1, σ_2, and σ_3 are identical to σ_1, σ_l, and σ_r.

5. Calculate the stress differences S_{12}, S_{23} and S_{31} from the relations:

$$S_{12} = \sigma_1 - \sigma_2$$

$$S_{23} = \sigma_2 - \sigma_3$$

$$S_{31} = \sigma_3 - \sigma_1$$

The stress intensity S is the largest absolute value of S_{12}, S_{23} and S_{31}.

Analysis for Cyclic Operation (NB-3222.4). Section NB-3222.4(d) prescribes a set of rules and limits which are used to determine the necessity of a fatigue analysis. The decision is based on a comparison of the average service stress due to startup, service pressure fluctuations, thermal gradients and thermal stresses to limits defined in this section. If the component needs no fatigue analysis, Subsection NB-3230 is used to analyze the component.

Design Conditions (NB-3231). The number and cross section of bolts to resist the design pressure shall be as prescribed by Appendix E using the larger of the bolt loads as the Design Mechanical Load. This process is identical to the Section VIII approach which considers a seating condition (using a 'y' factor) and an operating condition (using an 'm' factor).

Service Limits (NB-3232). The service stress in bolts which is produced by a combination of preload, pressure, and differential thermal expansion may be higher

than the same values given in Table I-1.3. The maximum value of service stress (not stress intensity) averaged across the bolt section ignoring bending and stress concentrations must be less than 2 S_m.

Maximum service stress at the periphery of the bolt including bending, but ignoring stress concentrations, must be less than 3 S_m.

If torque is used in preloading the stress intensity rather than service stress must be less than 3 S_m.

Level B service limits are the same as for Level A; fatigue analysis may be required depending on evaluation in NB-3222.4(d).

Level C has the same limits on average and maximum stress, 2 S_m and 3 S_m, respectively, as Level A and Level B. No fatigue analysis is required for Level C.

Level D service rules of Appendix F may be used for evaluating these loadings independently of any service loadings.

The remainder of Section NB is divided into subsections specific to various types of components. Each one of these subsections may give requirements for bolting in addition to the general requirements previously discussed.

Vessels (NB-3300). NB-3362 recommends ANSI B16.5 flanges for connections to external piping. NB-3364 recommends that supports be designed using Subsection NF. NF has bolting requirements which have been discussed separately.

Pumps (NB-3400). NB-3434 requires bolting in axisymmetric arrangements to be designed in accordance with NB-3230. This is the process illustrated on Figure 9-1, which considers fatigue as well as average service loading on the bolting.

Valves (NB-3500). NB-3546.1 requires body to bonnet joint to be designed in accordance with Appendix XI-3000, or by procedures of NB-3200, except that fatigue analysis of the bolts is not required. NB-3546.4 recommends that all valve parts be analyzed for cyclic stress duty, unless the valve can be exempted by the rules of NB-3222.4(d).

Piping (NB-3600). NB-3612.1 recommends that standard piping products (flanges and bolting) be in accordance with those specified in Table NB-3132-1. When non-standard flanges are used, they will be designed and tested to NB-3640. Flanges and bolting (NB-3647.1) shall be designed to XI-3000 using allowables from Table I-7.0.

NB-3658 details the procedures for calculating the moment due to piping movement transmitted into the flange bolts due to weight, thermal expansion of piping, mechanical loads, and anchor movement.

Mechanical Joints (NB-4700). Thread engagement of nuts, bolts and studs shall be in accordance with the design (NB-4711). Lubricants shall be suitable for the service and not react unfavorably with component material or service fluid (NB-4712). Gasket joints shall bear uniformly on the gasket and be properly compressed. All flanged joints shall be made up with relatively uniform bolt stress.

REFERENCES

1. B.F. Langer. Criteria of the ASME Boiler and Pressure Vessel Code for the Design by Analysis in Section III and VIII, Division 2. "Pressure Vessels and Piping: Design and Analysis - A Decade of Progress." Editors G.J. Bohm, R.L. Cloud, L.C. Hsu, D.H. Pai, R.F. Reedy, American Society of Mechanical Engineers, NY, 1972, p. 62.

2. B.F. Langer. Criteria of the ASME Boiler and Pressure Vessel Code for the Design by Analysis in Section III and VIII, Division 2. "Pressure Vessels and Piping: Design and Analysis - A Decade of Progress." Editors G.J. Bohm, R.L. Cloud, L.C. Hsu, D.H. Pai, R.F. Reedy, American Society of Mechanical Engineers, NY, 1972, p. 69.

3. E.C. Rodabaugh and S.E. Moore. "Evaluation of the Bolting and Flanges of ANSI B16.5 Flanged Joints - ASME Part A, Design Rules." Oak Ridge National Laboratory Report /Sub/2913-3, 1976.

Section 10

CRITIQUE OF BOLT PRELOAD ASPECTS OF ASME AND AISC CODES

SUMMARY OF THE ASSIGNMENT

The Joint AIF/MPC Task Group on Bolting has assigned Raymond Engineering "to critique existing preload sections of the ASME Code". This is that critique. Two questions of concern to the Task Group lay behind this request.

1. Do provisions of the Code contribute to the types of bolting failure experienced in the last decade or so by the nuclear industry? (Specific failures include stress corrosion cracking, erosion-corrosion, borated water corrosion and fatigue.) Specifically, as far as Raymond's assignment is concerned, does the Code demand preloads which are unnecessarily high; creating unnecessarily high stresses which encourage stress corrosion cracking?

2. Do omissions in the Code contribute to the types of bolting failure experienced by the nuclear industry? For example, should there be new and/or more stringent requirements for such things as bolting materials, the testing or inspection of bolting materials, the corrosion protection of bolting materials -- or new requirements concerning the control and/or inspection of bolt preload?

The assignment was limited to Code provisions or omissions concerning preload.

AISC SPECIFICATION FINDINGS

Provisions Which May be Causing Trouble

The AISC specification dictates minimum preloads of 70% of ultimate. It allows (even encourages, at least by implication) preloads well past yield. Such preloads were mandated, however, because years of tests, sponsored by the AISC and/or by the RCSC (Research Council on Structural Connections, which writes the AISC specification) have shown that such preloads are necessary for the integrity of friction type joints. The need for such joints is widely questioned (because of cost, not because of problems), but in June 1983 the RCSC voted not to relax the requirements, at least for now.

The only two bolt tightening methods currently approved by the specification lead, almost automatically, to tensions past the yield point of the fasteners. These methods include turn-of-nut and direct tension indicators (devices such as crush washers or twist-off bolts which theoretically show that they have been tensioned). Both methods are widely known to be inaccurate. The RCSC is looking for "something better", but there are no across-the-board, economically attractive solutions in sight at the moment.

Omissions Which May Be Causing Trouble

The AISC specification only deals with bolts up to 1-1/2" in diameter. Many of the bolts which have failed have been larger than this.

The specification does not distinguish between joint types when specifying minimum tensions, assembly procedures or the like. But an anchor bolt may not need the same preload as, for example, the bolt in a friction type shear joint.

The specification deals only with ASTM A325 and ASTM A490 bolting materials (or equivalents). None of the nuclear failures tabulated by the Task Group has involved these materials.

There is no clear provision for tightening fasteners to some point below yield. The use of a properly selected torque could do it, but torque control is not permitted by the present specification. It used to be permitted, but it was removed because the uncertainties in the torque-preload relationship caused too many field problems. Under pressure from the industry, however, the RCSC decided, in June, to reinstate torque control. This time they plan to add requirements covering the correct way to use and/or control torque.

The specification ignores the effects of corrosive environments on bolting. There are no provisions, for example, for such things as reduced preloads, reduced allowable working loads, corrosion resistant coatings or the like.

Although the specification attempts to define accurate ways to inspect tightened bolts, to see if they have been properly tightened, it does not define any methods which really work. (The RCSC knows this and is looking for an economically acceptable method; none is available at the moment.)

The specification does not insist that the bolt-by-bolt tightening procedure be supervised and/or monitored by an inspector. The results obtained in the field are often influenced, for the worse, by careless or untrained workmen. The specification would "really work" more often than it does if it were "really followed".

ASME CODE FINDINGS

Provisions Which May be Causing Trouble

Although the ASME Code, unlike the AISC specification, defines acceptable upper limits for bolt stresses (limits that are well below the yield points of the materials) it later undoes this precaution in Non-Mandatory Appendix S by saying, in effect, "if the assembled joint leaks you may increase the preload in the bolts to whatever level is required (as long as you do not, thereby, overload joint members)".

Some sections of the Code (e.g., NF-4724) allow "turn-of-nut" tightening, presumably by the procedures spelled out in the AISC specification (the ASME Code is mute on what turn-of-nut tightening means). Fasteners tightened this way will often, if not always, be tightened past yield.

Thanks to work by the Pressure Vessel Research Committee, it is now fairly well established that the Code rules for the design and preloading of gasketed joints will not result in leak free joints. Gasket factors and bolt preloads are especially suspect and are going to be changed (but probably not for several years). The present Code provisions, therefore, result in occasional leaks which probably contribute to some of the corrosion related problems tabulated by the AIF.

Omissions Which May be Causing Trouble

Section NF-4724 and others allow for calibrated wrench tightening of fasteners. No suggestions are given, however, for the amount of torque to be applied, how it is to be applied, how to reduce the scatter between applied torque and achieved preload, etc. Results are probably very erratic.

There are substantial elastic interactions between bolts when groups of them are tightened one or a few at a time. There are no provisions for compensating for these effects (which can result in zero residual preload in the first bolts tightened, for example). Techniques such as the use of higher torques on the first

bolts tightened, retorquing first ones, etc., can partially compensate for these interactions.

Maintenance crews often have to take corrective actions to stop a leak by hot bolting the joint, for example, or pumping leak sealants into the joint. Such common practices are totally ignored by the Code (and, therefore, are performed by a wide variety of procedures, using a wide variety of tools and sealants). In general, in fact, the Code focuses on design and ignores the maintenance of the equipment.

The Code mandates training for some job classifications, NDE inspectors, for example (or manufacturers), but it ignores the qualifications of the people who assemble and/or maintain the equipment. Yet something as simple as a "correct procedure" can make a very significant difference in the results. There are no provisions for the inspection of previously tightened fasteners.

BACKGROUND

There have been a number of bolting failures in the nuclear industry. Issue 29 of NUREG-0933 summarizes recent failure history (1). In order to minimize bolting problems in new plants and to assure adequate performance in existing plants, the reports suggest that improvements in one or all of the following areas might be required: design, materials, fabrication, installation and in-service inspection.

The Atomic Industrial Forum formed a Task Group on Bolting in June 1982. The Group's charter is to develop a program that addresses various bolting issues in the nuclear power industry. The expected output of the Task Group's efforts will be:

- Recommendations for industry action to prevent and mitigate fastener degradation and/or failure which could adversely affect plant safety.
- Recommendations on methods by which the industry (including manufacturers) can avoid problems with bolting degradation for future procurement and installations (2).

The documented fastener failures have occurred on equipment which has been designed, fabricated, procured and installed in accordance with various ASME codes. An obvious question being addressed by the AIF Bolting Program is whether there are deficiencies in the codes which contribute to these failures. One of the areas of concern is the preloading of fasteners as prescribed by the codes.

SCOPE

The objective of this section is to critique the various ASME and AISC codes relative to their treatment of fastener preload - preload being defined as the tensile force which is introduced into the fastener at joint assembly. It is the load in the fastener prior to application of external loads. There are many aspects of fastener preload which could be considered; however, this section will address only the code treatment of bolt preload with respect to design, methods of assembly and Quality Control.

GENERAL OBSERVATIONS

AISC Codes

AISC specification for structural joints using ASTM A325 or A490 bolts is the most detailed specification on bolt preload, assembly methods and Quality Control procedures. Other codes for structural joints such as ASME Boiler and Pressure Code Section III, Division I NF and the draft of the AISC N490 are subordinate to the AISC specification in detail on bolt preload, assembly and Quality Control.

ASME Section VIII

Pressure boundary bolting is covered by the ASME Boiler and Pressure Vessel Code Section VIII, Division 1. It is the most detailed of the codes on pressure boundary bolt preload and installation methods. All other codes in Division III (nuclear power plant components) Subsection NB, NC, ND, NE and Section VIII Division 2 (alternate rules) use very similar bolt preload requirements.

Code Preload Philosophy

Both the AISC and the ASME have a similar philosophy on bolting which, simply stated, is:

1. Joints perform better when they are assembled with high and uniform fastener preloads.

2. The joint design should allow make-up with the simplest tools and procedures available.

Codifying Preload and Installation Methods

The ASME and AISC codes are primarily design tools. They focus on sizing and selection of fasteners rather than assembly methods of Q.A. techniques. The process of codifying bolt preload and the installation methods is complex. The

Research Council on Structural Connections (RCSC) and the American Institute of Steel Construction (AISC) have led in the effort to codify the level of bolt preload, the installation, and Quality Control methods. The ASME Section VIII and III have not even attempted codification in these areas. The ASME codes establish design bolt loads but allow increasing them if necessary. No suggestions are given about assembly procedures, and Q.A. consists of requiring a written procedure and using calibrated tools.

Education

Code requirements in themselves do not insure that a safe, reliable product will result. People (designers, engineers, Quality Control, fabricators, mechanics) must understand, interpret and apply the codes. At each phase of the design, fabrication, installation and maintenance of plant components, decisions are made which have safety and code implications. These decisions must be based on a thorough understanding of the underlying reasons for the code requirement and the possible consequences of the action taken.

The AISC has been more diligent than the ASME with regard to education concerning bolting and preload. Many technical studies, articles and guidelines on bolt preload and procedures have been sponsored and published by the AISC. The information on preload and assembly of pressure boundary bolting from the ASME has been very scarce. Groups like the Welding Research Council are addressing pressure boundary problems. They wrote the present code; their latest efforts will be more definitive, but they are not yet incorporated.

Quality Control

Neither the AISC nor the ASME have good programs for insuring bolt preload. The AISC addresses this issue with the job inspecting torque, while the ASME covers it in a general manner by requiring that design specifications be translated into procedures and instructions and that tools and measuring devices be calibrated.

One of the conclusions drawn by J. Notch in his Survey of High Strength Bolting Using Ultrasonic Techniques (11) is that yesterday's technology, torque wrench and Skidmore tensile machine used for Q.A. have failed to keep pace with bolting technology. Aside from being outmoded, present Q.A. methods are also unreliable.

ASME Code and the Maintenance Man

The ASME codes basically ignore the maintenance man; the mechanic is left to his own devices. For example, if a joint is leaking in service and the leak cannot be controlled by tightening, very often the next action is to employ a leak sealing service. This service stops leaks by injecting chemical compounds into the joint. The codes give no guidance relative to the use of leak sealing services. Are these techniques legal relative to the code? Should they be outlawed, regulated, or what? These leak sealing practices are widely used, but the code ignores their existence as it ignores such common practices as hot bolting.

SPECIFIC CRITICISMS AND RECOMMENDATIONS

AISC Specification for Structural Joints Using ASTM A325 or A490 Bolts and AISC Specification N490

Problem. The AISC specification for structural joints does not cover bolts larger than 1-1/2" in diameter or over 18" in length. The only materials it covers are ASTM A325 and A490. The failures tabulated by the AIF included many bolts larger than this. None of the failures involved A325 or A490 materials.

Solutions. The AISC is developing a specification N490, Design Fabrication and Erection of Steel Safety Related Structures for Nuclear Facilities, N490 addresses the following issues:

- Defines alternate materials to the A325 and A490.
- These materials A354, A194, etc. are limited to less than 170 ksi ultimate strength. If specified ultimate strength is greater than 170 ksi, then--
- Impact testing is required.
- SCC must be considered. The environment service load, residual stress and assembly stress must be considered.

The Research Council on Structural Connections is currently considering sponsoring research on larger fasteners and concrete embedments. This could be a large project judging from the amount of work that formed the basis for the A325 and A490 AISC specification. Fisher's Guide to Design Criteria for Bolted and Riveted Joints (4) is a comprehensive review of the A325, A490 work.

High Fastener Preload in Structural Joints

Problem. The AISC code encourages high preload because structural joints work better with high bolt preloads. High bolt preload contributes to joint rigidity,

gives a better stress distribution in the connected plies, and provides security against bolt loosening.

AISC joint allowables are based on minimum bolt preloads of 70% of ultimate strength. The bolt loads often exceed the yield strength.

These high preloads are only a problem if the bolt material is susceptible to stress corrosion cracking (SCC).

Solution. These high preloads have not proved to be a problem with A325 or A490 bolts. AISC specification N490 is recommending bolt material toughness and strength requirements to insure that materials are not susceptible to SCC.

Turn-of-Nut Assembly of Structural Joints

Turn-of-nut procedure is recognized by AISC specification for A325 and A490, as well as by AISC N490 and ASME Section III, NF. This assembly method is a strain control method which yields high preloads (greater than 70% of ultimate strength).

Problem. Turn-of-nut produces accurate preloads only if:

- The load introduced is high enough to plastically deform the fastener.
- The joint assembly has the proper hole sizes and washers.
- The joint is properly snugged before incremental turn is applied.
- Torquing starts at that portion of the joint in closest proximity (e.g., the center of the bolt pattern) and proceeds to portions of the joint which are farther apart.

In short, turn-of-nut only works if the operators follow the procedure and practices intended by the authors of the specification.

Solution. Turn-of-nut installation is a reliable method of preloading A490 and A325 bolts. For successful joints, the method must be understood and properly applied.

Use of turn-of-nut on larger diameter, longer embedments has not been thoroughly tested. To achieve minimum specified tension in an A325 or A490 bolt, the incremental turn required from snug tight is a function of bolt length. This relation-

ship between turn and load has not been developed for large studs and bolts. Typically, embedments are large studs.

Torque and Structural Joints

Problem. Joint assembly using torque control results in a large variability in bolt preload for seemingly similar bolts and conditions. Variations in preload of ±30% to 50% are not uncommon. The major factor causing this scatter is friction in the threads and at the bearing surface of the nut and bolt head. ASME, Section III, NF and the N490 recognize torque as an assembly method.

In 1980, the AISC specification for A490 and A325 withdrew the torque method of assembly. Early editions of this specification listed torque values described as approximate equivalent of the minimum bolt tension specified for various size bolts. It was explained that these values were no more than observed experimental averages and that the value to be used, both in installing bolts and in inspection procedures, should be that determined by the actual condition of the application.

Use of formula and empirical friction factors, or tests in loading indicating machines to specify a torque value which will produce a minimum load, is often misleading. The specified torque will normally produce less load in the actual joint configuration primarily due to friction changes, misalignments and deformation of parts.

The intent of the code was to determine the torque required by actual conditions of application. This was a very good guideline but quite difficult to implement in the field.

Solution. There is no currently accepted solution to the vagaries of torque control. Conventional hydraulic wrench calibrators do not provide sufficient control because they differ too much from the actual joints in such important parameters as stiffness, hardness and surface finish. An emerging technology -- ultrasonic estimation of bolt stretch or stress -- can be used to design torquing procedures, to calibrate torque tools, or for quality control of achieved results (by measuring the results achieved in a random sample of previously tightened bolts in actual joints). But ultrasonics is not economically attractive in most non-critical applications.

The RCSC has recently voted to reinstate torque control in the A325/A490 specification, but only after defining and adding some as yet unidentified controls to improve the accuracy of the results achieved.

Pressure Boundary Bolting

Problem. The ASME Codes Sections III and VIII treat pressure boundary bolting in a similar manner. The fastener allowables stress, the "y" and "m" factors are used to size the fastener and calculate design bolt loads. These bolt loads are used to design the flange.

Often application of design bolt loads at assembly results in a joint which leaks.

Solution. Appendix S of Section VIII and Appendix XII of Section III of the ASME Code, Design Considerations for Bolted Flange Connections, address assembly considerations. These appendices recognize that conditions may exist which require tightening of bolts to stresses which exceed design allowables. This practice is allowable with the condition that neither the flange nor the gasket are damaged. The appendices also make the statement: "Another very important item in bolting design is the question whether the necessary bolt stress is actually realized and what special means of tightening, if any, must be employed."

This statement suggests that simple tools and procedures may not give sufficient preload and/or uniformity of preload to seal the joint. In these situations, other means of preload control are desirable.

The example developed in Appendix C of this section illustrates an example showing the results of the application of Code suggestions to solve a leak problem.

The Code encourages increasing preload to stop leaks. In practice, this course of action is often taken. The Code alludes to better control of preload but does not give any guidance on when better control is required or how to achieve the control.

It is my belief that the first step in addressing a leak problem should be to verify the preload across the joint. The average load across the joint determines the gasket stress which is known to be critical to leaks. The uniformity of bolt load is also thought to be important, but this theory has not been validated by testing.

The Code should not permit increasing the preload in bolts unless an extensometer or some other means is used to verify the resulting preloads.

A study should be performed of the assembly methods and preloads achieved in components which have generic leak problems; i.e., valve bonnet-to-body joints. The objective of this study would be to eliminate leaks by developing improved assembly procedures.

CONTENT OF APPENDICES

The remainder of this section is composed of appendices. The appendices go into greater detail on Code requirements and mechanics of using the code relative to bolt sizing and preload control. They give support to the conclusions and recommendations previously stated. A brief outline of each appendix follows.

Appendix 10A

Appendix 10A reviews the AISC Code on structural bolting. This review will explore the Code requirements for selecting target preloads, the methods of achieving the preloads at assembly and the requirements and methods of insuring that the preload exists in the fasteners. The underlying theories and logic of requirements will be explored. This discussion will be supported by examination of the relevant studies and test data which was used as the basis for the requirement. Actual field results and abuses of the requirement will be discussed.

Appendix 10B

Since the ASME Code is based on the AISC Code, the relationship and the differences between the two Codes will be explored. Section III, Subsection NF is discussed.

Appendix 10C

Appendix 10C reviews the ASME Division VIII and III Code requirements for pressure boundary bolting.

Appendix 10D

Appendix 10D is a comparison of the ASME Code sections relating to pressure boundary bolting.

Appendix 10A

AISC SPECIFICATION FOR STRUCTURAL JOINTS USING ASTM A325 OR A490 BOLTS

SCOPE

The scope of the code includes the design and assembly of structural joints using ASTM A325 high strength carbon steel bolts, ASTM A490 high strength alloy steel bolts, or equivalent fasteners, tightened to the tension specified herein (3).

The equivalent fasteners in this statement is left open to discussion, but probable intent is fasteners which have mechanical properties similar to the A490 and A325 - the important mechanical properties being strength, ductility, and resistance to stress corrosion cracking (SCC). The joint types covered by the code are generally classified as shear or tension. Figure 10A-1 shows two types of shear joints, and Figure 10A-2 is a typical tension joint.

The shear joints are required to resist loads at right angles to the bolt axes. Shear joints are subdivided into two types, friction and bearing. Friction joints transmit the shear loads by frictional resistance which is developed at the joint faying surfaces. These frictional forces are dependent on the high bolt preloads. Bearing joints, on the other hand, do not require high bolt preloads. The resistance to slip in this joint is provided by the bolts acting as pins and bearing against the holes of the joint plies.

A tension joint requires the bolts to support applied parallel to bolt axes. This type of joint is further subdivided into joints carrying static loads and joints subject to cyclic loading.

DESIGN

The AISC code gives tables of allowable working stress for fasteners in different types of joint configurations. These tables have been developed based on the results of numerous tests sponsored by the Research Council on Riveted and Bolted Structural Connections (RCRBSC). Fisher's "Guide to Design Criteria for Bolted and Riveted Joints" published in 1974 is a comprehensive summary of test data along

with analysis and explanation of the methodology used in developing the code rules, procedures and allowables.

The design approach, employing allowable working stresses, provides the designer with a simplified method of sizing the bolts and determining the number of bolts required in a joint. In all cases the designer computes the working load by calculating the external load plus tension resulting from prying (if applicable). The working load is assumed to act directly on the bolts; the working load divided by the appropriate nominal area of the fasteners is the working stress.

Calculations which assume that the total external or working load is applied to the bolts is conservative. The preload in a joint would have to approach zero to have such a condition exist. Despite the conservatism, this approach lends itself to a uniform treatment of each joint type.

The code calculates a fictitious (or very conservative) working stress. It assumes that the joint has been properly preloaded as specified. Then, it uses historical test data and appropriate factors of safety to set allowable bolt stresses. These allowables are in most cases joint allowable rather than bolt allowables, but they are calculated based on bolt area; so the term "bolt allowable" persists.

Finally, the code requires the working stress be less than the allowable for the joint. The result of all this is a standardized tool for sizing bolts.

In a Friction Type Shear Joint the bolts are not actually subjected to shear; the shear is transmitted through the joint by the frictional forces on the faying surfaces. But even in this case the allowable shear stress is calculated as if it is applied to the bolts. The allowable value actually represents shear stress permitted on a basis of joint strength (4) and not bolt strength.

In a Tension Joint the bolts are sized according to the following equation (5):

$$B_{all} = 0.375\ A_b\ \sigma_{u\ spec}$$

where B_{all} is the allowable bolt load on each bolt (kip), A_b is the nominal cross-sectional area of the bolt (in^2), and $\sigma_{u\ spec}$ is the minimum specified tensile strength (ksi).

Allowable stress is then compared to the external load plus any prying force due to the deformation of the connected parts. The working load is approximately two-thirds of the load induced during tightening. When this external load is applied to a properly tightened joint, the bolt experiences little, if any, increase in stress (6). This design approach subtly employs joint mechanics analysis. Joint mechanics would predict that only a small portion of the external load goes to increase the bolt load. The amount of load increase in the bolt is governed by the relative stiffness of the bolt and joint. This condition applies until the external load is high enough to separate the joint members.

AISC PRELOAD PHILOSOPHY

The AISC preload philosophy is that high bolt preloads are desirable for three reasons (7): (1) high bolt preload increases joint rigidity; (2) result in better stress patterns in the connected plies; and (3) provide security against loosening.

The code further encourages high preloads by prescribing minimum preload values of 70% of ultimate strength. There are no maximum loads stated; the code states that, if a properly installed bolt does not fail on installation, then, because of its reserve strength, it will not fail in service (8).

The same minimum bolt preload is specified regardless of the type of joint. Shear joints designed with the bolts in bearing do not require bolt preload. The AISC code requires the same preload in these bearing bolts that it required for friction joints and tension joints which do require high bolt preloads in order for the joint to perform. The aim of the AISC is to have one set of bolt preloads to avoid the possibility of assembly error.

AISC JOINT ASSEMBLY AND PRELOAD CONTROL

Presently the AISC prescribes two methods for preloading bolts in joint assembly turn-of-nut and direct tension indicators. The preloading methods are the same for all joint types, just as the bolt preload levels are the same for all types of joints.

Turn-of-nut method of tightening was developed by the American Association of Railroads for use in remote areas where power tools were not available. Bethlehem Steel modified the procedure to its present form (9).

The procedure calls for running the nut down to a snug position and then turning the nut an additional 1/2 or 3/4 turn, depending on the length of the bolt. The method is primarily a strain control method. The snug torque is designed to get the bolt load to approximately 50% of desired load; then, the additional turn brings the bolt load above the minimum specified and usually beyond yield. Figure 10A-3 (10) illustrates the process.

The procedure is a good one. When properly done, it gives bolt preloads which are reliably above the minimum specified value. The most significant problem with the procedure is controlling the snugging value. The whole joint must be snugged and then the final turn increment applied. If the joint members are not properly snugged, the final turn can be dissipated in pulling the plies together rather than stretching and preloading the bolt.

The procedure is designed for relatively ductile bolts. As can be seen from Figure 10A-3, the bolts are taken beyond the yield point. If the bolts are not ductile, they will fail at assembly.

The most commonly used direct tension indicators in the structural steel assembly are load indicating (crush) washers. A typical washer arrangement is shown in Figure 10A-4. At assembly, the bolts are loaded until a specified clearance exists between the washers. This clearance is checked with feeler gages. These indication washers are one-way devices. Since they plastically deform, they cannot respond to and indicate load relaxation. They must be used with hardened washers to prevent the crush washer from deforming into the hole in the joint member. The code also requires that the user demonstrate the relationship between the procedure (measuring the crush of the washer) and the minimum specified preload.

The code addresses such things as the use of hardened washers, minimum 5/16" thick, when A490 bolts are used in oversized holes. Standard thickness hardened washers are required under both ends of A490 bolts when the joint material is less than 40 ksi yield and under the turned end of an A490 installed using turn of the nut. These precautions have preload implications in that they are an attempt to set up standard conditions of assembly which will facilitate achieving minimum desired preload.

FIELD EXAMPLE

A field example illustrates the importance of the heavy (5/16" thick) washers. Using an ultrasonic extensometer, the preload developed in 1" and 1-1/4" A490 bolts

installed by turn-of-nut in oversized holes was studied. Some of the joint assemblies used heavy washers, while others had standard washers (11). The results of the test were:

- The preload achieved with the heavy washers was higher and more consistent.
- The incremental turn required to achieve the minimum specified load was consistently less for the heavy washers.
- The torque, as a measure of work, was less for the heavy washers.

These results indicate that the assembly using the heavy washer is more reliable. There is a higher probability of having the joint properly preloaded when the heavy washers are used. The AISC code requires heavy washers for bolts over 1", and there is evidence that smaller bolts could benefit from the use of heavy washers.

SNUG TIGHT CONSIDERATIONS

The AISC code gives guidelines on snugging the joint before applying the incremental turn. Snug tight is defined as a few impacts of an impact wrench or the full effort of a man with a spud wrench. The code suggests that a sufficient number of bolts in the joint be snugged in order to pull the joint plies together. The code also recommends working from the most rigid part of the joint to the free edges. The theory behind this recommendation is to eliminate the situation where the incremental turn of the nut is used to pull the joint together rather than preload the bolt.

The turn-of-nut method is a strain-controlled method. The joint must be solid so that the correct portion of the controlled strain (the incremental turn) goes into preloading the bolt. If the joints are not pulled tight, a high percentage of the incremental strain can go into pulling the joint together and not preloading the bolts.

CALIBRATED TORQUE WRENCH

Assembly by a calibrated torque wrench was permitted by previous codes, but this method was withdrawn in the 1980 edition of the code. Quoting from the 1980 edition of the AISC specification: "Early editions of this specification listed torque values described as approximate equivalent of the minimum bolt tension specified for various size bolts. It was explained that these values were no more than observed experimental averages and that the value to be used, both in install-

ing bolts and in inspection procedures, should be that **determined by the actual condition of the application.** With this edition of the specification, recognition of torque control methods is withdrawn because of the large variability of torque-to-tension relationship for seemingly similar bolts and conditions."

This statement of withdrawal of torque control is interesting and educational on several points. The key phrase in the statement is conveniently highlighted in the text. The statement that the installation torque values should be "determined by the actual condition of the application" is an excellent guideline. The problem with this guideline is that it is virtually impossible to implement in a field situation. The only way to truly simulate field conditions is to do the tests in the field on the actual structure. The problem then is to measure fastener load versus applied torque. The only means of doing this are by inserting a load indicating cell under the bolt head, by strain gaging bolts, by using an extensometer device to measure load related extension, or by simulating the joint in a Skidmore Wilhelm direct tension indicating device.

Use of a load collar changes the joint characteristics significantly by changing the grip length and changing the bearing surface under the nut and the bolt head. Both of these factors influence the torque/tension relationship. The use of strain gaged bolts is expensive, cumbersome and usually not practical. The use of a Skidmore Wilhelm tensile machine does not adequately simulate the joint (12). The makeup is softer due to the hydraulic cell. The bolt head and nut bearing surfaces are hard and parallel. These factors influence the results of torque-tension relationship. The tension produced on the Skidmore for a given torque is efficient, predictable and reliable. The same torque applied in the field often gives much less tension load and the variability is increased markedly. Notch (11) was able to make these observations by using an ultrasonic extensometer to measure strain in bolts in a Skidmore and then use the extensometer to measure strain in actual field joints. Notch suggests that torque might be a useful control method if it can be correlated to bolt loads in actual joints.

QUALITY ASSURANCE METHODS

The AISC code devotes one full page to inspection. The code states that an inspector will observe the installation to determine that the approved procedure is being properly followed.

The apparent code philosophy that control of the assembly procedure is the best quality approach is echoed by Fisher (13). Quoting from his paper: "Inspection is usually unnecessary if the installation method has been carefully followed."

An underlying reason for this quality approach is that the techniques for measuring the amount of bolt tension in an assembled joint are both difficult and unreliable. The most commonly used method for determining preload in bolts of assembled joints is the use of a calibrated torque wrench. This is the arbitration procedure specified in the AISC code. The procedure is:

1. Set up three bolts in a calibrated load measuring device.

2. Perform the prescribed turn-of-nut tightening on the three bolts including snugging to 15% of load, and then tighten further to achieve the specified minimum load. The incremental turn required to achieve specified load must be as specified by the code.

3. Measure the torque required to restart the nut and turn it 5° from the condition of step 2. The average of the three bolts is the job inspecting torque.

It is well known that the torque/tension results obtained on a calibrating device has a tenuous relationship to the torque/tension relationship in an actual joint. Fisher (13), the AISC (14) and Notch (12) have reported this finding.

Notch stated that the job inspecting torque is non-conservative, since for a given fastener tension more torque is required to restart the installed bolts than the bolt setup in a Skidmore tension machine. Using the inspecting torque as an estimate of installed bolt tension would lead to an overestimate of the existing bolt preload.

Notch used a Raymond ultrasonic extensometer in his test program to measure bolt strain (i.e., preload). He suggests that the extensometer can be used to establish a more realistic job inspection torque (12) or can be used in a sampling plan which would eliminate the inspecting torque wrench.

EDUCATION

Fisher's 1974 publication "Guide to Design Criteria for Bolted and Riveted Joints" is an excellent example of an educational effort sponsored by the Research Council on Riveted and Bolted Structural Joints. The book was a wealth of information concerning the code requirements with in-depth discussion of underlying theories and tests which were used in deriving the requirements.

Notch makes two relevant comments concerning education. The first concerns designers. Quoting from his report: "With regard to bolting, most designers in the past have taken a somewhat complacent attitude that installing a structural bolt is a foolproof procedure. On the contrary, the bolt testing program, as documented, has indicated that serious problems with achieving proper bolt pretension can and do occur in the simplest of bolted connections." (15)

The second comment concerns assembly. Quoting Notch again: "No matter how carefully thought out and potentially successful the turn-of-the-nut method is, if the man in the field does not adequately understand and follow its provisions, success cannot be expected." (16)

Notch's report illustrated these two points perfectly. Neglect of basic principles by designers and field personnel led to improperly preloaded bolts. Another interesting point is that all of Notch's findings had been reported in other works. He simply rediscovered things which have been known and previously reported. If these things are known, why then do they reoccur? There must be a breakdown in the process of communicating this knowledge to the practicing community, the designers, erectors and quality people. There is a constant need to educate and re-educate people on basic principles.

CONCLUSIONS AND RECOMMENDATIONS CONCERNING THE AISC TREATMENT OF BOLT PRELOAD

Education

The Research Council on Structural Connections has sponsored many studies on preload levels and assembly methods. These studies have well documented the importance of proper bolting, and some have resulted in changes to the code or precautionary notes. Despite this effort, there is evidence in the field (11) that assemblers do not understand or simply regard as too conservative the recommendations of these studies and the codes.

There is a communication problem evident here. The Council has done a good job defining problems and devising ways around them, but the people doing the bolting are not aware, do not understand, or do not believe in the recommendations.

Quality

The Quality Control methods employing a calibrated torque wrench need to be improved. Notch suggests using an extensometer as a Quality Control device or using the extensometer to develop a more appropriate job inspecting torque.

Turn of Nut

This method of assembly is reliable if the procedure is adhered to. The method fails horribly when the assembler does not follow the precautions of snugging the joint, match-marking the nut. If people do not understand the importance of these steps or do not believe that the steps are required, then the steps will be skipped or shortcuts will be taken.

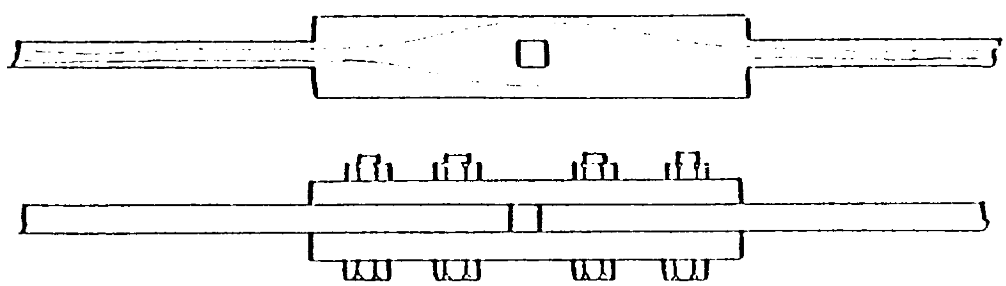
Torque by Calibrated Wrench

This method of assembly was disallowed in favor of the more reliable turn of nut. A sloppily-done turn-of-nut procedure, however, is not more reliable than torque control. Notch suggests that torque control used in conjunction with an extensometer may be a viable combination. The extensometer would be used on a sampling of joints to set up the torque values and bolting procedure required. The instrument could be used periodically as a process control tool and also as a quality check.

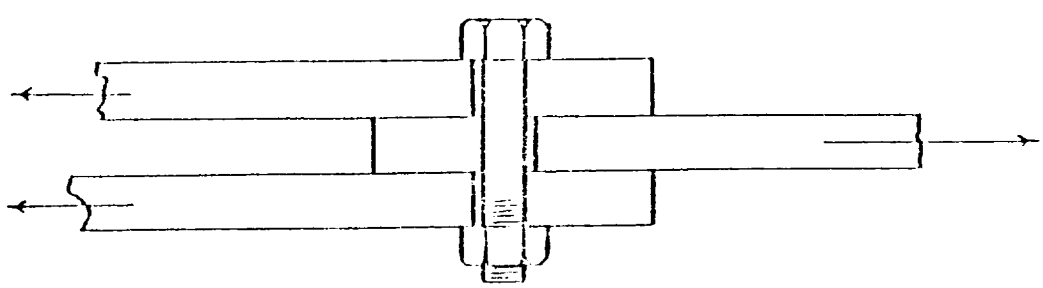
The Research Council has just voted to reinstall the torquing procedure but with some sort of control or procedural guidance.

Embedments

The AISC specification and the Research Council's work has been concentrated on A325 and A490 bolts which have a maximum diameter of 1-1/2". The Council is presently considering studies on larger diameter fasteners and embedments.



SHEAR JOINT LOAD TRANSFER BY FRICTION



SHEAR JOINT LOAD TRANSFER BY BEARING

Figure 10A-1. Shear Joint Load Transfer

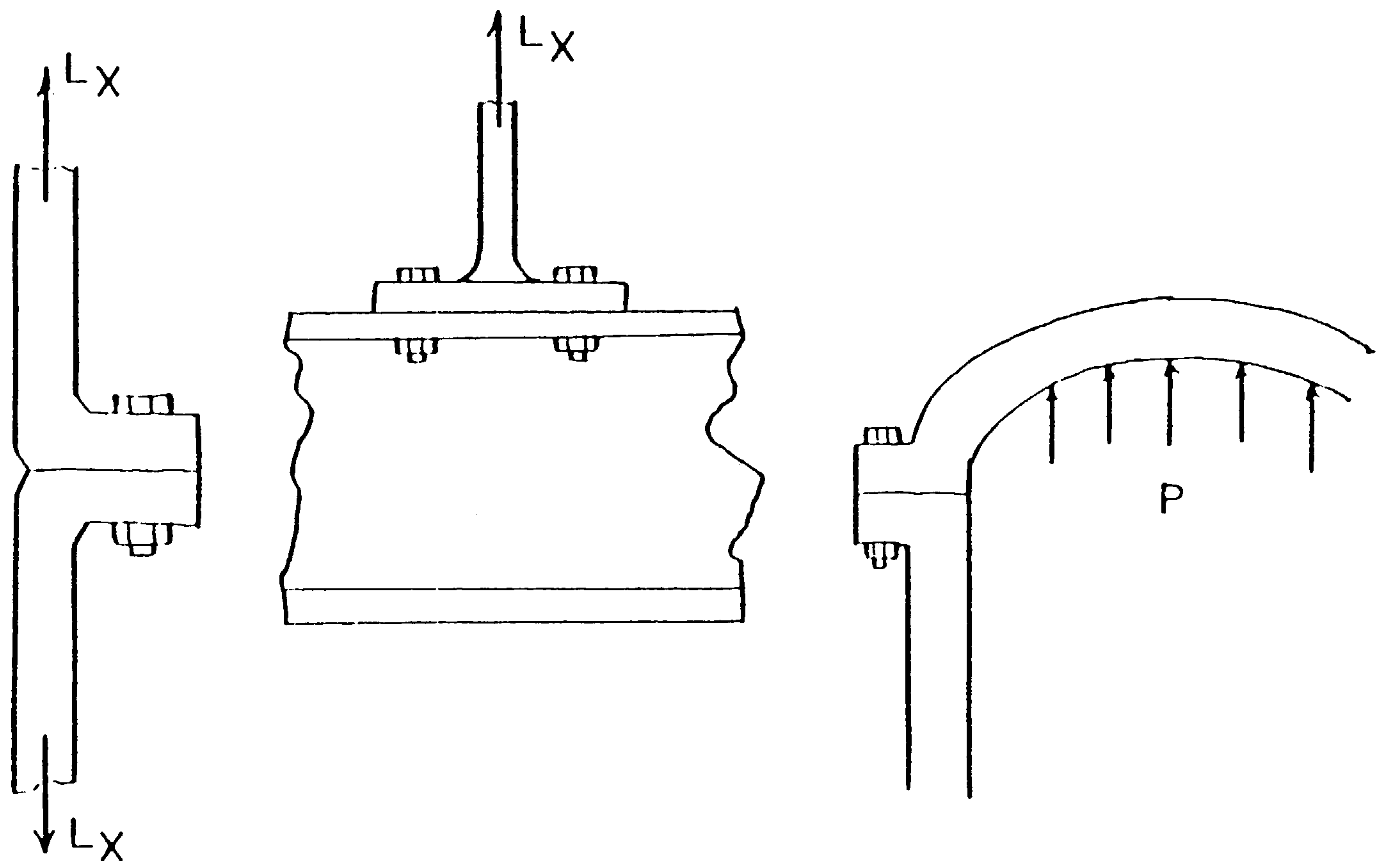


Figure 10A-2. Tension Joints

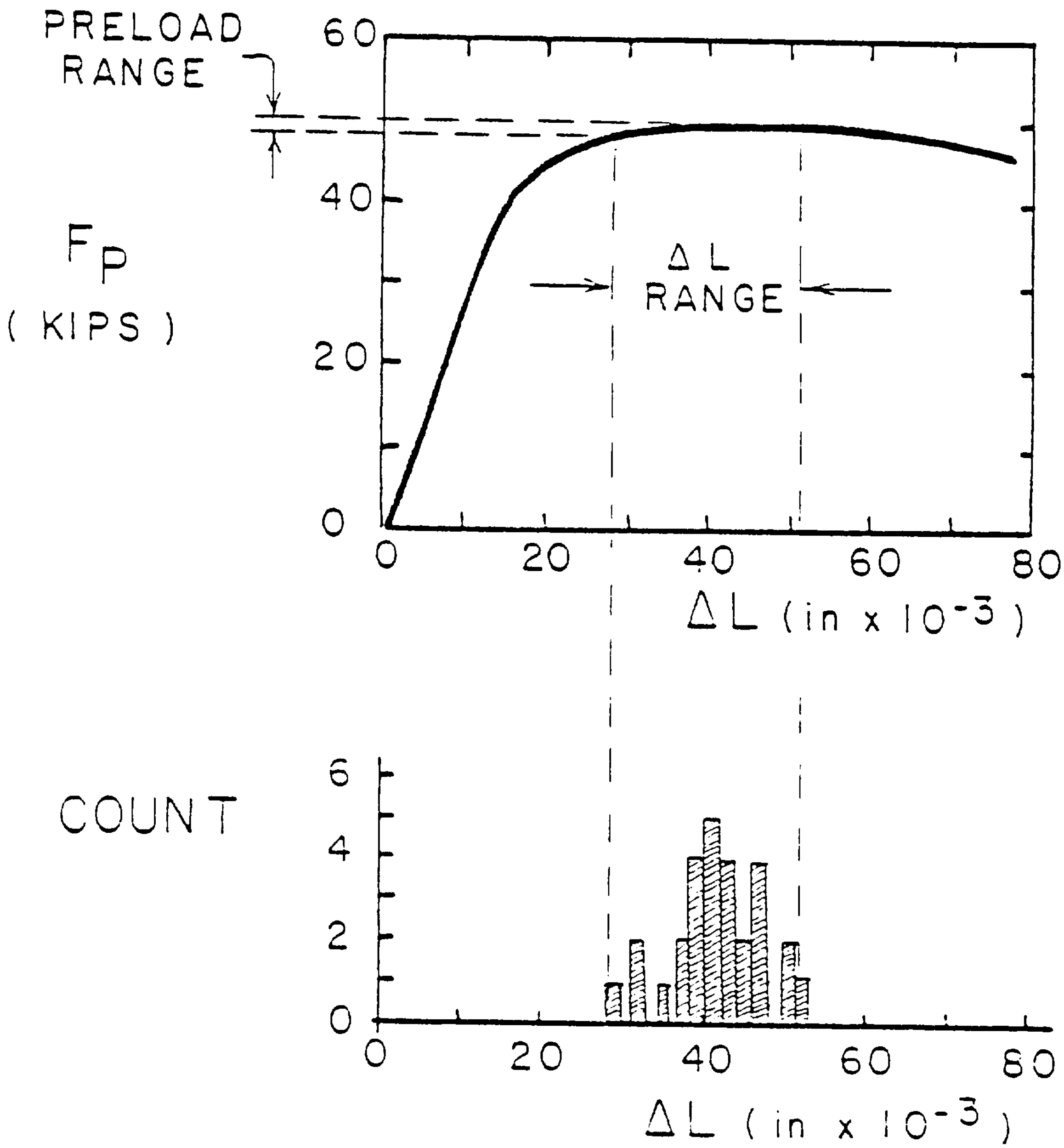


Figure 10A-3. Preload Developed Turn-of-Nut Method

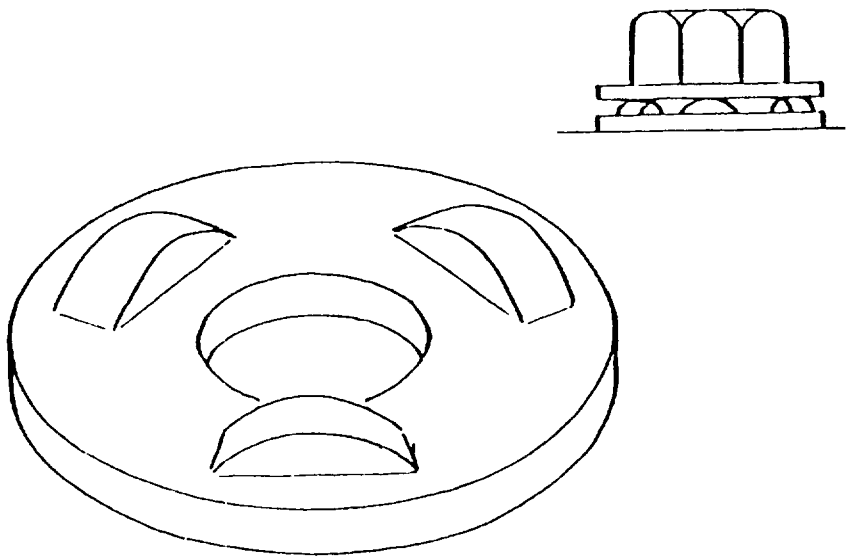


Figure 10A-4. Load Indicating Crush Washer

Appendix 10B

ASME BOILER AND PRESSURE VESSEL CODE, SECTION III, DIVISION 1, SUBSECTION NF

SCOPE

This subsection covers supports for components which are intended to conform to the requirements for Classes 1, 2, 3 and MC construction as set forth in Subsections NB, NC, ND and NE respectively of this section (17). Component supports are defined as metal elements which transmit loads between nuclear power plant components and the building structure. There may be intervening elements in the load path which are not covered by this section, and also the structure is not covered by this section.

The Code covers joints which are subject to tensile loads, shear load, and a combination of shear and tensile load. The shear joints are further subdivided into friction and bearing type.

This classification of joint types is very similar to the AISC Code. The only difference is that the AISC does not consider a case where combined loadings exist. Fisher's Guide, however, does treat this loading condition.

DESIGN

The design approach relative to bolts is covered in Appendix XVIII. Appendix XVIII uses an approach similar to the AISC specification for determining the size, number and type of bolts to be used in a joint.

TENSION JOINTS

For tension joints, allowable bolt stresses (F_{tb}) is specified as 0.5 S_u for ferritic steel and as 0.30 S_u for austenitic steel, where S_u is the ultimate tensile strength of the fastener at temperature. The factor of safety 2.0 for ferritic steels is consistent with AISC treatment.

The method of calculating the working stress is similar to the AISC approach. No credit is taken for the preload in the joint. The working stress is the external

load divided by the actual bolt tensile area available. The AISC uses the nominal bolt area for simplicity and then adjusts the allowable downward to compensate.

SHEAR JOINTS

The allowable shear stress for bolts in a bearing type shear joint is given as:

$$F_{vb} = \frac{0.62\ S_u}{3} \quad \text{for ferritic steels}$$

$$F_{vb} = \frac{0.62\ S_u}{5} \quad \text{for austenitic steels}$$

where F_{vb} is the allowable shear stress and S_u is the ultimate tensile strength at temperature. These equations for the bolt allowables are similar to the theory used in establishing the AISC allowables (18).

For friction type joints Section III calculates the slip resistance of the joint P_s:

$$P_s = m\ n\ T_i\ K_s$$

where P_s is the maximum slip resistance of the joint, m is the number of shear planes per bolt, n is the number of bolts in the joint, T_i is the initial clamping force per bolt (not to exceed 115,000 A_s, where A_s is the tensile stress area of the bolt), and K_s is the slip coefficient for a particular surface condition taken from Table XVII-2461.4-1. This equation is the same equation used in the AISC development (4). The slip coefficients specified in Table XVII-2461.4-1 seem to be conservatively low values taken from various studies reported by Fisher.

Theoretically there is no difference in approach between Section III and the AISC. The AISC simplified the process one step further by developing tables of bolt allowables (really joint allowable) for various type joints with different surface treatments.

PRELOAD

Section III requires no bolt preload for bearing or tension type joints. The AISC spec requires the same bolt preload (70% of ultimate) on all types of joints

(tension, bearing and friction). Section III does require bolt preload on friction joints, since the bolt preload enters into the calculation of the joint slip resistance.

JOINT ASSEMBLY

Paragraph NF-4700 details the requirements for bolted construction. It covers many details of the bolted parts which are similarly addressed by the AISC Code. Briefly listing the items considered:

- Hole size: guidance is given on use of oversized and slotted holes.
- Washers: use of hardened washers with oversized holes is specified.
- Use of beveled washers is recommended for slopes of more than 1:20.
- Hardened washer is required under the turned element when calibrated torque wrench is used.
- Winter 1982 Addenda states that threads will run the full height of the nut.
- Bolt tension is to be achieved by tightening to a torque not less than given in the design specification.
- Turn-of-nut method is allowed.
- Summer 1982 Addenda allows control of bolt tension by load indicating washers or by direct extension indicators.
- Hardened washers are required when using turn of nut or indicating washers.

CONCLUSIONS AND RECOMMENDATIONS ON THE ASME SECTION III, NF TREATMENT OF BOLT PRELOAD

Assembly

The same criticisms and recommendations stated previously for turn-of-nut and torque control relative to the AISC code apply.

Quality

Subsection NF makes no attempt to address quality or the methods of insuring bolt preload. Quality is covered generally in Subsection NA which requires procedures and instructions and calibrated tools. As discussed, determining the preload which exists in an assembled joint is not a trivial matter.

Appendix 10C

ASME BOILER AND PRESSURE VESSEL CODE, SECTION VIII, DIVISION 1

SCOPE

This section contains rules for construction of pressure vessels. Pressure vessels are defined as containers for containment of pressure, either internal or external. The pressure may be obtained from an external source of from heat (19). The code is limited to vessels having:

- Greater than 120 gallons
- Pressure greater than 15 psi
- Vessels greater than 6" inside diameter
- Vessels less than 3,000 psi
- Vessels not recognized as piping components

DESIGN APPROACH

Subsection UCS has tables of allowable stress as a function of temperature for materials used in the fabrication of vessels. At temperatures below the creep range, allowable stress values for bolting materials enhanced by heat treatment or strain hardening shall not exceed the lesser of 20% of the specified minimum tensile strength at room temperature or 25% of the specified minimum yield at room temperature. At temperatures in the creep range, the creep rate and stress rupture characteristics govern the allowables (20).

Division 1 is based on design by rule. The general philosophy is that simplified equations are used to calculate working stress. These equations do not require calculation of such things as principal stresses and stress intensifiers. The factor of safety and assigning allowables to the load situation compensate for the simplified analysis and provide a safe design.

The same philosophy carries over into bolting, thus the relatively low allowable stresses for the bolting materials.

The bolting is generally required to seal a pressure boundary which, in most cases, is a gasketed joint. The approach to sizing bolts and establishing the preload is detailed in Appendix II. The rules provide for and consider hydrostatic end loading on the joint due to the pressure of the contained fluid and gasket seating loads. The code design procedure for determining the bolt size and preload is as follows:

- The geometry of the joint must be fully defined including:

  G = the mean gasket diameter

  b = the effective seating width of the gasket; this is some fraction of the actual gasket width. Table UA-49.2 gives the relationship for various gasket configurations.

- Calculate the bolt load W_{m1}, which is the minimum required bolt load for operating conditions:

  $$W_{m1} = 0.785\ G^2P + 2b \times 3.14\ G\ m\ P$$

  where P is contained pressure, and m is the gasket factor or sealing maintenance factor.

The first term of the expression is the bolt load to restrain the hydrostatic end load. The second term is a multiple of the contained pressure which provides residual compressive load on the gasket at operating pressure. This residual force serves to seal the joint. The values of m for different gaskets are found in Table UA-49.1. These values are based on experience and experimentation, probably more of the former.

It is generally accepted that merely applying W_{m1} to the joint is sometimes not sufficient to seal the joint. It is required that a gasket seating force W_{m2} be applied prior to pressurizing. The code calculation of the seating load is:

$$W_{m2} = 3.14\ b\ G\ y$$

where y is the gasket unit seating load. The values of y for various gasket types are found in Table UA-49.1

Using W_{m1} and W_{m2} and the allowable bolt stress, the required bolt area A_m is calculated. The number and diameter of the bolts is selected to give at least the required bolt area to independently satisfy each load case. Normally the higher bolt load will prevail. These bolt loads are also used in the stress calculations

for the joint members. Two loading conditions must be considered in the flange design. The flange design bolt load is W; the two design conditions are:

$$W = W_{m1} \qquad \text{Operating conditions}$$

$$W = \frac{A_m + A_b}{2} S_a \qquad \text{Gasket seating}$$

where A_m is the required bolt area, A_b is the actual bolt area, and S_a is the bolt allowable stress at ambient conditions. This last equation is a load which would be expected if the maintenance man loaded the bolts to the maximum allowable stress, disregarding the W_{m1} and W_{m2} calculated by the designer. The code describes this load condition as abuse of the flange from overbolting. The code recommends that this load be used to design the flange to give a margin against such abuse. "If accidental safety against abuse is desired, W can be taken as:

$$W = A_b \times S_a$$

and the flange designed on that basis." (21)

BOLT PRELOAD

The bolt preload philosophy of the Code is expressed in Appendix S, Design Considerations for Bolted Flange Connections. The objective of this appendix is stated in the first sentence, "The primary purpose of the rules for bolted flange connections in Part A and B of Appendix II is to insure safety, but there are certain practical matters to be taken into consideration in order to obtain a serviceable design. One of the most important of these is the proportioning of the bolting, i.e., determining the number and size of the bolts." (22)

This appendix addresses the question of what preload should be put into the bolts at assembly and makes the following points regarding bolt preload:

1. Former practice or the loads determined in Appendix II should be sufficient to seal the joint. When unusual features exist (i.e., the joint will not seal), the following suggestions are made.

2. The maximum allowable bolting stresses used in Appendix II are design values to be used in determining the minimum amount of bolting required. Appendix S recognizes that conditions may exist which

require tightening of bolts to stresses which exceed the design allowables. One of these conditions, often encountered, is the requirement to seal during a 1.5 factor, hydrostatic test.

When bolt loads are increased, the effect on flange stress, flange distortion, gasket and yielding of the bolts must be considered. Having considered these possibilities, it is permissible to increase bolt loads above the design values. Quoting from Appendix S: "In any event it is evident that an initial bolt stress higher than the design value may, and in some cases must, be developed in the tightening operation, and it is the intent of this Division that such practice is permissible." (23)

Other bolting suggestions given in Appendix S are:

- Temperature effects can result in differential expansion of parts causing loss of bolt preload and leakage. Temperature can also induce stress relaxation in the bolt, flange and the gasket, resulting in a leakage due to loss of clamping force. In these situations retightening the bolts is permitted.

- When retightening, caution must be exercised to insure that the loosening was not caused by operating loads which caused yielding of the bolts. If this were the case, then repeated tightening would lead to bolt failure.

The appendix concludes the discussion on the preload level with the following statement: "From the foregoing, it is obvious that the bolt stress can vary over a considerable range above the design stress value. The design stress values for bolting in Subsection C have been set at a conservative value to provide a factor against yielding." (24) This statement acknowledges that bolting normally performs at stress levels above the code allowables and that this situation is not a code violation. This statement is closely followed by a warning that while the bolts can tolerate the higher stresses the "margin against flange yielding is not as great".

To summarize, the bolt stress may be greater than allowables, but consideration must be given to the other components of the system (gasket and flange).

ASSEMBLY AND PRELOADING METHODS

Appendix S expresses a philosophy of assembly in the following sentence: "Another very important item in bolting design is the question of whether the necessary bolt stress is actually realized and what special means of tightening, if any, must be employed." (24)

Appendix S suggests that the joint design should be capable of being assembled using the simplest methods of bolting. It recommends manual wrenching as most desirable. If required, more sophisticated methods, such as preheating the bolts, impact wrenches, and bolt tensioners, should be employed. When better preload control is required, lubricants may be used; as a last resort, bolt elongation measurements using an extensometer device may be required to control bolt preload.

QUALITY CONTROL

Section VIII of the Code does not address the problem of insuring that the proper bolt preloads are achieved.

SUMMARY AND RECOMMENDATIONS

Methods for sizing bolts and establishing design stress for bolting is adequately covered and relatively straightforward.

Selecting the bolt preload level required to seal the joint is left up to the assemblers' judgement. Higher bolt loads are allowable but must be applied with caution.

Recent work by the PVRC has shown that there is validity to the requirement for establishing a uniform gasket seating stress (the y value of the code). Uniformly seating the gasket to a relatively high stress does improve the sealing performance of the joint. The work seems to indicate that the required gasket seating stress may be a function of the contained fluid as well as acceptable leak rate, rather than a constant for a gasket.

The Code encourages simple assembly methods, but in some cases these techniques are not sufficient.

An industry group should sponsor a program to identify and correct generic leak problems, i.e., valve body-to-bonnet leaks. This approach should be a hands-on empirical approach, as opposed to the theoretical approach taken by the PVRC Task Group on Bolted Joints.

Appendix 10D

COMPARISON OF ASME CODES ON PRESSURE BOUNDARY BOLTING

SECTION VIII, DIVISION 1 AND 2

Section VIII, Division 2, Pressure Vessels, Alternative Rules, is similar to Section VIII, Division 1. Division 2 is design by analysis; Division 1 is design by rule. Appendix 3 of Division 2 covers bolting preload, and it is identical to Appendix II and Appendix S of Division 1.

SECTION III, NB

Section III, Division 1, Subsection NB covers the design and installation of Class 1 components. Article NB-3000 is the Design section of the code; Appendix E is used to size the bolts. The equations, the "m" and "y" factors are identical to those found in Section VIII, Division 1, Appendix II. Article 3000 also considers fatigue in sizing the bolts.

Installation of bolting is covered in Article 4700. Approximately one-third of a page is devoted to the subject. The subjects addressed are:

- NB-4712 - Thread lubricants will be suitable for the service and shall not react with the service fluid or component material.
- NB-4713 - Remove thread lubricants to seal weld.
- NB-4720 - Gasketed joints shall bear uniformly on the gasket and all flanged joints shall be made up with relatively uniform bolt stress.

This attempt at specifying assembly rules is very inadequate.

SECTION III, NC

The treatment of bolt preload in Section III, Division 1, Subsection NC for Class 2 components and Subsection NE for Class MC components is identical to the Subsection NB treatment.

SECTION III, ND

Subsection ND, Class 3 components has no treatment of preload and assembly.

SECTION III, NG

Subsection NG, core support structures has no rules for sizing bolting but offers the same suggestions as NB for assembly.

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Section 11

EVALUATION PROCEDURE FOR ASSURING INTEGRITY OF BOLTING MATERIAL IN COMPONENT SUPPORT APPLICATIONS

BACKGROUND

Failures of high strength bolting in Class 1 component supports and other safety-related equipment have been reported by a number of power plant licensees. The bolt failures have primarily occurred in pressurized water reactors (PWR) in both ambient and elevated temperature environments. Common characteristics among the reported incidents include:

- Materials that were overly hard and not within specification
- Aqueous environments that were created by high humidity or primary coolant leakage
- High sustained tensile loads caused by installation practices

The most frequently observed failure modes among the reported failures was stress corrosion cracking (SCC). Both low alloy quenched and tempered (LAQT) and maraging steels have been subject to degradation by SCC.

Due to the safety implication of these events, the Nuclear Regulatory Commission (NRC) has added a new issue designated as Generic Issue 29. This issue covers the NRC staff's concern with both pressure boundary and component support bolting. While the primary concern of Generic Issue 29 is with the integrity of the primary pressure boundary, the reliability of the component support structures under postulated accident conditions is also being questioned.

With regard to component support bolting, Aptech Engineering Services, Inc., issued a report (1) in May 1982 that presented the results of an integrity evaluation for the reactor coolant pump snubber anchor studs for the Midland Project of Consumers Power Company (CPCo). The objective of that evaluation was to assess the structural integrity of these anchors for both long-term and short-term loading situations. Specifically, a major portion of the assessment involved detailed computations to:

- Determine the potential for SCC in the materials purchased
- Evaluate the effects of low toughness properties
- Calculate the allowable loads under long- and short-term loading conditions

The basis of this assessment was originally developed under RP1757-2 (2) for the Electric Power Research Institute (EPRI) in conjunction with the review of the NRC proposed SCC review Plan under USI A-12. The evaluation performed for CPCo represents the first plant-specific utilization of the EPRI-developed methodology for the purpose of establishing a maximum allowable bolt stress for normal operating and postulated accident conditions.

SCOPE AND OBJECTIVES

The purpose of this section is to present an evaluation procedure for general application to bolting products used in component supports that are fabricated from steels commonly used support bolting materials. The evaluation procedure could be used to justify serviceability of materials that may be questioned under Generic Issue 29. It is anticipated that this report would be useful to a utility as part of a plant-specific plan to dispose of materials that require examination under this generic issue. Where possible, this report has expanded the work presented in Refs. (1) and (2) in order to allow for general use by the industry. For completeness, the basic assumptions and description of the input parameters are presented.

The primary objective of this section is to present the procedural steps and required information to determine allowable bolt loads to prevent SCC under steady-state or long-term conditions during normal operation. Plots of allowable bolt stress, as a function of material hardness bolt size, and thread pitch can be developed with the procedures. The allowable bolt stress could then be compared with the actual bolt stresses calculated for the design. A requirement of the procedure is that hardness testing be performed on the population of bolts so that hardness limits can be statistically determined. Also as part of the evaluation objective, allowable bolt stresses to prevent fracture under short-term (accident) loads are established when low toughness is implied by the hardness data.

METHOD OF APPROACH

Strategy

The basic approach of the evaluation method is summarized herein. The procedure employs fracture mechanics concepts to quantify the allowable bolt loads based on

the fracture properties of the material. In addition, the minimum strength of the material is estimated in order to compare with the design requirements based on strength.

A flowchart showing the integration of the required input information with the calculational steps is shown in Figure 11-1. In applying the principles of linear elastic fracture mechanics (LEFM), a philosophy has been adopted which involves the use of a "reference flaw" to calculate the allowable bolt loads. In the assessment strategy, this reference flaw is postulated at the thread root and represents a flaw which is large enough to be unlikely to exist in a bolt. The material behavior (i.e., mechanical strength, fracture resistance, and SCC resistance) are estimated from an analysis of the field hardness measurements. Hence, a key step in the evaluation is the determination of the hardness for the material for a reasonable sample size so that statistical limits can be established. Once the material properties are established, the remaining calculational steps are straightforward and simple.

Assumptions

Many assumptions were made in establishing the procedures. The background for most of the assumptions are discussed in detail elsewhere (1,2). For completeness, the major assumptions are outlined below.

- A flaw with a depth of 0.01 inches with an aspect ratio, a/ℓ, of 1-to-2 is assumed to exist at the thread root.
- A lower bound curve to fracture toughness data was used to establish K_{Ic} for the material.
- A lower bound curve to threshold stress intensity factor data was used to establish K_{Iscc} for the material.
- The variability in hardness with respect to length was assumed to be no better than the variability in hardness within the heat.
- A 90% probability of occurrence with 95% confidence was used as the statistical criterion for determining the tolerance limits for the bolt population.

The assumption that the material variability along the length is equal to the material variability determined for the entire heat may be very unrealistic, especially for short bolts. The variability in hardness with respect to axial position could be quantified by testing. Also, lower bound curves for K_{Ic} and K_{Iscc} could be very conservative. Statistically based curves may provide improvements.

Scope of Procedures

In order to ensure the proper use of this section of the report, this subsection has been prepared to present the scope of the procedures and highlight the potential limitations.

Failure Modes. In the evaluation procedure contained herein, the acceptability requirements for service have been established based on assuring against service failure from two potential failure modes. These modes of failure are:

- Crack propagation in a subcritical manner by intergranular stress corrosion cracking
- Brittle or fast fracture due to crack instability under monotonically increasing load

Each failure condition is unique so that assuring failure prevention for one mode does not guarantee safe conditions for the other.

When applying the evaluation method, the failure mode or modes to be prevented must be described by one of the above failure models; otherwise, irrelevant conclusions will be achieved. Specific failure modes that are not covered by the procedure, but are relevant to bolts in general, include general corrosion failure or wastage, fatigue, and corrosion-assisted fatigue. The procedures would require revision in order to expand the method to cover other modes of failure.

Materials. The material properties curves for SCC susceptibility and fracture toughness behavior were derived from a data base of laboratory tests for steels that can be classified as low alloy, quenched and tempered, or maraging types. Materials that satisfy the above conditions for chemistry and heat treatment can be evaluated by the methods described in this section of the report.

Environment. The SCC susceptibility of LAQT and maraging steels is very sensitive to the environmental conditions, specifically the corrosive medium and service temperature. The SCC threshold curves given in Appendix 11B were derived from K_{Iscc} data measured in the laboratory with either moist air, distilled water, aqueous NaCl solutions or seawater environments. Although not indicated in all cases, the testing temperature was typically at room temperature levels. However, a review of K_{Iscc} data given for LAQT steels as a function of test temperature indicated K_{Iscc} is temperature invariant for aqueous solutions.

Based on this background information, the following restriction for the SCC evaluation for computing the allowable stress level σ_a^{SCC} is applied:

- Service environments are restricted to moist air or aqueous NaCl environments, or environments that are viewed as being less aggressive than those from which the test data were developed.
- Highest service temperature for the bolting application in consideration of SCC limits should be limited to 250°F.

Caution should be exercised when extending the scope of the K_{ISCC} evaluation to other environments or elevated temperatures. Application to temperatures greater than 250°F could be allowed for the aqueous environments since the corrosive medium would not be present, provided that the creation of an aggressive environment, such as those that could be formed by the breakdown of thread lubricants or coatings, is not likely.

Geometry. The bolt geometry and thread-root characteristics are consistent with the Unified Inch Screw Thread Standards of ANSI B1.1 (3) and, when listed, the bolting sizes given in the ASTM specifications (4). The method is directly applicable to the thread-root region over the span of unengaged threads for studs and bolts. Furthermore, the procedure will be appropriate for evaluating the thread-root region of engaged threads within nuts or internally threaded connectors. Engineering judgement was used to establish the applicability to areas, that judgement being based on a comparison between engaged and unengaged regions as to the nature of the stress distributions and the magnitude of the stress concentration. These findings have been judged to be sufficient to allow the method to also be applicable to engaged thread regions as well. For these reasons, the procedure is deemed general in application to standard ANSI threads in both engaged and unengaged thread regions.

For headed bolts, another region of high local stress exists at the head-to-shank transition region. Although there is a potential for SCC to initiate at this location as well, it has been judged that the thread root region will be representative and, in many cases, be the limiting region from the standpoint of local stress effects.

Mode of Loadings. It is assumed in the evaluation methodology that the predominant loading mode is uniaxial tension. The source of the uniaxial stress can be preload, actively applied mechanical loads, or thermally-induced loading due to

expansion. For the situation where shear loads are to be carried by the bolts, it was judged (2) that for SCC and fracture, shear stresses other than torsion will not significantly contribute to the crack driving force of the postulated reference flaw. Bending stresses have been neglected in the procedure, so any applications where bolts will experience cross-sectional bending loads cannot be handled directly by the method in its present form. A conservative method to account for any bending loads is to add the bending stress magnitude to the tension stress, or

$$\sigma = \sigma_m + \sigma_b \qquad (11\text{-}1)$$

where σ_m is the membrane or tensile component and σ_b is the bending stress.

EVALUATION PROCEDURE

The outline presented below summarizes the steps required to perform the evaluation. Each analysis part is described in detail in the subsections that follow. The strategy shown in Figure 11-1 is divided into six parts as follows:

1. Determination of Hardness Limits
2. Estimation of Material Properties
3. Determination of K
4. Calculation of Allowable Bolt Loads Based on Stress Corrosion Cracking (Long-Term Conditions)
5. Calculation of Allowable Bolt Loads Based on Fracture (Short-Term Conditions)
6. Comparison with Acceptance Criteria

Part 1 - Establishment of the Hardness Limits

The minimum and maximum hardness limits for the lot of bolts must be established to provide a quantitative estimate of material properties. To determine the minimum and maximum limits, hardness testing is required to establish a data base for the lot. It possible, the lot of bolts should be defined as an individual heat of material or a single size of bolt. The following steps should then be followed:

1. Establish a data base of hardness measurements by bolt lot by implementing a suitable test sampling plan.
2. Establish the probability function that best represents the frequency of the data. A normal distribution function may provide a reasonable fit when the hardness data has been first converted to their

equivalent value in tensile strength units in accordance with ASTM A370 (5) and the normal function is applied to the tensile strength data set. If a sufficient number of data points exist, a nonparametric approach will provide statistical limits to be determined without the need of assuming a particular distribution function.

3. Determine the two-sided tolerance limits for the bolt population that provides a 90% probability that measurements will fall between these limits with 95% confidence.

4. If the statistical analysis was performed on the equivalent tensile strength values, then convert the computed results for tensile strength limits to the appropriate hardness units.

5. Compare the two-sided hardness limits with the appropriate specification requirements (see Appendix 11A for a listing of hardness limits by specification). If the computed limits satisfy the requirements for which the material was purchased, then compliance with the intent of the original purchase specification is achieved and no additional evaluation would be required.

6. If additional analysis is required beyond Step 5, compute the one-sided tolerance limits for minimum and maximum hardness level (or strength level) with the same 90% to 95% criteria.

7. Compare the one-sided hardness limit for maximum hardness level to the conditionally acceptable limit of 41 R_C. If the computed limit is less than or equal to 41 R_C, then the lot is acceptable, and no further evaluation is required. If this limit is exceeded, then proceed with the remaining evaluation steps.

The above procedure can be repeated for each material group or stratum that was identified as requiring evaluation. The computed one-sided tolerance limits for minimum and maximum hardness will be used in Part 2 of the procedure.

Part 2 - Estimation of Material Properties

The procedures outlined below are the steps that will define conservative estimates of yield and ultimate strength, SCC threshold, and fracture toughness:

1. Identify the material supplied to the purchase specification from chemistry information, etc.

2. Define the specified minimum yield strength, S_y, and the specified minimum ultimate tensile strength, S_u, for the governing material specification.

3. Convert the minimum and maximum hardness (or tensile strength) limits to material yield strengths (σ_{ymin} and σ_{ymax}) with the curve provided in Appendix 11B.

4. Convert the minimum hardness limit to equivalent tensile strength units with the tables in ASTM A370 (5).

5. From the hardness versus K_{Iscc} curves given in Appendix 11B, use the maximum hardness from Step 3 above to define a lower bound level for K_{Iscc} called $\bar{K}_{Iscc}$.

6. From the hardness versus K_{Ic} curves given in Appendix 11B, use the maximum hardness from Step 3 above to define a lower bound level for K_{Ic} called $\bar{K}_{Ic}$.

It should be noted that, since both $\bar{K}_{Iscc}$ and $\bar{K}_{Ic}$ reach a lower bound "threshold" value with respect to increasing material yield strength, the Part 1 evaluation could be deleted by conservatively assuming the lower bound threshold levels for materials with trends that appear on the hard side. Provided one is assured that there is no difficulty in meeting the specified minimum strength requirements, the analysis would be simplified significantly if Part 1 can be eliminated.

Part 3 - Determination of K

The following is the procedure to calculate the applied stress intensity factors for a unit applied stress. The calculation for K assumes a reference flaw at the root of a thread with depth of 0.01 inches and a flaw aspect ratio (a/ℓ) equal to 1/2.

1. Define the geometry of the fastener in terms of the following parameters:

   (a) Nominal diameter, D

   (b) Thread pitch $p = 1/n$, where n is the number of threads per inch

   (c) Net tensile or stress area, A_s

2. For the threaded fasteners, including studs and bolts, the value of K_I is determined by the following procedure:

   (a) For the given fastener geometry (i.e., diameter, D, and thread pitch, p) use tables in Appendix 11C to define the reciprocal of stress intensity factor for a unit applied stress, defined as C_k.

   (b) If the exact bolt diameter or thread pitch is not listed in the tables, then use linear interpolation to determine the value of C_k.

Part 4 - Calculation of Allowable Bolt Load Based on SCC

The allowable bolt load for prevention against SCC for long-term loading under normal operating condition is calculated by the following relationship:

$$\sigma_a^{scc} = C_k \bar{K}_{Iscc} \qquad (11\text{-}2)$$

where $\bar{K}_{Iscc}$ is the lower bound K_{Iscc} level established under Step 5 of Part 2, and C_k is the reciprocal of stress intensity factor for the postulated reference flaw and unit applied stress from Step 2 of Part 3. The allowable bolt load based on SCC can be computed from

$$P_a^{scc} = \sigma_a^{scc} A_s \qquad (11\text{-}3)$$

where A_s is the net tensile or stress area for the bolt. It should be noted that fracture toughness is not considered in the determination of allowable bolt stress for long-term load since K_{Iscc} will be less than K_{Ic} and, therefore, limiting.

Part 5 - Calculation of Allowable Bolt Loads Based on Fracture

The allowable bolt load based on fracture for short-term or accident loading conditions is determined from the following expression:

$$\sigma_a^{f} = C_k \bar{K}_{Ic} \qquad (11\text{-}4)$$

where K_I is determined from Step 2 of Part 3, and $\bar{K}_{Ic}$ is the lower bound fracture toughness from Step 6 of Part 2. The allowable bolt load based on fracture can be computed from

$$P_a^{f} = \sigma_a^{f} A_s \qquad (11\text{-}5)$$

where A_s is the net tensile or stress area for the bolt.

Part 6 - Comparison with Acceptance Criteria

Define the service stress for normal operation ($\sigma^{\ell t}$) and postulated accident (σ^{st}) conditions. If $\sigma^{st}/\sigma^{\ell t}$ is less than or equal to 1.10, then the material lot is considered acceptable if

$$\sigma^{\ell t} < \sigma_a^{scc} \qquad (11\text{-}6)$$

If $\sigma^{st}/\sigma^{\ell t}$ is greater than 1.10, then a dual criterion must be satisfied.

For this case, the material lot is acceptable if

$$\begin{aligned} \sigma^{\ell t} &< \sigma_a^{scc} \\ \sigma^{st} &< \sigma_a^{f} \end{aligned} \qquad (11\text{-}7)$$

If the conditions above are satisfied, then the concerns for SCC and toughness have been addressed, and no further action is required. This completes the details of the evaluation.

SUMMARY

The preceding presentation gives the required steps for evaluating bolting materials for SCC and toughness concerns. At the end of the Parts 4 and 5, the allowable bolt stress (or loads) for SCC and fracture considerations have been quantified. The acceptable of the existing material is established in Part 6 of the procedure.

General evaluation procedures were developed based on fracture mechanics concepts. These procedures can be used, in a plant-specific plan, to evaluate bolting materials in component support structures that fall under the NRC Generic Issue 29. The methodology is structured to demonstrate that the material condition is adequate to prevent SCC and low toughness behavior for the anticipated service stress levels and environment.

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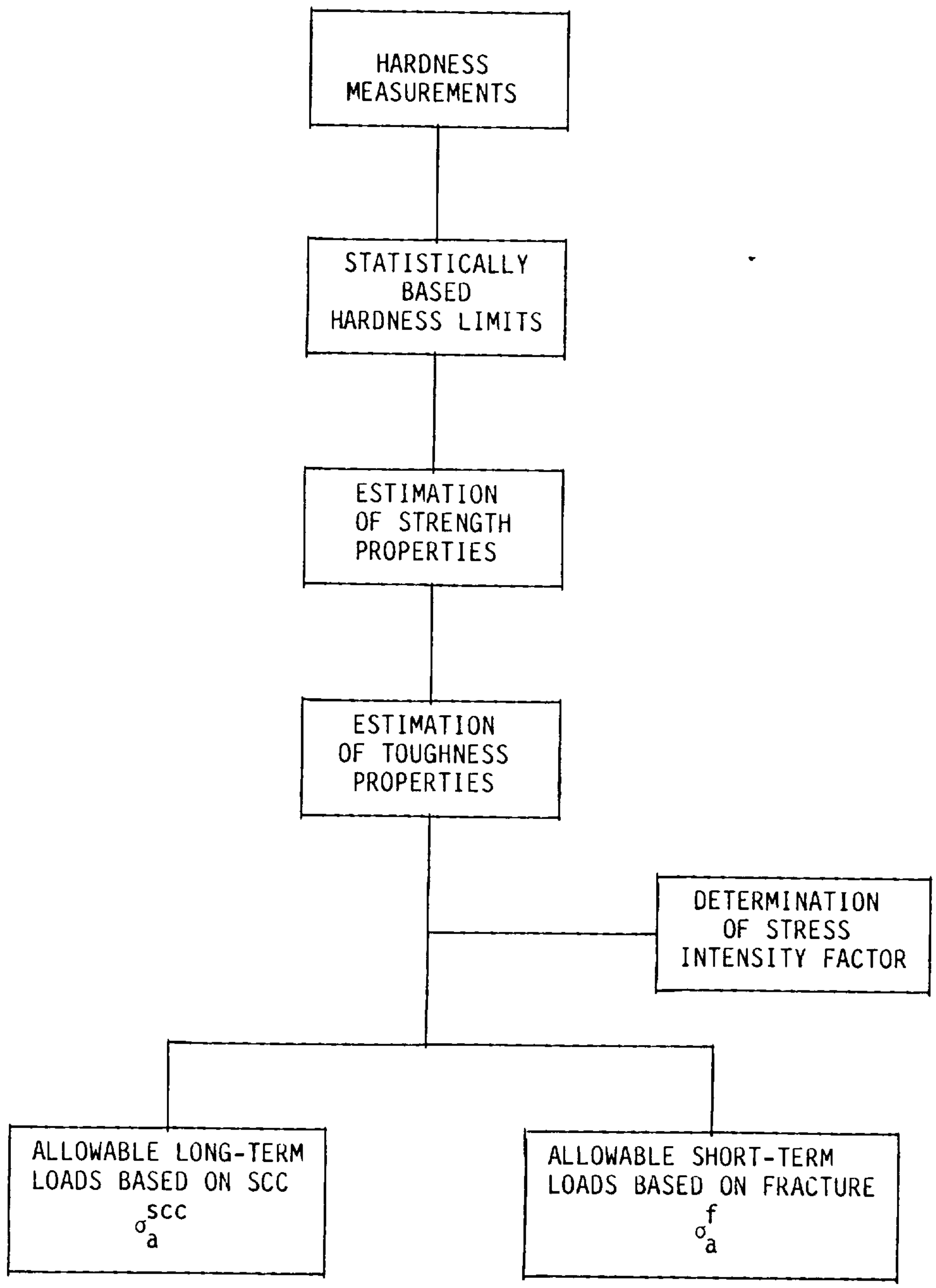

Figure 11-1. Strategy of Evaluation Methodology

NOMENCLATURE

Symbol	Definition
a	Crack depth
a_c	Critical crack depth
a_r	Crack depth for a postulated "reference flaw"
a/ℓ	Crack aspect ratio
A	Cross-sectional (shank) area
A_s	Net tensile area or "stress" area
C_f	Yield strength reduction factor for temperature
D	Nominal (major) diameter
d	Minor diameter
F_y	Specified minimum yield strength
F_u	Specified minimum ultimate tensile strength
h	Hardness
h_{max}	Statistically based maximum hardness limit
h_{min}	Statistically based minimum hardness limit
K	Stress intensity factor
K_I	Stress intensity factor for Mode I loading
K_{II}	Stress intensity factor for Mode II loading
K_{Ic}	Plane strain fracture toughness for Mode I loading
K_{IIc}	Plane strain fracture toughness for Mode II loading
$K_{\bar{I}c}$	Lower bound to K_{Ic} data
K_{Iscc}	Threshold stress intensity factor for crack propagation by stress corrosion cracking
$K_{\bar{I}scc}$	Lower bound to K_{Iscc} data
ℓ	Crack length
L	Leeb-scale units for hardness
n	Number of threads

Symbol	Definition
p	Thread pitch (p = 1/n)
P	Axial load
P_a^f	Allowable tension load based on fracture
P_a^{scc}	Allowable tension load based on stress corrosion cracking
$P_a^{\ell t}$	Allowable tension load for long-term (normal) loading conditions
P_a^{st}	Allowable tension load for short-term (accident) loading conditions
R_b	Rockwell-B scale units for hardness (also HRB)
R_c	Rockwell-C scale units for hardness (also HRC)
S_y	Specified minimum yield strength (ASME Code)
S_u	Specified minimum ultimate tensile strength (ASME Code)
σ	Nominally applied stress
σ_a	Allowable stress
σ_a^f	Allowable stress based on fracture toughness
σ_a^s	Allowable stress based on strength
σ_a^{scc}	Allowable stress based on stress corrosion cracking
$\sigma_a^{\ell t}$	Allowable stress for long-term loading conditions
σ_a^{st}	Allowable stress for short-term (accident) loading conditions
σ_y	Yield strength
σ_{ym}	Minimum yield strength
σ_{ymax}	Maximum yield strength limit based on h_{max}
σ_{ymin}	Minimum yield strength limit based on h_{min}
σ_u	Ultimate tensile strength
σ_{um}	Minimum ultimate tensile strength
σ_{umax}	Maximum tensile strength limit based on h_{max}
σ_{umin}	Maximum tensile strength limit based on h_{min}
τ	Nominally applied shear stress
τ_a	Allowable shear stress

Symbol	Definition
τ_a^f	Allowable shear stress based on fracture toughness
τ_a^s	Allowable shear stress based on strength
τ_a^{sa}	Allowable shear stress based on stress corrosion cracking
$\tau_a^{\ell t}$	Allowable shear stress based on long-term (normal) loading conditions
V_a^f	Allowable shear load based on fracture
V_a^{scc}	Allowable shear load based on stress corrosion cracking
$V_a^{\ell t}$	Allowable shear load for long-term (normal) loading conditions
V_a^{st}	Allowable shear load for short-term (accident) loading conditions

Appendix 11A

RECOMMENDED HARDNESS LIMITS FOR SATISFYING ASTM/ASME SPECIFICATIONS

SUMMARY

Hardness limits were established for candidate LAQT materials supplied to the Midland site. These limits are provided in Table 11A-1 and give the minimum and maximum hardnesses in Rockwell-scale and Leeb-scale units. The technical basis for the limits is documented in Refs. (1,2,3). Specifically, the limits were established under the following conditions:

- When a hardness limit (either minimum or maximum) is given as a requirement in the material specifications, then this limit is given in Table 11A-1. If the hardness limit is given in units other than those listed in Table 11A-1, then the hardness limit was converted to equivalent Rockwell-scale units according to ASTM A370 (4).
- When a hardness limit (either minimum or maximum) is not specified, then engineering judgement was used to establish a limit based upon consideration of specified material yield strength, tensile strength and product thickness.

The limits that were established by engineering judgement are identified in Table 11A-1 by an asterisk (*).

REFERENCES

1. Letter to J.A. Pastor (CPCo) from R.C. Cipolla (APTECH). "Hardness Limits for Receipt Inspection Program." January 14, 1982.
2. Letter to J.A. Pastor (CPCo) from R.C. Cipolla (APTECH). "Revised Hardness Limits for CPCo Receipt Inspection Program." September 17, 1982.
3. Letter to J.A. Pastor (CPCo) from R.C. Cipolla (APTECH). "Response to Questions of LAQT Determinations and Hardness Limits." October 28, 1982.
4. ASTM Annual Standards, Part 4, A370. "Mechanical Testing of Steel Products." 1979.

Table 11A-1

RECOMMENDATIONS ON HARDNESS LIMITS FOR LAQT MATERIALS RECEIPT INSPECTION

ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	Hardness Limits[7] Rockwell-Scale Minimum	Hardness Limits[7] Rockwell-Scale Maximum	Hardness Limits[7] Leeb-Scale (L) Minimum	Hardness Limits[7] Leeb-Scale (L) Maximum
A7-66	(See Note 1)	--	--	--	--	--
A36-77a	(See Note 1)	--	--	--	--	--
A125-73	(See Note 2)	--	38HRC*	50HRC	634L*	731L
SA155-75	CMSH-80[3]	≤ 2-1/2" Thick	86HRB* (≈4HRC)	22HRC*	434L*	514L*
		Over 2-1/2" to 4"	83HRB* (≈1HRC)	22HRC*	421L*	514L*
A182-78/SA182-78	F1	--	78HRB	91HRB (≈10HRC)	400L	462L
	F2	--	78HRB	91HRB (≈10HRC)	400L	462L
	F11	--	78HRB	94HRB (≈14HRC)	400L	479L
	F12	--	78HRB	94HRB (≈14HRC)	400L	479L
	F21	--	82HRB	94HRB (≈14HRC)	418L	479L
	F22	--	82HRB	94HRB (≈14HRC)	418L	479L
	F22a	--	69HRB*	86HRB (≈4HRC)	372L*	435L

Table 11A-1 (Continued)

ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	Hardness Limits[7] Rockwell-Scale Minimum	Rockwell-Scale Maximum	Leeb-Scale (L) Minimum	Leeb-Scale (L) Maximum
A193-78a/SA193-78a	B7	≤ 2-1/2" Diam.	26HRC*	36HRC*	544L*	618L*
		Over 2-1/2" to 4"	22HRC*	33HRC*	514L*	596L*
		Over 4" to 7"	95HRB* (≈16HRC)	28HRC*	485L*	558L*
	B7M	≤ 2-1/2" Diam.	94HRB (≈14HRC)	22HRC	473L	514L
	B16	≤ 2-1/2" Diam.	26HRC*	36HRC*	544L*	618L*
		Over 2-1/2" to 4"	20HRC*	31HRC*	500L*	581L*
		Over 4" to 7"	95HRB* (≈16HRC)	28HRC*	485L*	558L*
A194-80a/SA194-80a	4	All	24HRC	38HRC	529L	634L
	7	All	24HRC	38HRC	529L	634L
	7M	All	83HRB (≈1HRC)	22HRC	421L	514L
A234-80/SA234-78	WP1	All	65HRB*	92HRB (≈12HRC)	361L*	468L
	WP12	All	69HRB*	92HRB (≈12HRC)	372L*	468L
	WP11	All	69HRB*	92HRB (≈12HRC)	372L*	468L
	WP22	All	69HRB*	92HRB (≈12HRC)	372L*	468L
	WPR	All	72HRB*	96HRB (≈17HRC)	382L*	490L
A304-79	(See Note 4)	--	--	--	--	--

Table 11A-1 (Continued)

ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	Hardness Limits[7] Rockwell-Scale Minimum	Rockwell-Scale Maximum	Leeb-Scale (L) Minimum	Leeb-Scale (L) Maximum
A320-80b/SA320-78[5]	L1	≤ 1" Diameter	26HRC*	36HRC*	544L*	618L*
	L7, L7A, L7B, L7C	≤ 2-1/2" Diam.	26HRC*	36HRC*	544L*	618L*
	L7M	≤ 2-1/2" Diam.	94HRB (≈14HRC)	22HRC	473L	514L
	L43	≤ 4" Diameter	26HRC*	37HRC*	544L*	626L*
A322-80	(See Note 4)	--	--	--	--	--
A325-78a/SA325-78a	2,3 (See Note 6)	1/2" to 1" Diameter	24HRC	35HRC	529L	611L
		1-1/8" to 1-1/2" Diam.	19HRC	31HRC	497L	581L
A331-74	(See Note 4)	--	--	--	--	--
A333-79	8	--	95HRB* (≈16HRC)	28HRC*	485L*	558L*
A354-78a/SA354-78a	BC	1/4" to 2-1/2" Diam.	26HRC	36HRC	544L	618L
		Over 2-1/2" Diameter	22HRC	33HRC	514L	596L
	BD	1/4" to 2-1/2" Diam.	33HRC	38HRC	596L	634L
		Over 2-1/2" Diameter	31HRC	38HRC	581L	634L
A434-76	BB	1-1/2" Diam. and Less	20HRC*	31HRC*	500L*	581L*
		Over 1-1/2" to 2-1/2"	97HRC* (≈19HRC)	28HRC*	496L*	558L*
		Over 2-1/2" to 4"	95HRB* (≈16HRC)	28HRC*	485L*	558L*
		Over 4" to 7"	93HRB* (≈13HRC)	25HRC*	471L*	536L*
		Over 7" to 9-1/2"	91HRB* (≈10HRC)	22HRC*	460L*	514L*
	BC	1-1/2" Diam. and Less	28HRC*	38HRC*	558L*	634L*

Table 11A-1 (Continued)

ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	Hardness Limits[7]			
			Rockwell-Scale		Leeb-Scale (L)	
			Minimum	Maximum	Minimum	Maximum
A434-76	BC	Over 1-1/2" to 2-1/2"	26HRC*	36HRC*	544L*	618L*
		Over 2-1/2" to 4"	22HRC*	33HRC*	515L*	596L*
		Over 4" to 7"	20HRC*	32HRC*	500L*	588L*
		Over 7" to 9-1/2"	97HRB* (≈19HRC)	30HRC*	496L*	573L*
	BD	1-1/2" Diam. and Less	34HRC*	40HRC*	603L*	649L*
		Over 1-1/2" to 2-1/2"	33HRC*	38HRC*	596L*	634L*
		Over 2-1/2" to 4"	31HRC*	38HRC*	581L*	634L*
		Over 4" to 7"	29HRC*	38HRC*	566L*	634L*
		Over 7" to 9-1/2"	28HRC*	37HRC*	558L*	626L*
A487-80	1Q,2Q	--	91HRB* (≈10HRC)	22HRC*	460L*	514L*
	4Q,11Q,12Q,13Q	--	97HRB* (≈19HRC)	34HRC*	496L*	603L*
	4QA	--	22HRC*	33HRC*	514L*	596L*
	6Q	--	24HRC*	34HRC*	529L*	603L
	7Q	2-1/2" Thick	22HRC*	33HRC*	514L*	596L*
	8Q,9Q	--	95HRB* (≈16HRC)	29HRC*	485L*	566L*
	10Q	--	25HRC*	34HRC*	536L*	603L*
	14Q	--	24HRC*	38HRC*	529L*	634L*
A490-80a	All Grades	1/2" to 1-1/2" Diam.	33HRC	38HRC	596L	634L
A514-77	All Grades	To 3/4" Thick	22HRC	31HRC	514L	581L
	--	Over 3/4" to 2-1/2"	22HRC*	32HRC*	514L*	588L*
	--	Over 2-1/2" to 6"	95HRB* (≈16HRC)	33HRC*	485L*	596L*

Table 11A-1 (Continued)

ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	Hardness Limits[7] Rockwell-Scale Minimum	Rockwell-Scale Maximum	Leeb-Scale (L) Minimum	Leeb-Scale (L) Maximum
A519-80	(See Note 4)	--	--	--	--	--
A521-76	CG	≤4" Solid Dia. or Thick or ≤ 2" Bored Wall Thick	90HRB* (≈10HRC)	22HRC	456L*	514L*
		>4" to 7" (Solid) or >2" to 3-1/2" (Bored)	88HRB* (≈7HRC)	96HRB* (≈17HRC)	440L*	490L*
		>7" to 10" (Solid) or >3-1/2" to 5" (Bored)	88HRB* (≈7HRC)	96HRB* (≈17HRC)	440L*	490L*
		>5" to 10" (Bored)	88HRB* (≈7HRC)	96HRB* (≈17HRC)	440L*	490L*
	AD	≤7" Solid Dia. or Thick or ≤3-1/2" Bored Wall Th.	92HRB* (≈12HRC)	25HRC*	468L*	536L*
		>7" to 10" (Solid) or >3-1/2" to 10" (Wall)	90HRB* (≈10HRC)	22HRC*	456L*	514L*
	AE	≤7" Solid Dia. or Thick or ≤3-1/2" Bored Wall Th.	95HRB* (≈16HRC)	29HRC*	485L*	566L*
		>7" to 10" (Solid) or >3-1/2" to 5" (Bored)	95HRB* (≈14HRC)	29HRC*	479L*	566L*
		>10" to 20" (Solid) or >5" to 8" (Bored)	92HRB* (≈12HRC)	25HRC*	468L*	536L*
	AF	≤4" Solid Dia. or Thick or ≤2 Bored Wall Thick	25HRC*	34HRC*	536L*	603L*
		>4" to 7" (Solid) or >2" to 3-1/2" (Bored)	22HRC*	32HRC*	514L*	588L*
		>7" to 10" (Solid) or >3-1/2" to 5" (Bored)	97HRB* (≈19HRC)	31HRC*	497L*	581L*

Table 11A-1 (Continued)

ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	Hardness Limits[7] Rockwell-Scale Minimum	Rockwell-Scale Maximum	Leeb-Scale (L) Minimum	Leeb-Scale (L) Maximum
A521-76	AG	≤4" Solid Dia. or Thick or ≤2" Bored Wall Thick	31HRC*	38HRC*	581L*	634L*
		>4" to 7" (Solid) or ≥2" to 3-1/2" (Bored)	30HRC*	37HRC*	573L*	626L*
		>7" to 10" (Solid) or >3-1/2" to 5" (Bored)	28HRC*	36HRC*	558L*	618L*
	AH	≤4" Solid Dia. or Thick or ≤2" Bored Wall Thick	36HRC*	43HRC*	618L*	673L*
		>4" to 7" (Solid) or >2" to 3-1/2" (Bored)	36HRC*	43HRC*	618L*	673L*
		>7" to 10" (Solid) or >3-1/2" to 5" (Bored)	34HRC*	42HRC*	603L*	665L*
SA537-78	2	≤ 2-1/2" Thick	86HRB* (≈4HRC)	22HRC*	434L*	514L*
		Over 2-1/2" to 4"	83HRB* (≈1HRC)	22HRC*	421L*	514L*
A540-77a/SA540-77a	B21,CL5	≤ 2-1/2" Thick	23HRC	30HRC	522L	573L
		Over 2" to 6"	24HRC	32HRC	529L	588L
		Over 6" to 8"	25HRC	33HRC	536L	596L
	B21,CL4	≤ 3" Thick	28HRC	36HRC	558L	618L
		Over 3" to 6"	29HRC	38HRC	566L	634L
	B21,CL3	≤ 3" Thick	31HRC	38HRC	581L	634L
		Over 3" to 6"	32HRC	40HRC	588L	649L
	B21,CL2	≤ 4" Thick	33HRC	43HRC	596L	673L
	B21,CL1	≤ 4" Thick	34HRC	46HRC	603L	698L

Table 11A-1 (Continued)

ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	Hardness Limits[7] Rockwell-Scale Minimum	Rockwell-Scale Maximum	Leeb-Scale (L) Minimum	Leeb-Scale (L) Maximum
A540-77a/SA540-77a	B22,CL5	≤ 2" Thick	24HRC	31HRC	529L	581L
		Over 2" to 4"	25HRC	32HRC	536L	588L
	B22,CL4	≤ 1" Thick	28HRC	37HRC	558L	626L
		Over 1" to 4"	29HRC	39HRC	566L	642L
	B22,CL3	≤ 2" Thick	31HRC	39HRC	581L	642L
		Over 2" to 4"	32HRC	40HRC	588L	649L
	B22,CL2	≤ 3" Thick	33HRC	43HRC	596L	673L
	B22,CL1	≤ 1-1/2" Thick	34HRC	43HRC	603L	673L
	B23,CL5	≤ 6" Thick	24HRC	33HRC	529L	596L
		Over 6" to 8"	25HRC	34HRC	536L	603L
		Over 8" to 9-1/2"	27HRC	34HRC	551L	603L
	B23,CL4	≤ 3" Thick	28HRC	37HRC	558L	626L
		Over 3" to 6"	29HRC	38HRC	566L	634L
		Over 6" to 9-1/2"	30HRC	39HRC	573L	642L
	B23,CL3	≤ 3" Thick	31HRC	39HRC	581L	642L
		Over 3" to 6"	32HRC	40HRC	588L	649L
		Over 6" to 9-1/2"	33HRC	42HRC	596L	665L
	B23,CL2	≤ 3" Thick	33HRC	42HRC	596L	665L
		Over 3" to 6"	33HRC	43HRC	596L	673L
		Over 6" to 9-1/2"	34HRC	45HRC	603L	689L
	B23,CL1	≤ 3" Thick	34HRC	45HRC	603L	689L
		Over 3" to 6"	36HRC	46HRC	618L	698L
		Over 6" to 8"	37HRC	47HRC	626L	707L
	B24,CL5	≤ 6" Thick	24HRC	33HRC	529L	596L
		Over 6" to 8"	25HRC	34HRC	536L	603L
		Over 8" to 9-1/2"	27HRC	34HRC	551L	603L

Table 11A-1 (Continued)

ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	Hardness Limits[7] Rockwell-Scale Minimum	Rockwell-Scale Maximum	Leeb-Scale (L) Minimum	Leeb-Scale (L) Maximum
A540-77a/SA540-77a	B24,CL4	≤ 3" Thick	28HRC	37HRC	558L	626L
		Over 3" to 6"	29HRC	38HRC	566L	634L
		Over 6" to 8"	30HRC	39HRC	573L	642L
	B24,CL3	≤ 3" Thick	31HRC	39HRC	581L	642L
		Over 3" to 8"	32HRC	42HRC	588L	665L
		Over 8" to 9-1/2"	33HRC	42HRC	596L	665L
	B24,CL2	≤ 7" Thick	33HRC	43HRC	596L	673L
		Over 7" to 9-1/2"	34HRC	45HRC	603L	689L
	B24,CL1	≤ 6" Thick	34HRC	45HRC	603L	689L
		Over 6" to 8"	36HRC	46HRC	618L	698L
	B24V,CL3	≤ 4" Thick	31HRC	39HRC	581L	642L
		Over 4" to 8"	32HRC	40HRC	588L	649L
		Over 8" to 11"	33HRC	42HRC	596L	665L
	B24V,CL2	≤ 4" Thick	33HRC	42HRC	596L	665L
		Over 4" to 8"	33HRC	43HRC	596L	673L
		Over 8" to 11"	34HRC	45HRC	603L	689L
	B24V,CL1	≤ 4" Thick	34HRC	45HRC	603L	689L
		Over 4" to 8"	36HRC	46HRC	618L	698L
		Over 8" to 11"	36HRC	47HRC	618L	707L
A574-80	(See Table 2)	≤ 1/2" Diameter	39HRC	45HRC	642L	689L
		≤ 5/8" Diameter	37HRC	45HRC	626L	689L
A563-78a	DH3	1/4" to 4" Size	24HRC	38HRC	529L	634L
	C3	1/4" to 4" Size	78HRB	38HRC	400L	634L
A668-79a	F,FH	≤ 4" Thick	90HRB (≈10HRC)	22HRC	456L	514L
		Over 4" to 7"	88HRB (≈7HRC)	96HRB (≈17HRC)	440L	490L

Table 11A-1 (Continued)

ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	Hardness Limits[7] Rockwell-Scale Minimum	Rockwell-Scale Maximum	Leeb-Scale (L) Minimum	Leeb-Scale (L) Maximum
A668-79a	F,FH	Over 7" to 10"	88HRB (≈7HRC)	96HRB (≈17HRC)	440L	490L
		Over 10" to 20"	88HRB (≈7HRC)	96HRB (≈17HRC)	440L	490L
	J,JH	≤ 7" Thick	92HRB (≈12HRC)	25HRC	468L	536L
		Over 7" to 10"	90HRB (≈10HRC)	22HRC	456L	514L
	K,KH	≤ 7" Thick	95HRB (≈16HRC)	28HRC	485L	558L
		Over 7" to 10"	94HRB (≈14HRC)	28HRC	479L	558L
	L,LH	≤ 4" Thick	25HRC	34HRC	536L	603L
		Over 4" to 7"	22HRC	32HRC	514L	588L
		Over 7" to 10"	97HRB (≈19HRC)	31HRC	497L	581L
	M,MH	≤ 4" Thick	31HRC	38HRC	581L	634L
		Over 4" to 7"	30HRC	37HRC	573L	626L
		Over 7" to 10"	28HRC	36HRC	558L	618L
	N,NH	≤ 4" Thick	36HRC	43HRC	618L	673L
		Over 4" to 7"	36HRC	43HRC	618L	673L
		Over 7" to 10"	34HRC	42HRC	603L	665L
A687-79	All Grades	--	25HRC*	34HRC*	543L*	603L*
A739-76/SA739-76	B11	--	79HRB*	25HRC*	405L*	536L*
	B22	--	82HRB*	25HRC*	417L*	536L*
F568-79	8.8	--	23HRC	34HRC	522L	603L
	8.8.3	--	23HRC	34HRC	522L	603L

Table 11A-1 (Continued)

ASTM/ASME Specification	Grade and/or Class	Diameter or Thickness	Hardness Limits[7] Rockwell-Scale Minimum	Hardness Limits[7] Rockwell-Scale Maximum	Hardness Limits[7] Leeb-Scale (L) Minimum	Hardness Limits[7] Leeb-Scale (L) Maximum
F568-79	9.8	--	27HRC	36HRC	551L	618L
	10.9	--	33HRC	39HRC	596L	642L
	10.9.3	--	33HRC	39HRC	596L	642L
	12.9	--	38HRC	44HRC	634L	682L

Notes:

1. Bolts or nuts when included with material purchased can be supplied to A325.

2. The specified or indicated minimum hardness must be sufficient to develop the required strength to withstand the solid stresses of the spring design.

3. Same material grade as A537 Class 2.

4. Maximum surface Brinell hardness, if specified by purchaser as a supplementary requirement, shall be agreed upon between the manufacturer and the purchaser. Mechanical strengths are not specified.

5. SA320-78 is identical to A320-76 except for the deletion of Grade L1.

6. Bolts shall not exceed maximum hardness specified. Bolts less than 3 diameters in length shall have a hardness value not less than the minimum nor more than the maximum in hardness limits, as hardness is the only requirement.

7. Hardness values supplied are in HRC and L-scale numbers unless otherwise noted. Mechanical strengths are not specified.

* These limits are not ASTM specified limits, but based upon a review of yield and tensile strength requirements and a comparison with other ASTM materials with specified hardness requirements.

Appendix 11B

REFERENCE CURVES FOR σ_y VERSUS HARDNESS CONVERSION AND K_{Iscc} AND K_{Ic} VERSUS STRENGTH

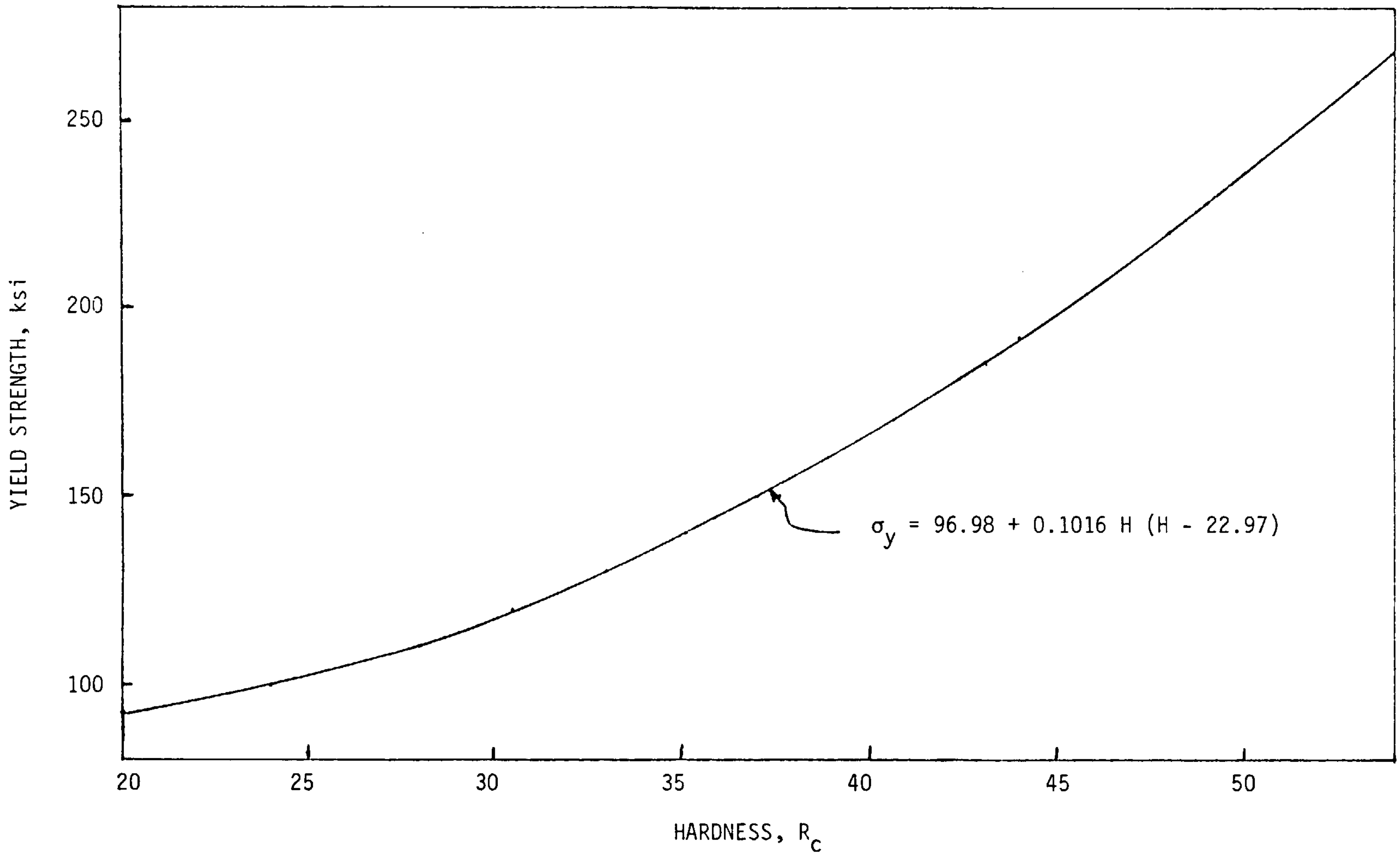

Figure 11B-1. Yield Strength Versus Hardness for LAQT Steels

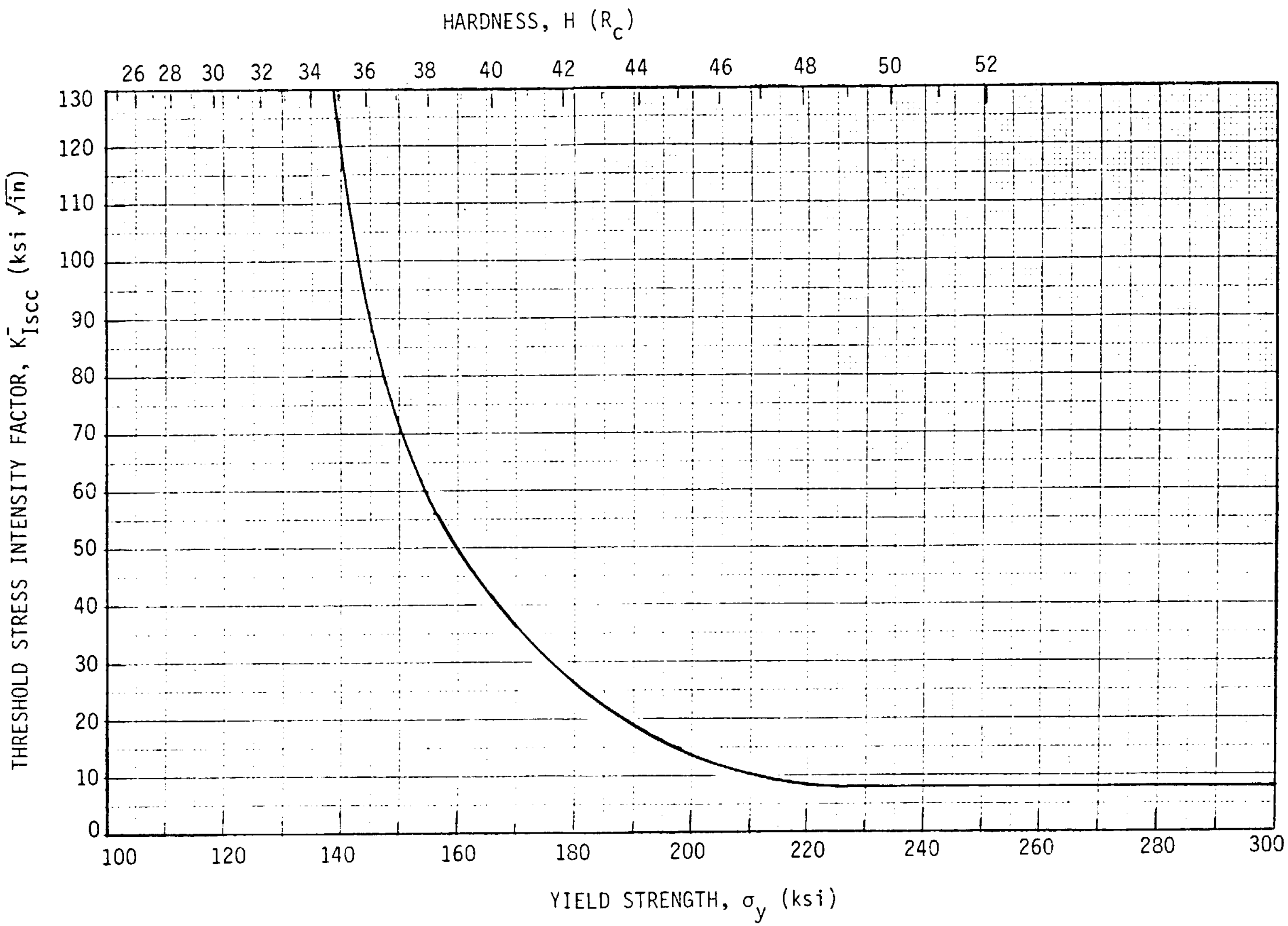

Figure 11B-2. $\bar{K}_{Iscc}$ Versus Yield Strength for LAQT Steels

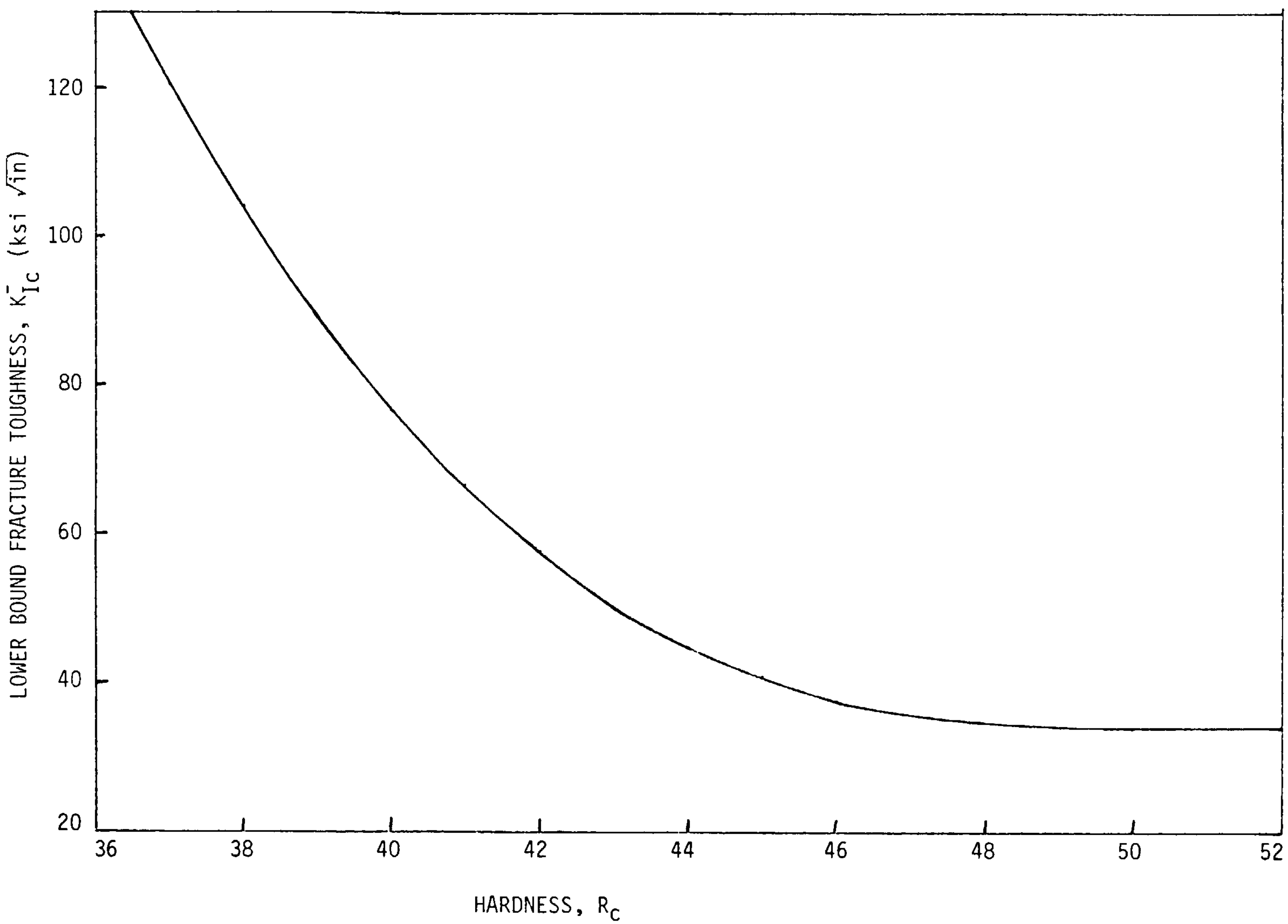

Figure 11B-3. K_{Ic}^{-} Versus Hardness for LAQT Steels

Appendix 11C

TABULATED VALUES OF COEFFICIENT C_k

Table 11C-1

TABULATED VALUES FOR C_k FOR EXTERNAL FOUR-THREAD SERIES (4-UN/4-UNR)

Primary Size (Inches)	Basic Major Diameter, D (Inches)	Minor Diameter, d (Inches)	Tensile Stress Area, A_s (Inches^2)	Reference Flaw Factor, C_k (Inches$^{-1/2}$)
2-1/2	2.5000	2.1933	4.00	2.420
2-3/4	2.7500	2.4433	4.93	2.371
3	3.0000	2.6933	5.97	2.336
3-1/4	3.2500	2.9433	7.10	2.298
3-1/2	3.5000	3.1933	8.33	2.270
3-3/4	3.7500	3.4433	9.66	2.245
4	4.0000	3.6933	11.08	2.224
4-1/4	4.2500	3.9433	12.61	2.206
4-1/2	4.5000	4.1933	14.23	2.189
4-3/4	4.7500	4.4433	15.90	2.175
5	5.0000	4.6933	17.80	2.162
5-1/4	5.2500	4.9433	19.70	2.150
5-1/2	5.5000	5.1933	21.70	2.139
5-3/4	5.7500	5.4433	23.80	2.130
6	6.0000	5.6933	26.00	2.121

Note: Reference flaw factor $C_k = 1/\tilde{K}_I = \sigma_s/K_I$ where K_I is based on a 10-mil semicircular flaw at a thread root.

Table 11C-2

TABULATED VALUES FOR C_k FOR EXTERNAL SIX-THREAD SERIES (6-UN/6-UNR)

Primary Size (Inches)	Basic Major Diameter, D (Inches)	Minor Diameter, d (Inches)	Tensile Stress Area, A_s (Inches^2)	Reference Flaw Factor, C_k (Inches$^{-1/2}$)
1-3/8	1.3750	1.1705	1.155	2.728
1-1/2	1.5000	1.2955	1.405	2.668
1-5/8	1.6250	1.4205	1.680	2.619
1-3/4	1.7500	1.5455	1.980	2.577
1-7/8	1.8750	1.6705	2.300	2.540
2	2.0000	1.7955	2.650	2.509
2-1/4	2.2500	2.0455	3.420	2.457
2-1/2	2.5000	2.2955	4.290	2.417
2-3/4	2.7500	2.5455	5.260	2.384
3	3.0000	2.7955	6.330	2.356
3-1/4	3.2500	3.0455	7.490	2.333
3-1/2	3.5000	3.2955	8.750	2.314
3-3/4	3.7500	3.5455	10.110	2.297
4	4.0000	3.7955	11.570	2.283
4-1/4	4.2500	4.0455	13.120	2.270
4-1/2	4.5000	4.2955	14.780	2.259
4-3/4	4.7500	4.5455	16.500	2.249
5	5.0000	4.7955	18.400	2.240
5-1/4	5.2500	5.0455	20.300	2.231
5-1/2	5.5000	5.2955	22.400	2.224
5-3/4	5.7500	5.5455	24.500	2.218
6	6.0000	5.7955	26.800	2.211

Note: Reference flaw factor $C_k = 1/\tilde{K}_I = \sigma_s/K_I$ where K_I is based on a 10-mil semicircular flaw at a thread root.

Table 11C-3

TABULATED VALUES FOR C_k FOR EXTERNAL EIGHT-THREAD SERIES (8-UN/8-UNR)

Primary Size (Inches)	Basic Major Diameter, D (Inches)	Minor Diameter, d (Inches)	Tensile Stress Area, A_s (Inches^2)	Reference Flaw Factor, C_k (Inches$^{-1/2}$)
1	1.0000	0.8466	0.606	2.929
1-1/8	1.1250	0.9716	0.790	2.842
1-1/4	1.2500	1.0966	1.000	2.774
1-3/8	1.3750	1.2216	1.233	2.719
1-1/2	1.5000	1.3466	1.492	2.673
1-5/8	1.6250	1.4716	1.780	2.635
1-3/4	1.7500	1.5966	2.080	2.602
1-7/8	1.8750	1.7216	2.410	2.575
2	2.0000	1.8466	2.770	2.550
2-1/4	2.2500	2.0966	3.560	2.510
2-1/2	2.5000	2.3466	4.440	2.479
2-3/4	2.7500	2.5966	5.430	2.453
3	3.0000	2.8466	6.510	2.432
3-1/4	3.2500	3.0966	7.690	2.414
3-1/2	3.5000	3.3466	8.960	2.399
3-3/4	3.7500	3.5966	10.340	2.386
4	4.0000	3.8466	11.810	2.375
4-1/4	4.2500	4.0966	13.380	2.365
4-1/2	4.5000	4.3466	15.100	2.356
4-3/4	4.7500	4.5966	16.800	2.348
5	5.0000	4.8466	18.700	2.341
5-1/4	5.2500	5.0966	20.700	2.335
5-1/2	5.5000	5.3466	22.700	2.329
5-3/4	5.7500	5.5966	24.900	2.324
6	6.0000	5.8466	27.100	2.319

Note: Reference flaw factor $C_k = 1/\tilde{K}_I = \sigma_s/K_I$ where K_I is based on a 10-mil semicircular flaw at a thread root.

Table 11C-4

TABULATED VALUES FOR C_k FOR EXTERNAL TWELVE-THREAD SERIES (12-UN/12-UNR)

Primary Size (Inches)	Basic Major Diameter, D (Inches)	Minor Diameter, d (Inches)	Tensile Stress Area, A_s (Inches^2)	Reference Flaw Factor, C_k (Inches$^{-1/2}$)
7/8	0.8750	0.7728	0.495	3.050
1	1.0000	0.8978	0.663	2.970
1-1/8	1.1250	1.0228	0.856	2.909
1-1/4	1.2500	1.1478	1.078	2.861
1-3/8	1.3750	1.2728	1.315	2.822
1-1/2	1.5000	1.3978	1.580	2.790
1-5/8	1.6250	1.5228	1.870	2.763
1-3/4	1.7500	1.6478	2.190	2.740
1-7/8	1.8750	1.7728	2.530	2.720
2	2.0000	1.8978	2.890	2.703
2-1/4	2.2500	2.1478	3.690	2.675
2-1/2	2.5000	2.3978	4.600	2.652
2-3/4	2.7500	2.6478	5.590	2.634
3	3.0000	2.8978	6.690	2.619
3-1/4	3.2500	3.1478	7.890	2.606
3-1/2	3.5000	3.3978	9.180	2.595
3-3/4	3.7500	3.6478	10.570	2.585
4	4.0000	3.8978	12.060	2.577
4-1/4	4.2500	4.1478	13.650	2.570
4-1/2	4.5000	4.3978	15.300	2.564
4-3/4	4.7500	4.6478	17.100	2.558
5	5.0000	4.8978	19.000	2.553
5-1/4	5.2500	5.1478	21.000	2.548
5-1/2	5.5000	5.3978	23.100	2.544
5-3/4	5.7500	5.6478	25.200	2.540
6	6.0000	5.8978	27.500	2.537

Note: Reference flaw factor $C_k = 1/\tilde{K}_I = \sigma_S/K_I$ where K_I is based on a 10-mil semicircular flaw at a thread root. Sizes less than 7/8 inch are not listed.

Table 11C-5

TABULATED VALUES FOR C_k FOR EXTERNAL COARSE THREADS (UNC/UNRC) WITH 4-1/2, 5, 7, AND 9 THREADS PER INCH

Size (Inches)	Threads Per Inch	Basic Major Diameter, D (Inches)	Minor Diameter, d (Inches)	Tensile Stress Area, A_s (Inches^2)	Reference Flaw Factor, C_k (Inches$^{-1/2}$)
7/8	9	0.8750	0.7387	0.419	3.027
1-1/8	7	1.1250	0.9497	0.693	2.864
1-1/4	7	1.2500	1.0747	0.890	2.787
1-3/4	5	1.7500	1.5046	1.740	2.598
2	4-1/2	2.0000	1.7274	2.500	2.528
2-1/4	4-1/2	2.2500	1.9774	3.250	2.461

Note: Reference flaw factor $C_k = 1/\tilde{K}_I = \sigma_S/K_I$ where K_I is based on a 10-mil semicircular flaw at a thread root.

Section 12

ALTERNATE ALLOYS

A considerable portion of the effort of the AIF/MPC Task Group on Bolting and the EPRI Generic Bolted Joint Integrity Program was related to materials concerns -- namely, degradation of fasteners due to boric acid corrosion or stress-corrosion cracking. This work also dealt with the effect of environmental variables, such as lubricants and leak sealants on these degradation mechanisms. The results of five such projects are summarized here.

COMBUSTION ENGINEERING PROJECT (RP2058-7)

In pressurized water reactors, the use of high strength low alloy steel threaded fasteners is widespread in closures of primary, auxiliary, safety and other systems which contain borated water and in major component support systems. Potentially serious degradation of low alloy steel fasteners used in PWR systems has occurred with increasing frequency in recent years. The observed degradation has been in the form of accelerated general corrosion of reactor coolant pump and valve closure studs and stress corrosion cracking of steam generator manway cover studs and component support structure fasteners. Because of interest in fastener corrosion, EPRI initiated project RP2058-7, "Literature Survey of Carbon and Alloy Steel Fastener Corrosion in the PWR Plants." The objective of this project was to determine the extent of low alloy steel fastener corrosion problems in the domestic PWR industry and to review available literature data on boric acid corrosion and stress corrosion cracking of fasteners.

A total of 28 plant occurrences of fastener corrosion, attributable to boric acid, have been reported since the initial event at Connecticut Yankee in 1968. The most widely affected components were various valves (10 events) and reactor coolant pumps (9 events). In several instances, bonnet-to-body studs in valves were corroded through and resulted in leakage that exceeded technical specification limits. In the most severe incident involving RCP closure studs, the boric acid corrosion process reduced the diameters of several studs in localized areas from 3-1/2 inches to approximately 1 inch.

A paucity of laboratory data on boric acid corrosion exists, and most of the relevant data that is available has not been published. Unpublished data from Combustion Engineering indicate that corrosion rates as high as 1.7 inch per year may result when low alloy steels are exposed to borated environments under conditions that cause concentrations of wetted boric acid to develop. Contrary to current assumptions, the corrosion process may be active at service temperatures (greater than 350°F) because of localized cooling of hot studs.

Austenitic and martensitic stainless steels are resistant to boric acid corrosion and, in many applications involving borated water service, have replaced low alloy steels. However, the strengths of these alloys preclude their use in all applications. Coatings and platings evaluated to date have not been completely satisfactory in preventing boric acid corrosion.

A total of twelve events of stress corrosion cracking of fasteners were identified. Five of these involved the failure of steam generator primary manway cover closures studs, six involved the failure of fasteners in component support applications, and one involved failure of internal fasteners. The failure of the closure studs is of particular concern because the failures constitute a potential loss of reactor coolant primary boundary integrity, and in an extreme case a loss-of-coolant-accident could occur if the failures are not detected. The closure fastener failures occurred in materials that apparently had nominal chemical and mechanical properties. A common factor in these failures may have been the use of a MoS_2 based lubricant, which under high temperature aqueous environments may decompose to form H_2S. Even at low concentrations, H_2S will cause stress corrosion cracking in low alloy steel fasteners heat treated to yield strengths greater than 90 ksi (hardness greater than 22 HRC). Laboratory testing, however, has not demonstrated that MoS_2 decomposition will result in stress corrosion cracking.

Most of the stress corrosion cracking failures of support fasteners occurred in high strength materials loaded to high stress levels in moist environments. Under these conditions, the fastener materials are susceptible to stress corrosion cracking at or near ambient temperatures.

The complete report is cited as "A Survey of the Literature on Low-Alloy Steel Fastener Corrosion in PWR Power Plants", by J.F. Hall, Report No. EPRI NP-3784, December 1984.

BATTELLE-COLUMBUS LABORATORIES PROJECT (RP2058-12)

Joint failures have occurred in nuclear components due to the degradation of fasteners. This degradation has occurred due either to boric acid corrosion or stress-corrosion cracking. Since cracking of these high-strength bolts in Class 1 supports could compromise the pressure boundary integrity, a concentrated effort has been undertaken by the industry to examine various options to minimize the problem. As part of the effort, this review has been undertaken primarily to determine if austenitic age hardenable materials could be used for bolting applications. A secondary objective of the effort was to review the boric acid corrosion and stress-corrosion cracking behavior of currently used low alloy steels and issues relating to lubricants and sealants. Based on the review, recommendations have been made for further work to improve the industry's capability in dealing with the bolting problem.

The review has indicated a lack of available data on all the issues noted above. Based on strength considerations, the austenitic alloys can be easily used for bolting applications in the nuclear industry. However, there are other considerations that would have to be resolved for their safe application. In applications in which these fasteners will come in contact with a low alloy steel structure, galvanic corrosion and differences in coefficient of thermal expansion will pose a problem. In PWR applications, lithiated water with low oxygen content may not create a galvanic corrosion problem, but acceptable oxygen concentration levels will have to be defined for specific low alloy steel and austenitic material couples. A coating may have to be developed to provide electrical insulation between the structure and the fastener. The high coefficient of thermal expansion of austenitic materials implies that high preload would have to be applied to the fastener at room temperature to avoid a loose joint with increasing temperature. This means the threshold for stress-corrosion cracking (K_{ISCC}) of the material may be exceeded at room temperature. Simple analytical and experimental work will have to be done to evaluate how much extra preload will have to be exerted on the fastener to avoid thermal-expansion-related loss of preload at high temperature.

From the standpoint of corrosion- and stress-corrosion cracking-related properties, the austenitic materials seem to be resistant to boric acid corrosion, but stress-corrosion cracking occurs in chloride- and oxygen-containing water environment as well as chloride-containing hydrogen sulfide environments. Heat treatments will have to be developed that produce microstructure resistant to SCC in environments

typical of nuclear applications. K_{ISCC} data will then have to be developed in these environments at various temperatures.

Existing low alloy steels in service are susceptible to boric acid corrosion. Prevention of leakage may be the best way to minimize this problem. A better understanding of the influence of boric acid concentration, oxygen concentration, chloride ion concentration, and temperature on boric acid corrosion needs to be developed to ascertain the extent of the problem in service. Stress-corrosion cracking in these alloys can also occur in high-temperature water environment at high strength levels. Presence of hydrogen sulfide and chlorides can make the situation worse. The conditions under which molybdenum disulfide lubricant reacts with water to form hydrogen sulfide must be established. Review of existing data suggests that hydrogen sulfide can form by the reactor of molybdenum disulfide with water at temperatures above 60°C (140°F). The role of subsurface (low alloy steel versus austenitic material), temperature, oxygen concentration and contaminants in the lubricant on the evolution of hydrogen sulfide and the subsequent embrittlement of the alloy needs to be established. In a more general sense, the purity levels expected of all the lubricants and sealants used in the industry need to be established. No such standard currently exists and lubricants have been found to contain unacceptably high levels of contaminants that can cause stress-corrosion cracking.

The complete report is cited as "Stress Corrosion Cracking of Alternative Bolting Alloys", R. Rungta, Final Report, RP 2058-12, Battelle-Columbus Lab., Sept. 1984.

MATERIALS ENGINEERING ASSOCIATES PROJECT (RP2455-15)

Several value studs were found failed recently by Virginia Power. These studs were purchased to ASTM specification A193 Grade B6, with a supplemental requirement of 125 ksi tensile strength specified by Virginia Power. A Virginia Power investigation focused on the improper heat treatment of the studs, resulting in temper embrittlement. The embrittlement permitted stress corrosion cracking, with stud failure occurring once the critical flaw size was achieved.

To access the fracture properties of the stud material, pieces from several failed studs were decontaminated and sent to Materials Engineering Associates, Inc. (MEA). Characterization of the material was performed using impact (Charpy-V notch specimens), strength (tensile specimens), and static fracture toughness (compact

tension specimens) tests. The impact tests were conducted at temperatures ranging from +30°F to 550°F, while the strength and fracture toughness tests were conducted at 40°F, 120°F and 200°F.

The strength tests revealed conformance with ASTM and Virginia Power requirements in terms of 0.2% offset yield and ultimate strengths, although three of the six specimens had less than 50% reduction of area.

The impact tests revealed low toughness, with 20 ft-lb and 20% shear not eclipsed until 430°F. While the upper shelf was not achieved at 550°F, indications are that the upper shelf occurs near 86 ft-lb.

The static fracture toughness tests indicate low toughness at 40°F and 120°F, with moderate toughness at 200°F. In all cases, the failure mode was cleavage, with no stable crack growth in any case. The static upper shelf is probably initiated between 300°F and 400°F.

The complete report is cited as "Fracture Toughness Characterization of Type 410 Stainless Steels", A.L. Hiser, Final Report, RP 2455-12, Materials Engineering Associates, Inc., Jan. 1987.

WESTINGHOUSE ELECTRIC PROJECT (RP2181-2)

The objective of this program ("Improved Stress Corrosion Resistance of Ni-Cr-Fe Alloys", T.R. Mager, Annual Report, September 1985) is to minimize the cracking of age-hardenable Ni-Cr-Fe alloys in PWRs and BWRs. Several instances of stress corrosion cracking in bolts, beams and pins have been observed in reactors using Alloys X-750, 718 and A286. Some failures have been attributed to corrosion fatigue. This program looks at these three alloys in different heat treated conditions. Alloy X-750 with an increased Zr content, which had previously been shown to be beneficial, is also included.

Stress corrosion cracking studies have been conducted on eleven conditions of Alloy X-750, two of Alloy 718 and two of A286. U-bend specimens and pre-cracked 1/2 T-CT, fracture mechanics specimens were used to look at stress corrosion crack initiation and growth in a PWR primary coolant environment at 680°F (360°C). The total exposure time for this task was 6000 hours with intermediate inspections at 500, 1500, and 3000 hours. No crack initiation was observed on any of the U-bend samples. Crack growth was observed for all 15 material conditions at the first

inspection. Crack growth rates of 1 μ m/h were observed at the higher stress intensities (66 MPa $\sqrt{m}$). The greatest resistance to crack growth was exhibited by the alloy X-750 materials solution annealed at 1107°C and aged at 704°C or 760°C. These materials are the ones with the preferred $M_{23}C_6$ grain boundary precipitates. This group was closely followed by alloy X-750 in the No. 1 temper, which also has a grain boundary $M_{23}C_6$ precipitate, and alloy A-286. The least resistance to crack growth was exhibited by alloy X-750 in the two-step aged (AH) and the spring temper conditions and Alloy 718. These materials exhibited final stress intensities of 22 MPa $\sqrt{m}$ or less. Increasing the Zr level from 0.05% to 0.09% conferred no significant benefit to the crack growth resistance of alloy X-750.

Nine of the fifteen materials were selected for further crack initiation testing using plain beam samples and blunt notched 1/2 T-CT specimens with stress concentrations (K_t) of 2.18, 5.40 and 8.73. The beam samples were loaded in 3 pt loading jigs to 0.8 Y.S. and the 0.2% offset Y.S. and to 1.5%, 3.25% and 6.5% total strain. U-bend specimens were fabricated from the same blanks. The deflections for the specimens in the jigs were calibrated using strain gauged samples. The blunt notched specimens were loaded, using wedges driven into the front face at the notch, to 1.5%, 3.25% and 6.5% total strain at the notch tip. The deflections were calculated using compliance tables and Neuber's rule. These materials were exposed to a PWR primary coolant environment at 650°F (343°C) and to a BWR coolant environment at 550°F (288°C). Total exposure on these is beyond 10,000 hours and inspections, using ultrasonics and a light microscope at 30X, have been conducted at approximately 2500, 5000 and 10,000 hours. Cracked specimens have been destructively examined.

In the PWR environment, crack initiation has only been observed in alloy X-750 in the two-step aged (AH) and spring temper conditions loaded to 1.5% strain or above.

In the BWR environment, crack initiation has been observed in seven of the nine materials tested. Condition 5, alloy X-750 in the spring temper, exhibited the most cracking followed by alloy X-750 in the AH, two-step aged condition and alloy A-286. Single incidents of crack initiation were also observed in alloy X-750 in the No. 1 temper, alloy 718 and alloy X-750 in the HTH condition, with and without added Zr. The latter condition, which has the preferred $M_{23}C_6$ carbide precipitation at the grain boundaries, only exhibited cracks in the U-bend specimens which have >15% total strain. The only materials not to initiate cracks at 10,000 hours

exposure were the X-750 materials, with and without added Zr, in the overaged, HOA condition.

Crack initiation and growth in all instances was predominantly intergranular.

The performance of these alloys is obviously different in the two environments, and the short-time screening tests cannot be universally applied.

At the 10,000 hour inspection, the loads on selected, notched 1/2 T-CT specimens were increased. The specimens selected were the lowest loaded of the materials which had exhibited little or no cracking. All autoclave exposures are continuing.

Tests in the PWR environment at high mean load with low, high frequency, alternating loads, using notched 1/2 T-CT specimens of X-750 have not produced accelerated crack initiation. Comparison with smooth bar data indicates a notch strengthening effect in air. This is being investigated in the high temperature aqueous environments.

BABCOCK & WILCOX PROJECT (RP2181-1)

The high-strength, age-hardenable Ni-Cr-Fe alloys X-750, 718 and A-286 have been used in light water reactors for bolts, springs, beams, guide tube pins and other structural members where high strength, relaxation resistance and corrosion resistance are required. While the performance of these alloys has generally been good, failures of some components, such as the jet pump beam failures in boiling water reactors (BWRs), have resulted in plant shutdowns.

Failures have been attributed to fatigue, corrosion fatigue, and intergranular stress corrosion cracking (IGSCC). The metallurgical condition produced by thermomechanical processing greatly affects susceptibility to failure by these mechanisms.

The results presented in the interim report ("Improved Stress Corrosion Resistance of High-Strength, Age-Hardenable Ni-Cr-Fe Alloys", Third Report, August 1984) are part of a larger program that has been undertaken to determine the optimal processing conditions and heat treatments for alloys X-750, 718 and A-286. This report includes detailed microstructural characterization and corrosion testing of these alloys subjected to 15 different combinations of melting practice and thermomecha-

nical processing. Light-optical and high-resolution electron-optical analysis were performed to determine whether differences in microstructures among the 15 conditions could be correlated with quality assurance (QA) tests of IGSCC susceptibility including slow-strain-rate tests (SSRT), rising-load, and microstructural-etch tests. As part of the larger program, these test materials are also being subjected to crack initiation, crack growth rate, and crack arrest tests in high-temperature water, the results of which will be reported separately.

Preliminary findings indicate that alloy X-750 has better resistance to IGSCC when it has been heat-treated (HTH heat treatment -- 1107°C (±14°)/1 hr; rapid cool; 704°C/20 hr) to precipitate $M_{23}C_6$ at the grain boundaries. Resistance to IGSCC was determined from the microstructural-etch and rising-load tests. These tests appear to yield fairly reproducible results, which agree with field experience; however, there is room for improvement in both test techniques.

Section 13

STANDARD SPECIFICATION FOR SUPPLEMENTAL REQUIREMENTS FOR STRUCTURAL FASTENERS FOR NUCLEAR APPLICATIONS

BACKGROUND COMMENT AND DISCUSSION

The proposed specification is being developed and coordinated by a Task Group of the ASTM F16 Committee. Because it is of equal major concern to the Joint AIF/MPC Task Group on Bolting, the specification is also being circulated for concurrent review.

Several areas of experience have prompted the approach to the proposed specification. For the most part, structural fasteners used by the nuclear industry are intended to conform to ASTM or equivalent SA (ASME) specifications. Recent inspections and examinations have indicated that various fasteners have exhibited mechanical properties (tensile strength and hardness) outside of existing specification requirements. In some instances, the fasteners were already installed in structures.

This raises some significant questions. Is any screening or testing undertaken by industry to in fact verify the mechanical properties of procured fasteners? Are existing specifications complete or discriminating enough to accept only acceptable lots and reject defective or out-of-tolerance lots of fasteners? Or does it really matter whether "out-of-spec" parts are employed in nuclear systems?

In addition, a review of the overall system of ASTM specs has indicated varying options of manufacture as well as varying levels of quality assurance requirements. Considering the wide appeal of ASTM specs, such differences may be suitable for general industrial applications. However, it is not considered that they represent the quality needed by or which should be uniformly acceptable to the nuclear industry. In particular, the long-term service required or expected from structural fasteners in itself suggests the highest degree of quality which can be obtained by today's technology.

One further aspect has also been considered in outlining the new proposed specification. Practically, fasteners can be ordered from manufacturers, or procured through distributors. Both are vital suppliers to industry. In the case of distributors though, there have been situations of mixing and subsequent contamination of lots of similar fasteners. Just as serious is the concern with off-shore fasteners without proper, and in some instances, any head or other identifications.

To reflect these concerns, the proposed specification has been drafted to include the following requirements for fasteners for the nuclear industry:

1. Establish sampling and quality levels for all series of structural fasteners on a uniform basis.

2. Establish mandatory lot control and traceability of fasteners. By maintaining such control, prevent mixing and possible contamination of parts intended for nuclear systems.

3. Require positive identification and source of fasteners intended for nuclear systems as evidence of adherence to required quality level.

4. Require preferential full-scale testing of finished fasteners in lieu of reliance on possible machined coupons from fasteners. Actual full-scale testing is designed to confirm integrity of finished fastener not possible by coupon evaluation.

5. Permit utilization of state-of-the-art technology and beneficial effects of heading and thread rolling by specific call-out. Other major industries such as automotive and aerospace have similarly specified such requirements as mandatory.

6. Recognizing the potential long-term degradation resulting from the presence of discontinuities such as cracks and seams, etc., establish specific requirements to define acceptable and rejectable criteria for nuclear system use.

ASTM F XXX - STANDARD SPECIFICATION FOR QUALITY ASSURANCE AND INSPECTION REQUIREMENTS FOR STRUCTURAL FASTENERS FOR NUCLEAR AND OTHER SPECIAL APPLICATIONS

Scope

This specification covers quality assurance and inspection requirements for finished externally and internally threaded fasteners, such as bolts, screws, studs, stud bolts, and nuts, intended for use in nuclear and other special applications.

The requirements of this specification, when required, shall be referenced in the inquiry or contract for threaded fasteners for nuclear and other special applications, and shall be in addition to the requirements of the applicable ASTM product specification.

In the event of conflict between the ASTM product specification and this specification, the requirements of this specification shall take precedence.

Applicable Documents

Ordering Information

Fasteners shall not be ordered solely to the requirements of this specification. They shall be ordered to the requirements of the applicable product specification, and this specification shall be invoked as supplemental requirements, when specified.

- Example - 10,000 pieces, Hex Structural Bolts

  1-1/4 - 8 x 4" ASTM A-325, Type 1, dated ______

- Supplemental Quality Assurance & Inspection Requirements for Structural Fasteners for Nuclear Applications ASTM F XXX dated ________ shall apply.

Quality Assurance Program

The fastener manufacturer shall be responsible for establishing and maintaining a quality system program to control in-process and final inspection, testing, and quality, to assure that finished fasteners conform to the requirements of the applicable product specification or standard.

The quality system program shall be documented in a Quality System Manual which shall be implemented by procedures which are maintained by the fastener manufacturer. The program shall be subject to audit and shall include the following.

Organization. The authority and responsibilities of personnel in charge of the quality system program shall be clearly established and be independent of the individual or group performing the specific manufacturing activity.

Calibration of Measuring and Test Equipment. Procedures shall be in effect to assure that all gages, tools, measuring instruments, and testing equipment used for in-process or final acceptance inspection are in current calibration. All such equipment shall be calibrated at scheduled intervals against measurement standards traceable to the National Bureau of Standards (NBS), or other equivalent National Standards, where applicable. The dates of calibration and equipment checks shall be recorded, and shall be kept for a minimum of one year.

When discrepancies in examination of inspection instruments or testing equipment are found during scheduled calibration which significantly affect the measurement of dimensional or mechanical performance characteristics, corrective action is required, and shall be noted on applicable records. Methods for resolution of these discrepancies shall be part of the quality system program.

Test Procedures. All test examinations shall be performed in accordance with written detailed procedures that are capable of defining acceptable and rejectable criteria for specific inspection characteristics. Personnel performing or interpreting tests shall be qualified for the techniques and methods used.

Records. The fastener manufacturer shall maintain logs and records of inspection and tests as required. Such records shall indicate the nature and number of observations made, the number and type of deficiencies found, the quantities of material or parts approved and rejected, and the nature of the corrective action taken. Records shall also include the disposition of rejected parts. All records shall be traceable from raw material through finished part for shipment, including destination. Records shall be maintained for a minimum of one year from date of shipment.

Audits. The procedures and requirements of the quality system program shall be subject to periodic audits to assure compliance with the program. Written procedures and checklists shall be used by personnel not having direct responsibility in the areas being audited. Corrective action, including re-audit of areas found to be deficient, shall be taken where indicated.

Sampling

The fastener manufacturer shall be responsible for performing all inspection tests and requirements under this specification.

The tests of the finished fasteners may be conducted by the fastener manufacturer or by a certified test laboratory acceptable to the purchaser, at the option of the supplier.

The purchaser reserves the right to perform any or all of the tests specified to assure conformance with the requirements of this specification and the product specification.

Production Lot. A production lot shall consist of fasteners which are of the same size and style, fabricated from a single mill heat by the same process, heat treated in the same manner, coated and/or finished in the same manner, and produced as one continuous run or order.

Each production lot shall be identified by a lot number assigned by the fastener manufacturer. The lot number shall be maintained throughout the manufacturing process and further maintained by packaging until the fasteners are used.

Maximum fastener production lot size shall be no larger than 20,000 pieces.

Inspection Lot. An inspection lot shall consist of finished fasteners representing completion of all manufacturing operations from a single production lot.

Section 14

THE BOLTING TECHNOLOGY COUNCIL

GENERAL PURPOSE

The Bolting Technology Council (BTC) was formed to provide opportunities for threaded fastener and tool users to engage in a variety of cooperative activities. As stated in their bylaws, the purpose of the Council is "to sponsor research; to recommend practices; to act as a clearing house for information; and to provide education concerning the art and science of the installation and behavior of mechanical fasteners and their interaction with the joints they are used in."

Although a large number of engineering and industrial societies have organized committees to deal with various aspects of fasteners and joints, very little attention has been paid by such groups to the important job of installing fasteners correctly. It is the intent of the Council to focus on this topic and, therefore, to complement rather than duplicate these other efforts.

As anyone who has attempted to understand joint behavior will realize, the task selected by the BTC is not a simple one, nor will the effort be inexpensive. Because of the magnitude of the job, members feel that it will be desirable to pool a portion of their technical and financial resources and attack the problems jointly. Results achieved by cooperative efforts, furthermore, often have greater credibility, are more widely accepted, and are most economically achieved. Benefits provided to industry through the Council consist of: interaction with recognized experts in bolting technology; opportunities to participate in seminars and symposia; to share in cooperatively funded research which will be planned, monitored, and directed by BTC groups; to preview publications and results of research well before general release; and the like.

AFFILIATION

The BTC is affiliated with the Materials Properties Council, Inc. (MPC), formerly the Metal Properties Council, which provides administrative services as required. MPC is a non-profit corporation, formed to identify major unfulfilled needs for

reliable data and to evolve, plan, and conduct programs for generating and evaluating such data. MPC serves industry and cooperating societies including its sponsors, ASTM, ASME, ASM and AWS.

GENERAL ACTIVITIES

BTC meets two times each year, although committees and task groups will meet more often as required to perform work assignments.

In recent months members of the Council have identified over 130 "unresolved bolting problems or questions" which one or more members feel deserve attention. Three committees have been formed to deal with various sets of these issues. One committee is dealing, for example, with the development and maintenance of proper preload. A second is addressing those issues pertaining to in-service inspection of bolted joints. A third has selected topics dealing with the post-assembly behavior of bolted joints.

An effort is currently under way to identify and collect literature dealing with any one of the 130 "issues". In some cases, we believe that a fair amount of valid material already exists. In other cases, there is little or no material available.

In subsequent meetings we will review the available material, decide which areas need further attention, establish priorities, and solicit proposals for research in the most important topics.

MEMBERSHIP

A partial list of industries expected to benefit from BTC activities includes the fastener, chemical, petroleum, aerospace, nuclear power, automotive, and manufacturing industries. Currently, the BTC has representatives from many industries, including all of those listed above.

BTC welcomes participation from all who have a professional interest in fastener and joint technology. Individual memberships are available (annual fee: $50) and entitle the holder to full participation in the meetings and technology. Corporations are encouraged to become sustaining members (annual fee: $300) to support the work of the Council. Anyone interested in joining the Council should contact:

Bolting Technology Council
c/o MPC
345 East 47th Street
New York, New York 10017

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EPRI—*Leadership in Science and Technology*

ABOUT EPRI

The mission of the Electric Power Research Institute is to discover, develop, and deliver advances in science and technology for the benefit of member utilities, their customers, and society.

Funded through annual membership dues from some 700 member utilities, EPRI's work covers a wide range of technologies related to the generation, delivery, and use of electricity, with special attention paid to cost-effectiveness and environmental concerns.

At EPRI's headquarters in Palo Alto, California, more than 350 scientists and engineers manage some 1600 ongoing projects throughout the world. Benefits accrue in the form of products, services, and information for direct application by the electric utility industry and its customers.

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