NUREG-1339

Resolution of Generic Safety Issue 29: Bolting Degradation or Failure in Nuclear Power Plants

Manuscript Completed: March 1990
Date Published: June 1990

Richard E. Johnson

Division of Safety Issues Resolution
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

ABSTRACT

This report describes the U.S. Nuclear Regulatory Commission's (NRC's) Generic Safety Issue 29, "Bolting Degradation or Failure in Nuclear Power Plants," including the bases for establishing the issue and its historical highlights. The report also describes the activities of the Atomic Industrial Forum (AIF) relevant to this issue, including its cooperation with the Materials Properties Council (MPC) to organize a task group to help resolve the issue. The Electric Power Research Institute, supported by the AIF/MPC task group, prepared and issued a two-volume document that provides, in part, the technical basis for resolving Generic Safety Issue 29. This report presents the NRC's review and evaluation of the two-volume document and NRC's conclusion that this document, in conjunction with other information from both industry and NRC, provides the bases for resolving this issue.

CONTENTS

ABBREVIATIONS

ACRS	Advisory Committee on Reactor Safeguards
AIF	Atomic Industrial Forum
AISC	American Institute of Steel Construction
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BTC	Bolting Technology Council
B&W	Babcock and Wilcox
BWR	boiling-water reactor
CGWT	cylindrically guided wave technique
EPRI	Electric Power Research Institute
GSI	generic safety issue
HSLA	high-strength, low-alloy (steel)
IE	(Office of) Inspection and Enforcement (NRC)
IGSCC	intergranular stress-corrosion cracking
ISI	inservice inspection
LAQT	low-alloy quenched and tempered (steel)
LOCA	loss-of-coolant accident
MPC	Materials Properties Council
NDE	nondestructive examination
NRC	Nuclear Regulatory Commission
NRR	(Office of) Nuclear Reactor Regulation (NRC)
NSSS	nuclear steam supply system
PWR	pressurized-water reactor
RCPB	reactor coolant pressure boundary
SCC	stress-corrosion cracking
SRP	Standard Review Plan
SOER	Significant Operating Event Report
USI	unresolved safety issue
UT	ultrasonic test
UTS	ultimate tensile strength
WOG	Westinghouse Owners' Group

1 INTRODUCTION

1.1 The Bolting Safety Issue

The bolting safety issue originally was an integral part of the Nuclear Regulatory Commission's (NRC's) Unresolved Safety Issue (USI) A-12, "Fracture Toughness of Steam Generator and Reactor Coolant Pump Supports." Recognizing that the types and variety of failure mechanisms active in bolting safety problems were distinctly different from those to be addressed in structural steel supports, the NRC staff separated the bolting safety issue from USI A-12 (Ref. 1) and identified it as Generic Safety Issue (GSI) 29, "Bolting Degradation or Failure in Nuclear Power Plants." The identification of bolting integrity as a separate issue received impetus from the Advisory Committee on Reactor Safeguards (ACRS) in October 1981. The ACRS recommended that the NRC staff expand its concerns about stress-corrosion cracking (SCC) of high-strength, low-alloy (HSLA) steel bolts to include a more comprehensive approach to the degradation and failure of bolting and threaded fasteners. Separating the bolting issue from USI A-12 created no conflict with the other USI A-12 goals. No structural materials were liable to the same kinds of degradation mechanisms as bolting materials, and adequate fracture toughness criteria for bolting materials were available within the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code).

The safety aspects of GSI 29 can be summarized as follows. Critical bolting applications in nuclear power plants constitute an integral part of the reactor coolant pressure boundary (RCPB) and include closure studs or bolts on reactor vessels, reactor coolant pumps, and steam generators. Failure of these bolts or studs could result in the loss of reactor coolant and jeopardize safe operation of the plant. Bolting also is an integral part of the pressure boundary and other safety-related systems, such as component supports and embedded anchor bolts or studs. In June 1982, the NRC staff issued Office of Inspection and Enforcement (IE) Bulletin No. 82-02 (Ref. 2). The bulletin required responsive actions by all pressurized-water-reactor (PWR) licensees because threaded fastener failures had shown an increasing frequency of occurrence and a variety of underlying mechanisms. Motivated by the issuance of NRC requirements regarding fastener integrity, the Atomic Industrial Forum (AIF) joined with the Materials Properties Council (MPC) to form the Joint AIF/MPC Task Group on Bolting, also in June 1982. This task group was composed of representatives from AIF member organizations—utilities, vendors, and architect-engineers—plus representatives from the Electric Power Research Institute (EPRI). The coordinated industry responses to Bulletin 82-02 and, earlier, to the "For Comment" version of NUREG-0577 (issued in October 1979) gave added emphasis to the importance of GSI 29.

When the NRC prioritized generic issues in November 1982, GSI 29 was assigned a high priority (Ref. 3).

1.2 Problem

The NRC noted (Ref. 4) that from 1964 to the early 1980s the incidence of reported failures in high-strength bolting in Class 1 component supports and other safety-related equipment increased. Common characteristics among the reported incidents included materials that were subjected to high sustained tensile stresses, out-of-specification pretorquing, an aqueous environment caused by high humidity, primary and borated water leakage, and materials that were overly hard and out of specification. The most frequently observed failure mode for the structural bolting was SCC. Both low-alloy quenched and tempered (LAQT) steels and maraging steels were degraded by SCC. A small number of overstress failures was traced to improper heat treatment or low-strength material. Pressure-retaining bolts failed from corrosion wastage*. Included in the RCPB components were steam generator manway closures, reactor coolant pumps, pressurizer manway closures, reactor vessel closures, chemical and volume control system isolation valves, check valves in the emergency core cooling system that form part of the RCPB, and other check valves. Some reactor vessel internal components, mainly the lower thermal shield bolts and upper core barrel bolts, were degraded, requiring extensive and expensive replacement of bolts in some plants.

Millions of threaded fasteners, including nuts, bolts, studs, and capscrews, are used in a nuclear power plant. The most important application of these fasteners is their use as an integral part of the RCPB, such as in pressure-retaining closures on reactor vessels, pressurizers, reactor coolant pumps, and steam generators. The NRC received reports of a number of degraded threaded-fastener incidents that involved the RCPB and major component supports. Although none of the reported incidents resulted in an accident, they do reflect an undesirable level of degradation in operating nuclear power plants by impairing the integrity of the RCPB or component supports.

Most of the reported bolting degradations were discovered either during refueling outages or scheduled inservice inspections (ISIs) or maintenance and repair outages. Thus far, bolting degradation has not caused an accident, and has not produced any immediate adverse effect on public health and safety. However, NRC is somewhat concerned that inadequate ISI of fasteners, either because of ineffective nondestructive examination (NDE) methods or failure to include fasteners in the ISI program, could contribute to the potential for reduction in the integrity of the RCPB and structural supports. Experience has shown that either wastage from borated-water corrosion or SCC can go undetected. Furthermore, such

*See Ref. 2 for a description of the wastage problem.

degradation in bolting important to the RCPB integrity could lead to a loss-of-coolant accident (LOCA) because of bolting failures.

1.3 Plan for Resolution

The NRC considered possible solutions to GSI 29 as part of the process for prioritizing generic issues. The NRC noted in Ref. 3 that bolting has a wide range of application in nuclear power plants and that no single solution to the problem is known. Therefore, to minimize potential bolting problems in new power plants, improvements in one or all of the five following areas could be recommended: design, materials, fabrication, installation, and inservice inspection. The NRC suggested that the efficiency and adequacy of the ISI program be emphasized.

The NRC action plan for GSI 29, as it finally evolved, included four tasks in its scope of work:

(1) Develop the technical bases for bolting application requirements by the NRC staff through a technical assistance contractor at the Brookhaven National Laboratory.

(2) Review licensees' responses to IE Bulletin No. 82–02, "Degradation of Threaded Fasteners in the Reactor Coolant Pressure Boundary of PWR Plants."

(3) Draft staff recommendations for proposed criteria and guidelines to be incorporated into the NRC Standard Review Plan (SRP).

(4) Develop a proposed plan for implementing bolting application requirements.

Meanwhile, the Joint AIF/MPC Task Group on Bolting became more active. 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 related document, NUREG–0577, issued in 1979 as the "For Comment" version. The industry response was to emphasize (1) a bolting survey, (2) stress-corrosion-cracking susceptibility criteria, and (3) corrective actions to deal with the problem. However, through meetings of the task group, by itself and with NRC staff, a more comprehensive industry program evolved. The 19-task Generic Bolting Program was presented for review and comment to the parent AIF Subcommittee on Material Requirements in February 1983; the program was officially transmitted by the AIF to the NRC in July 1983. The basic objective, which was attractive to the NRC staff, was that the nuclear industry itself would provide the technical basis for resolution of GSI 29; therefore, NRC's activities regarding this generic issue were delayed until the NRC received industry's findings.

2 INDUSTRY RESOLUTION

2.1 Planned Program

The technical program eventually formulated by the AIF/MPC Task Group on Bolting was a comprehensive, 19-task action plan aimed at resolving GSI 29. The Electric Power Research Institute (EPRI) organized a matrix-managed Generic Bolted Joint Integrity Program to carry out the research. The results, to the extent that they provide relevant technical findings, are summarized in Section 2.2 of this report.

Early in its existence, the task group reviewed information on fastener service failures and categorized them into four basic groups:

Group I – Degradation or Failure of Pressure Boundary Bolting Caused by General Borated Water Corrosion (Wastage or Erosion/Corrosion)

Group II – Degradation or Failure of Pressure Boundary Bolting Caused by Stress-Corrosion Cracking

Group III – Degradation or Failure of Internals Bolting Caused by Fatigue and Stress-Corrosion Cracking

Group IV – Degradation or Failure of Supports and Embedment Bolting Caused by Stress-Corrosion Cracking, with Two Sub-Classes Separated at the Minimum Specified Yield Strength Level of 150,000 psi

Three of these groups (Group III was excluded) formed the basis for what was called the Generic Bolting Program. EPRI assumed the lead for technical integration and research support in this generic program. Work related to Group III (internals bolting) failures was assigned to individual vendor owners' groups. Resolution of the fastener integrity issue involved many disciplines. Input was needed from the areas of metallurgy, fracture mechanics, nondestructive examination, design, specifications and standards, quality assurance, manufacturing or quality control, corrosion engineering, joint design, and tensioning control. The AIF/MPC task group considered all of these disciplines. Assessment of priorities related to fastener applications led to the focus of action on primary pressure boundary components. The action plan designed by the task group encompassed the following 19 tasks (several of which were divided into sub-tasks). These 19 tasks were grouped under 3 headings: General Bolting Tasks, Pressure Boundary Bolting Tasks, and Tasks Associated with Internals Bolting.

2.1.1 General Bolting Tasks (Tasks 1 Through 9)

Task 1 – Assessment of Priorities and Safety Significance

Task 1.1. – To monitor bolting priority ranking and to assess the failure and success history for each of the four degradation or failure groups listed previously. (See Section 2.1 of this report.)

Task 1.2. – To conduct a pilot scoping study, under EPRI direction, on the use of decision analysis for bolting aimed at developing a methodology for determining the technical parameters that influence the likelihood of bolt failure.

Task 2 – Literature Survey of Fastener Corrosion

To perform a literature survey of carbon and alloy steel fastener corrosion in PWRs.

Task 3 – Stress-Corrosion Cracking

To study and evaluate the effects of water environments on quenched and tempered low-alloy steel bolting materials.

Task 3.1 – Fracture Mechanics Analysis. To develop stress intensity factors for realistic flaw shapes and loading conditions in bolts.

Task 3.2 – Data Review. To obtain detailed descriptions of failures involving stress-corrosion of HSLA material from previously unpublished accounts.

Task 4 – Include Hardness Test Data into the Bolting Database

To include data obtained by utilities from hardness surveys of installed and spare bolting in a bolting database and to assess impact of these data on the issue.

Task 5 – Bolting Database

To maintain a database containing hardness data and other properties of bolting materials and to update the database as necessary to support industry efforts.

Task 6 – Development of Bolting Specifications and Standards for Nuclear Power Plant Applications

Task 6.1 – To develop a general specification for bolting requirements that eventually could be adopted by nuclear utilities.

Task 6.2 – To initiate action in American Society for Testing and Materials (ASTM) Committee F-16 (responsible for structural bolting) to revise sampling requirements in new and existing specifications to be more consistent with end-product expectations.

Task 6.3 – To prepare a draft ASTM standard entitled, "Standard Test Method for Leeb Hardness Testing of Metallic Materials," based on Equotip hardness test experience.

Task 7 – ASME Code Bolting Requirements

Task 7.1 – To prepare a critique regarding ASME Code bolting requirements, particularly as related to pretensioning of both pressure boundary and structural bolting joints.

Task 7.2 – To review ASME Code Section III bolting requirements to determine the need for revising or improving.

Task 8 – Develop Field NDE Techniques to Detect Wastage and Stress-Corrosion Cracking

To focus pilot studies that were under way on the development of field techniques, utilizing advanced ultrasonic techniques to detect wastage or stress-corrosion cracking in pressure boundary and support fasteners.

Task 9 – Information Exchange

Task 9.1 – To hold bolting workshops to exchange information on industry efforts regarding bolting integrity.

Task 9.2 – To produce and distribute to utilities videotapes on the behavior and maintenance of flanged pressure boundary connections as aids to improving bolting design, installation, and maintenance.

Task 9.3 – To produce a videotape on design, behavior, and tensioning practices as applicable to structural joints if warranted from the Task 16 results.

2.1.2 Pressure Boundary Bolting Tasks (Tasks 10 Through 17)

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

To develop a strategy for identifying bolts in pressure boundary applications that may be susceptible to boric acid corrosion or stress-corrosion cracking and recommend corrective actions.

Task 11 – Recommend ASME Code Section XI Changes

To review ASME Code Section XI requirements and send comments and recommendations to the code committees for action, including (1) appropriateness of Section XI size limits for inspection requirements;

(2) provisions to ensure adequate visual inspection; and (3) assurance that NDE inspections are effective in detecting corrosion wastage and stress-corrosion cracking.

Task 12 – Recommend Research Programs to EPRI on Degradation of Fasteners

To recommend three projects to EPRI that would increase 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 (the impact of the recommendations on the contracted work under Task 3 also was evaluated).

Task 13 – Alternative Materials and Coatings

To recommend alternative materials and coatings and provide guidance regarding selection criteria for the purpose of eliminating borated water corrosion concerns (this task was included in the contracted work under Task 3).

Task 14 – Component Support Bolting Screening Criteria

To develop a strategy for identifying component support bolts that may be susceptible to stress-corrosion cracking and recommend plant-specific methods for resolving findings regarding materials that require review.

Task 15 – Assess Fastener Integrity Based on Fracture Mechanics

To develop a technique to evaluate the integrity of bolting material in component support fasteners.

Task 16 – Preload Technology Assessment

To evaluate the need for high preloads, to identify potential relief in preload requirements, to investigate preload application techniques and resulting preload variability, and to recommend optimum techniques. Also, to discuss methodologies for estimating existing preloads based on knowledge of the tensioning techniques, sampling, or some combination of information and to discuss risks of detensioning existing joints.

Task 17 – Develop UT Procedures for Inspection of Ultra-High-Strength Low-Alloy Maraging Steels

To develop a field procedure for ultrasonic test (UT) inspection of ultra-high-strength bolts in the lower support feet of the Westinghouse-designed steam generator, using Westinghouse Owners' Group (WOG) funding.

2.1.3 Tasks Associated with Internals Bolting (Tasks 18 and 19)

Task 18 – High-Strength Bolting

To conduct research to improve the stress-corrosion resistance of high-strength, age-hardenable, Ni-Cr-Fe alloys and A 453 Gr. 660 (A286) bolting materials and to investigate the influence of irradiation and stress and strain on the behavior of structural materials.

Task 19 – Owners' Groups Liaison

To maintain liaison with owners' groups to ensure that duplication of effort is minimized and that pertinent information on the efforts of the task group is exchanged.

The 19 tasks were modified during the progress of the program. Redistribution of effort reflecting reassessment of relative priorities among the tasks occurred.

2.2 Technical Findings

The results of the Joint AIF/MPC Task Group on Bolting Program, described in this section, constitute a recommended technical basis for resolution of GSI 29 by the nuclear industry. The program, outlined in Section 2.1 of this report, was presented in detail along with the results from the executed tasks in a two-volume report, EPRI NP-5769, "Degradation and Failure of Bolting in Nuclear Power Plants" (Ref. 5). The report was published in two volumes to make the results of the research easy to review and to aid utility engineers in addressing plant-specific bolting and fastener problems with a single source document. Volume 1 included the background information, a description of the action plan for the AIF/MPC Task Group on Bolting, the approach to resolution of the bolting issue and the basis for this resolution, summaries of the findings from the 19 action plan tasks (Section 2.1.1), and the conclusions and recommendations.

Volume 2 included more complete supporting references and data. Publication of the two-volume report completed a comprehensive, generic review and analysis program. A major finding indicated that the design of critical closure joint bolting involves enough redundancy to ensure that there is virtually no pressing cause for concern regarding bolting integrity. A brief review of the EPRI report by volume and section follows.

2.2.1 Basis for the Resolution

EPRI NP-5769, Volume 1.

- Section 1, "Introduction," provided an historical review and the planned tasks (i.e., those given in Section 2.1 of this report).
- Section 2, "Industry Resolution of the Bolting Issue," presented additional details on the Joint Task

Group approach to the problem, the results obtained from research according to the task action plan, and brief discussions of two principal contributions of the work—development (1) of a generalized closure integrity model and (2) of joint leak-tightness criteria. The resulting information led to the conclusion that the technical basis for resolution of the generic bolting issue was reached.

- Section 3, "Pressure Boundary Bolting," concluded that closure integrity can be ensured through application of a leak-before-break criterion and provides three analyses (primary manway cover, reactor coolant pump main flange, and check valve flange) to illustrate the methods. The work led to a proposed ASME Code Section XI code case (see the discussion of Section 6, Volume 1, EPRI NP-5769, in this report) on inspection of bolted closures with observed or detected leakage.

- Section 4, "Structural and Component Support Bolting," presented results from Task 14 of the action plan. Component support bolting that may be susceptible to SCC was identified, and both generic and plant-specific review procedures were recommended. It was concluded that application by licensees of the proposed screening and disposition (of materials which failed to pass the screen) steps would be an adequate bolting integrity program and would serve to resolve GSI 29 with regard to component support bolting.

- Section 5, "Owners' Groups Summary," presented results from the Babcock and Wilcox (B&W) and Westinghouse Owners' Group programs on primary pressure boundary bolting. The B&W program lent further support to findings by others (see the discussion of Section 3, Volume 1, EPRI NP-5769, in this report) that a leak-before-break approach and conservative failure criteria can be used to ensure the integrity of bolted closures. Failure mechanisms included SCC and chemical wastage. A steam generator manway closure with SCC and a reactor main coolant pump closure with wastage were analyzed as examples to demonstrate the adequacy of this approach and these criteria. The WOG program originally included the following 10 tasks (Ref.6) (see Table 5-1, Vol. 1, EPRI NP-5769):

  (1) 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).

  (2) Provide installation procedures for bolting for primary boundary closures.

  (3) Catalogue service experiences for primary boundary closures, and identify service-sensitive closures based on utility input.

  (4) Follow the AIF/MPC bolting programs, provide liaison for the WOG plants, and prevent any duplication of effort.

  (5) Develop nondestructive methods for bolting for primary boundary closures.

  (6) Prepare specifications for primary boundary bolting, including quality assurance requirements for procurement, receipt, and preinstallation inspections.

  (7) Evaluate and qualify sealants for primary boundary closures.

  (8) Evaluate and qualify lubricants for primary boundary closure.

  (9) 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.

  (10) Establish feasibility of having an inventory of bolting (considering Task 3) for primary boundary closures.

Of the original 10 tasks, the WOG actually sponsored the first 4 tasks; the other tasks were judged to be adequately covered by separate efforts sponsored by EPRI, ASTM bolting standards committees, ASME Code committees, or other MPC activities. The WOG did assume responsibility for Task 17 (see Section 2.1.2 of this report), the development of an ultrasonic field procedure applicable to ultra-high-strength bolts.

A discussion of the first 4 of the 10 tasks for the WOG's program on bolting follows (Ref. 6):

- Task 1 supported a leak-before-break approach to closure integrity by addressing the complete bolted closure rather than individual fasteners and resulted in publication of a user's manual.

- Task 2 investigations resulted in recommended installation procedures. To arrive at these procedures, the WOG compared several preload measurement techniques, including those for torque wrenches, stud heaters, stud tensioners, and the Bolt Gage (a Raymond Engineering, Inc., development). The Bolt Gage was the preferred technique.

- Under Task 3, from available data, the WOG listed and analyzed primary boundary closure leakage. It was concluded that (1) the available information useful in determining service-sensitive closures is limited, (2) the leak-before-break approach recommended by the AIF/MPC Task Group on Bolting is a sound engineering attack, and (3) the ASME Code should be changed to address bolt/stud flaw limits based on closure integrity and fastener redundancy.

- Task 4 provided for liaison with others in the AIF/MPC task group.

An NDE field procedure was developed for bolts under AIF/MPC Task 17 that provided *in situ* techniques for inspection of Westinghouse PWR steam generator support bolts. The procedure can obviate costs previously borne by utilities for removal and surface examination.

- Section 6, "ASME & ASTM Codes and Standards," included the results of Tasks 6 and 7 of the action plan (Section 2.1 of this report). Subtask 6.1 was completed with the preparation of "Utility Recommendations and Guidelines for the Purchase Specification and Receipt/Installation Inspection Requirements for ASME Section III, American Institute of Steel Construction (AISC), American National Standards Institute ANSI/ASME B31.1, and ANSI B31.5 Bolts and Threaded Fasteners." The report is published in its entirety as Section 1 of Vol. 2, EPRI NP-5769. Subtask 6.2 addressed the advisability of changing the sampling requirements for structural bolting specifications under the jurisdiction of ASTM Subcommittee F16.02, and, at the time of publication of EPRI NP-5769, approval of the proposed changes was still pending. Subtask 6.3 resulted in preparation of the draft standard, "Standard Test Method for Equotip Hardness Testing of Metallic Materials," its submittal to ASTM Subcommittee E28.06, and its publication as Section 2, Vol. 2, of EPRI NP-5769. Task 7 resulted in two products: First, the many places in the ASME Code where rules are given for the design and construction of bolted joints, scattered among voluminous rules for welding and other fabrication methods, were listed and explained in Section 9, Vol. 2, EPRI NP-5769. Until such time as changes in the ASME Code make the Section 9, EPRI NP-5769, listing obsolete, it will serve as a useful single reference source. Second, the results of a review of ASME Code bolting requirements were published as Section 10, "Critique of Bolt Preload Aspects of ASME and AISC Codes," Volume 2, EPRI NP-5769. The material in this section was limited to ASME Code treatment of bolt preload with respect to design, assembly methods, and quality control, even though additional aspects of fastener preload could have been considered.

- Section 7, "NDE of Bolting," presented the results of studies designed to attain the goal of developing field techniques as stated in Task 8 of the AIF/MPC bolting action plan (see Section 2.1 of this report). Conventional UT methods were evaluated and their limitations determined. EPRI funded three separate contracts and asked the contractors to develop and evaluate new techniques that lend themselves to field application and that are capable of detecting both SCC and wastage. One contractor developed acoustic resonance and reverberation techniques for detection of wastage, another contractor further developed the acoustic resonance technique to detect SCC, and the third contractor developed the cylindrically guided wave technique (CGWT) for detection of SCC as well as wastage.

  The reverberation technique used a spectrum analyzer to quantify the frequency content of a pulse-echo envelope and detect characteristic time spacing changes and then compared the reverberation spectrum of a target bolt to that of an unflawed bolt to detect degradation.

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

- Section 8, "Lubricants and Sealants," included three sub-tasks as part of Task 12 in the AIF/MPC task plan (Section 2.1.2 of this report). Several projects and studies, described in EPRI NP-5769, provided useful data. The text of Section 8 was adapted from a more detailed report (Ref. 7). The influence of several lubricants on boric acid wastage was studied with results too varied to review in detail here. However, one result reported was the detrimental influence of MoS_2 and the difficulty of removing it from fasteners that have been exposed to service conditions. The studies of leak sealants and concerns derived from them led to several recommendations; principal among them was that the responsible design organization (e.g., ASME) should establish standards for leak sealants.

- Section 9, "Alternative Materials," the task identified as number 13 in Section 2.1.2 of this report, was drawn from the more detailed reports of "Stress-Corrosion Cracking of Alternative Bolting Alloys," EPRI RP-2058-12 (Ref. 8) and Section 3, Vol. 2, EPRI NP-5769. This work also is related to Task 3 of the action plan. The resulting four conclusions can be restated briefly as follows: (1) whereas low alloy steels are vulnerable to boric acid corrosion, other alloy steels generally are resistant; (2) galvanic corrosion, depending on specifics of the material composition and environmental chemistry, can occur, but data are needed for each combination if sensible decisions are to be made; (3) MoS_2 lubricant was shown to be a factor in laboratory corrosion testing when conditions favored the liberation of hydrogen sulfide, but its role in service-related failures remains to be clarified; (4) more K_{ISCC} data are needed if a damage-tolerant methodology is to be adopted.

- Section 10, "Training Package," consisted of a brief description of two EPRI-sponsored actions aimed at information exchange. First, a workshop was held November 2 through 4, 1983, at Knoxville, Tennessee. Participants included representatives from the U. S. Nuclear Regulatory Commission, the Atomic Industrial Forum, the Electric Power Research Institute, its contractors and consultants, and the nuclear power generating industry. The stated objectives included alerting industry to the NRC's generic bolting safety issue and the regulator's perspective of the issue. Also, speakers reviewed the AIF program and the EPRI efforts toward resolution, including bolting design criteria, codes and standards, specifications, fabrication, quality control, tools, procedures, and general bolting problems. Second, a set of three videotapes was produced and made available to any interested party. They are identified as "Electric Power Research Institute Pressure Boundary Bolting Problems; Part I: The Basics; Part II: Engineering Problems; Part III: The Mechanic and Bolting." Although they were aimed at the manager, the engineer, and the mechanic, respectively, viewed together, they constitute a rather complete tutorial on bolting.

- Section 11, "Conclusions and Recommendations," summarized the many conclusions derived from completion of the Joint AIF/MPC Task Group on Bolting 19-task program. The diverse disciplines and the many activities were joined and integrated to provide what the industry believed to be a basis for resolution of the NRC GSI 29.

2.2.2 Supporting Data for the Resolution

EPRI NP-5769, Volume 2.

- 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," presented recommended guidelines for utilities constructing or operating nuclear power plants, including certification, identification, NDE, and storage requirements for bolting material (bolts, studs, and nuts) to be used in permanent features. It also included recommended guidelines for receipt or preinstallation inspection designed to help ensure fastener integrity. Recommended guidelines were given for tightening fasteners when neither preloading, torquing, nor both are specified by other documents. The guidelines were written specifically for ASME Code Section III Code-of-Record plants. They were given as adequate for pre-ASME Code Section III Code-of-Record plants (i.e., ANSI B31.1 and B31.7), but, for plants of such vintage, the user was cautioned to consider the safety class of the system in which the bolting is used and to 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 American Nuclear Society Safety Class 1.

- Section 2, "Standard Test Method for Equotip Hardness Testing of Metallic Materials," covered the use of the Equotip Hardness Tester to determine the Leeb hardness of metal components. The discussion included definitions, test procedures, instrument verification, test-block calibration, and a table of hardness conversion. As previously noted under Section 6, Vol. 1, EPRI NP-5769, the text of Section 2, Vol. 2, was a draft ASTM standard, submitted to ASTM Subcommittee E 28.06. As will be explained in Section 3 of this report, the NRC understands the need for *in situ* hardness measurement as part of a program by licensees to ensure conformity to codes and standards, and the NRC agrees that properly conducted Leeb hardness tests can be part of that program. However, Section 2 of EPRI NP-5769 contained what appear to be technical errors because tabulated hardness conversion values disagree with published ASTM Standards. The apparent disagreements must be clarified, presumably by ASTM Subcommittee E 28.06.

- Section 3, "Evaluation of Bolting Experiences in Primary Pressure Boundary Closures," presented the results of compiling and analyzing 125 incidents of bolting failure reported by nuclear utilities. The principal failure mechanisms, in order of decreasing importance, were boric acid corrosion (wastage), maintenance damage, corrosion pitting, and stress-corrosion cracking. Not included in the analysis were a number of flange bolt problems in the control rod drive mechanism that were judged to be related mainly to one nuclear steam supply system (NSSS).

Although the fastener rejection rate* varied with the component and generally was small (not more than about 10%), the rate was sufficient to justify ranking NRC GSI 29 as a high priority task.

- Section 4, "Sampling Inspection and Acceptance Criteria for Bolted Connections," provided a statistical evaluation of fastener loads. The evaluation addressed the main concerns in highly stressed high-strength fasteners, that is, failures that were due either to the external load exceeding the preload across the joint (overload) or to stress-corrosion cracking. If the preload of a given fastener were known, then one could decide about preload adequacy simply by checking whether the preload is inside or outside the acceptable design range for that fastener. Because uncertainties exist about the actual value of preload, the deterministic checking procedure must be replaced with a probabilistic criterion.

  Ideally, standards for bolted connections susceptible to overload and stress-corrosion cracking should be set by establishing maximum acceptable probabilities for the occurrence of each failure mode, based on the severity of the consequences. To apply such standards, uncertainties on the external loads, the state of preload, and the maximum flaw size should be quantified. Unfortunately, the state of knowledge (e.g., about SCC) and current deterministic practice make it impossible to fully implement probabilistic standards. A semi-probabilistic format, explicitly recognizing uncertainties on fastener preload, but avoiding failure probability calculations, was proposed. The uncertainty is changed by sampling inspection, for which a simple method of sample size determination and uncertainty updating was proposed, consistent with the format of the acceptance criteria.

- Section 5, "Nuclear Structural Bolting Preload Evaluation," reported on the results of completing Task 16 (see Section 2.1.2 of this report). The task consisted of evaluating the need for high preloads, identifying potential relief in preload requirements, and investigating preload application techniques and variability. Section 4 of EPRI NP-5769 provided the statistical nature of the preloading process, and Section 5 evaluated 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 report discussed conclusions that were reached about design criteria, load relief, preload range acceptability, preload estimation, and preload accuracy.

- Section 6, "The Bolting Database: An Example of a Numeric Database Application in the Nuclear Power Industry," briefly discussed the nature of the database, the stored information and classification scheme, access, software, and applications.

- Section 7, "Assessment of Field Hardness Measurements on Low-Alloy Quenched and Tempered (LAQT) Bolting Materials at Midland," presented the collection (from four nuclear sites) and analysis of LAQT fastener steels. Significant deviation from specification requirements was observed. It was estimated that the portion of bolts at one site (Midland) with a hardness indicating a susceptibility for SCC was less that 1% of the total population; not a serious concern.

- Section 8, "Good Bolting Practices," briefly reviewed the two reference manuals for nuclear power plant maintenance personnel that were developed under EPRI sponsorship and were intended for rapid-access field or office use by utility staff who must disassemble and assemble bolted joints in nuclear power plants. This section described bolting practices that should help staff members identify, understand, and solve (or minimize) bolted joint problems such as leaks, vibration loosening, fatigue, and stress-corrosion cracking.

  The first of the manuals was entitled, "Good Bolting Practices: Large Bolt Manual;" the second was entitled, "Good Bolting Practices: Small Bolt Manual." The manuals described the problem-reducing steps in order of increasing complexity and cost, recognizing that the options available to maintenance personnel are generally limited.

  The manuals were not intended for use by designers; therefore, the theories behind the recommended procedures were not discussed at any length. The encyclopedia format for the manuals was intended to make the topics easy to locate. Topics were listed alphabetically and identified by legends printed in bold face. Each topic was described briefly, with typical data, if pertinent, and with cross-references to related topics, also in bold-face type.

- Section 9, "Bolting Rules of the ASME Boiler and Pressure Vessel Code," presented a detailed, point-by-point, review of the ASME Code with explanations, interpretations, and suggestions for improvement. The many scattered bolting requirements were collected in this one section of the EPRI report to provide a source document for reference. This was noted in the discussion of Section 6, Vol. 1, EPRI NP-5769.

*Rejection rate was the relative number of failures, degradations, inspection call-outs, etc., as a percent of the total fasteners inservice.

- Section 10, "Critique of Bolt Preload Aspects of ASME and AISC Codes," is a companion piece to Section 9, Vol. 2 (and was cited in Section 6, Vol. 1) of the EPRI report. The stated assignment was "to critique existing preload sections of the ASME Code." The Joint AIF/MPC Task Group on Bolting posed two questions to guide this effort:

  (1) Do provisions of the ASME Code contribute to the types of bolting failure experienced in the last decade or so by the nuclear industry?

  (2) Do omissions in the ASME Code contribute to the types of bolting failure experienced by the nuclear industry?

  The investigators were directed to limit the responses to preload aspects of bolting problems. The review identified several provisions of the AISC and ASME Codes that could be troublesome. The points raised and the rectifications suggested were too numerous to be reported here, but are described in EPRI NP-5769. In addition to general observations concerning the ASME Code, preload philosophy, preload and installation method codification, education, quality control, and the role of the mechanic, five specific problems were cited and solutions offered. Four appendices completed the section; they went into greater detail on specific problems and gave support to the conclusions and recommendations stated in the text of Section 10. The titles of the appendices follow:

  (1.) Appendix 10A, "AISC Specification for Structural Joints Using ASTM A325 or A490 Bolts"

  (2.) Appendix 10B, "ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NF"

  (3.) Appendix 10C, "ASME Boiler and Pressure Vessel Code, Section VIII, Division 1"

  (4.) Appendix 10D, "Comparison of ASME Codes on Pressure Boundary Bolting"

- Section 11, "Evaluation Procedure for Assuring Integrity of Bolting Material in Component Support Applications," is the companion piece on structural bolting to the RCPB discussion, Section 3, Vol. 2, EPRI NP-5769. The Section 11 presentation describes an evaluation procedure for general application to bolting products used in component supports and fabricated from steels commonly used for support bolting. The evaluation procedure could be used to justify serviceability of questionable materials. It was anticipated that this section would be useful to a utility as part of a plant-specific plan to deal with materials that require some evaluation under the generic issue.

  The primary objective was to present the procedural steps and required information to determine allowable bolt loads to avoid SCC under steady-state or long-term normal operating conditions. Allowable bolt stress as a function of material hardness, bolt size, and thread pitch could be determined with the procedures. The allowable bolt stress then could be compared with actual bolt stresses calculated for the design. A requirement of the procedure was that hardness testing be performed on the population of bolts so that hardness limits could be statistically determined. Also, as part of the evaluation objective, allowable bolt stresses to prevent fracture under short-term (accident) loads must be established when low toughness was implied by the hardness data.

- Section 12, "Alternate Alloys," consisted of brief reports on five separate research projects, all sponsored by EPRI and dealing with steel corrosion in nuclear reactor environments. Each project had been reported in more detail elsewhere; the five published documents were cited in the EPRI NP-5769, Volume 2, reference list.

  The Combustion Engineering Project grew out of interest in fastener corrosion and is entitled, "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 data in the literature on boric acid corrosion and stress-corrosion cracking of fasteners. Service failures from both mechanisms were collected and analyzed. A common factor in six SCC events involving steam generator primary manway closure studs, which pose a potential for a LOCA, was the use of MoS_2 lubricant. Decomposition at high temperatures can yield hydrogen, which can induce SCC in HSLA steels even at low concentrations.

  The Battelle, Columbus, Laboratories Project was closely allied to the Combustion Engineering Project. It involved a review of joint failures in nuclear components from either boric acid wastage or SCC. The primary objective was to determine if austenitic, age-hardenable materials could be used for bolting applications. A secondary objective 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 were made for further work to improve the industry's capability for dealing with the bolting problem. It was concluded that austenitic materials seem to be resistant to boric acid wastage but vulnerable to SCC. The report presented so many qualifications regarding the use of high-strength high-alloy steels that Battelle could hardly be accused of recommending them. Much of the report discussed conditions that can lead to failure of low-alloy steels without recommending alternative resistant materials.

The Materials Engineering Associates Project was part of a failure analysis of Type 410 stainless steel valve studs purchased to ASTM specification A 193, Grade B6, with a supplemental requirement of 125 ksi tensile strength specified by the utility. The utility's investigation focused on improper heat treatment of the studs, resulting in temper embrittlement. The embrittlement permitted SCC, with stud failure occurring once the critical flaw size was achieved. Mechanical property tests confirmed that the material exhibited low fracture toughness. In combination with the experimentally determined rather high tensile strength and somewhat reduced ductility (less than 50% reduction in area in three of six specimens), the studs would be vulnerable to SCC.

The Westinghouse Electric Project sought a solution to the cracking of age-hardenable Ni-Cr-Fe alloys in PWRs and boiling-water reactors (BWRs). Several instances of stress corrosion or, in some cases, corrosion fatigue in bolts, beams, and pins were observed in reactors using Alloys X-750, I-718, and A 286. The object was to examine the three alloys in different heat-treated conditions. Alloy X-750 with increased amounts of zirconium, which previously had been shown to be beneficial, also was included. Stress-corrosion cracking studies, involving both crack initiation and crack propagation specimens in PWR and BWR conditions, were conducted on alloy X-750 in 11 conditions, alloy I-718 in 2 conditions, and alloy A 286 in 2 conditions. The operating conditions of BWRs were shown to be more detrimental to the alloys than operating conditions of the PWRs. Alloy X-750 exhibited the most resistance to cracking (or propagation) in one of the several heat treatments that were applied, but, in a different condition, it was the least resistant. Long-term (more than 10,000 hours) tests are continuing.

The Babcock and Wilcox Project was a companion to the Westinghouse project, using the same high-strength, age-hardenable Ni-Cr-Fe alloys, X-750, I-718, and A 286. Service failures were attributed to fatigue, corrosion fatigue, and intergranular stress-corrosion cracking (IGSCC). Susceptibility to failure by these mechanisms depended strongly on the metallurgical condition produced by thermo-mechanical processing. The project included detailed microstructural characterization and corrosion testing of the alloys subjected to 15 different combinations of melting practice and thermomechanical processing. As in the Westinghouse study, preliminary findings indicated that Alloy X-750 had the best resistance to SCC when in a particular metallurgical condition. As in the companion study, the conclusions were not solid and unambiguous except for recommending further studies.

- Section 13, "Standard Specification for Supplemental Requirements for Structural Fasteners for Nuclear Applications," consisted of some background and introductory material and the proposed ASTM standard: *F XXX—"Standard Specification for Quality Assurance and Inspection Requirements for Structural Fasteners for Nuclear and Other Special Applications." Experience with fasteners has created several concerns. The draft specification includes requirements for nuclear fasteners as follows:

  - Establish sampling and quality levels for all series of structural fasteners on a uniform basis.
  - Establish mandatory lot control and traceability of fasteners. By maintaining such control, prevent mixing and possible contamination of parts intended for nuclear systems.
  - Require positive identification and source of fasteners intended for nuclear system as evidence of adherence to required quality level.
  - 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.
  - Permit utilization of state-of-the-art technology and beneficial effects of heading and thread rolling by specific callout. Such other major industries as automotive and aerospace have similarly mandated such requirements.
  - Recognizing the potential long-term degradation resulting from the presence of discontinuities such as cracks and seams, establish specific requirements to define acceptable and rejectable criteria for nuclear system use.

This very important standard, now in the hands of the cognizant ASTM committee, was supported by the Joint AIF/MPC Task Group on Bolting.

*This standard is being developed; the number will be assigned after it is completed and approved.

- Section 14, "The Bolting Technology Council" (BTC), provided a brief description of the Council, its activities, and its makeup. The BTC is affiliated with the Materials Properties Council, Inc., formerly the Metals Properties Council, which provides administrative services as required. The BTC was formed to provide opportunities for threaded fastener and tool users to engage in a variety of cooperative activities. As stated in its 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." As anyone who has attempted to understand bolted 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 felt that it would 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. The Council expects to provide benefits to industry through interaction with recognized experts in bolting technology, opportunities to participate in seminars and symposia, opportunities to share in cooperatively funded research to be planned, monitored, and directed by BTC groups, and opportunities to review publications and research results well before general release. It is anticipated that the BTC will identify unresolved bolting problems recognized now and as they arise from experience in the future. Through its resources in personal expertise and in financial assistance, the BTC will be instrumental in developing solutions to generic bolting issues.

3 CONCLUSIONS

The NRC staff has reviewed the technical findings developed by the industry and presented in EPRI NP-5769 (Ref. 5) as well as other relevant industry-generated information. The staff has concluded that the technical basis for resolution of GSI 29 is available.

The conclusion that GSI 29 can be resolved is based on the availability of several relevant documents. Actions taken by the Joint AIF/MPC Task Group on Bolting resulted in EPRI NP-5769, three video training films (see Section 10, Vol. 1, Ref. 5) and the Good Bolting Practices reference manuals, Vols. 1 and 2 (see Section 8, Vol. 2, Ref. 5). Industry representatives established the Bolting Technology Council (an MPC affiliate) to take the lead in sponsoring bolting research, recommending practices, gathering and providing information, and promoting education on installation, application, behavior, and interactions of fasteners. The Institute of Nuclear Power Operations can be expected to act in response to potentially unsafe conditions as in the past when Significant Operating Event Report (SOER) No. 84-5 on bolting (Ref. 9) was issued. Further refinement in codes and standards will be provided by the responsible committees in ASME and ASTM (e.g., Committee F16 on Fasteners).

During the period in which GSI 29 was being resolved, the NRC took several additional steps that must be factored into the resolution of the issue. Incidents of threaded fastener degradation and failure from October 1969 to March 1982 were identified and analyzed (see Ref. 4). Five documents were prepared based on results of technical assistance contracts in support of the bolting generic issue (Refs. 10 through 14). In addition, action items included the following NRC notices, bulletins, and generic letters:

- IE Bulletin 74-03, "Failure of Structural or Seismic Support Bolts on Class 1 Components," April 29, 1974.
- IE Bulletin 79-02, "Pipe Support Base Plate Designs Using Concrete Expansion Anchor Bolts," March 8, 1979.
- IE Bulletin 79-07, "Seismic Analysis of Safety-Related Piping," April 14, 1979.
- IE Bulletin 79-14, "Seismic Analysis for As-Built Safety-Related Piping Systems," July 2, 1979, (also: Revision 1 of page 2 of 3, July 18, 1979; Supplement 1, August 15, 1979; Supplement 2, September 7, 1979).
- IE Bulletin 82-02 (Ref. 2), which resulted in W. Anderson and P. Sterner, "Evaluation of Responses to IE Bulletin 82-02," NUREG-1095, May 1985.
- NRC Compliance Bulletin 87-02, "Fastener Testing to Determine Conformance with Applicable Material Specifications," November 6, 1987 (later: Supplements 1 and 2).
- NRC Bulletin 89-02, "Stress Corrosion Cracking of High-Hardness Type 410 Stainless Steel Internal Preloaded Bolting in Anchor Darling Model S350W Swing Check Valves or Valves of Similar Design," July 19, 1989.
- NRC Generic Letter 88-05, "Boric Acid Corrosion of Carbon Steel Reactor Pressure Boundary Components in PWR Plants," March 17, 1988.
- NRC Generic Letter 89-02, "Actions to Improve the Detection of Counterfeit and Fraudulently Marketed Products," March 21, 1989.

- IE Circular 78-14, "HPCI Turbine Reversing Chamber Hold Down Bolting," July 12, 1978.

- IE Information Notice 80-27, "Degradation of Reactor Coolant Pump Studs," June 11, 1980.

- IE Information Notice 80-29, "Broken Studs on Terry Turbine Steam Inlet Flange," August 7, 1980.

- IE Information Notice 80-36, "Failure of Steam Generator Support Bolting," October 10, 1980.

- IE Information Notice 82-06, "Failure of Steam Generator Privacy Side Manway Closure Studs," March 12, 1982.

- IE Information Notice 86-25, "Traceability and Material Control of Material and Equipment, Particularly Fasteners," April 11, 1986.

- IE Information Notice 86-108, "Degradation of Reactor Coolant System Pressure Boundary Resulting from Boric Acid Corrosion," November 1986 (later: Supplements 1 and 2).

- NRC Information Notice 87-56, "Improper Hydraulic Control Unit Installation at BWR Plants," November 4, 1987.

- NRC Information Notice 88-11, "Potential Loss of Motor Control Center and/or Switchboard Function Due to Faulty Tie Bolts," April 7, 1988.

- NRC Information Notice 89-22, "Questionable Certification of Fasteners," March 3, 1989.

- NRC Information Notice 89-59 and Supplement 1, "Suppliers of Potentially Misrepresented Fasteners," August 16 and December 6, 1989.

- NRC Information Notice 89-70, "Possible Indications of Misrepresented Vendor Products, October 11, 1989.

In various ways, these NRC notices, bulletins, letters, and circular will influence actions that the NRC or licensees will need to take in the wake of the resolution of GSI 29. Although they do not, individually or collectively, form a basis for the resolution, neither will these documents nor the responses made to them change as a result of the resolution of GSI 29.

The NRC staff concludes that all of the available information that has been discussed in this report (from industry and regulatory sources combined) provide a sufficient technical basis to resolve GSI 29.

It must be understood that although the NRC staff recognized the value of the several products of the industry effort (the work of the Joint AIF/MPC Task Group on Bolting) in helping to resolve GSI 29, that recognition does not constitute unqualified endorsement of their technical content. The NRC staff found technical disagreement with several specific discussions in EPRI NP-5769, the three videotapes on training, and the Good Bolting Practices reference manuals. The technical disagreements, except for the following, however, generally were not important enough to mention.

First, the staff notes that a general plan for evaluation of bolting integrity can be derived from Section 11, Vol. 2, EPRI NP-5769. Section 11, "Evaluation Procedure for Assuring Integrity of Bolting Material in Component Support Applications," was written to fulfill a specific assignment for the Joint AIF/MPC Task Group on Bolting. With appropriate modifications, the procedure could serve for other than component-support bolting. The screening process should use fastener material properties and fracture mechanics analyses to ensure that safety-related fasteners are unlikely to be susceptible to stress-corrosion cracking. Material properties should be experimentally verified rather than assumed to be as specified.

Second, and closely related to the first comment, inconsistencies found in EPRI NP-5769 regarding the criteria for categorizing bolting steels according to strength must be reconciled. Categorization should be based only on the **actual** measured yield strength, S_y, of the material (or S_y determined by conversion of measured hardness values) and not on the specified minimum yield strength. The justification for this position is that high-strength steels are vulnerable to SCC. A bolt made of high-strength steels may be obtained through an order which specifies a relatively low-yield strength, but by improper heat treatment, for example, the bolt may develop an actual strength far in excess of the minimum specified. Specifically, that high-strength bolts should be those with $S_y \geq 150$ ksi; medium-strength bolts should be those with 120 ksi $< S_y <$ 150 ksi. The following portions of EPRI NP-5769 need to be modified in order to make them consistent with the above definitions:

- In Vol. 1, Section 4, page 4-3, bolting steels are categorized as "high strength" if: "$S_y >$ 150 ksi, where S_y is the yield strength" (compare the greater-than symbol to the greater-than-or-equal-to symbol recommended). At the same location, medium-strength materials are identified as those with 120 ksi $< S_y <$ 150 ksi, which would be consistent except for the explanatory text that follows on page 4-4: "Therefore, it seems appropriate for the industry to examine the use of materials with specified minimum yield strengths greater than 150 ksi" (emphasis added). The same words are used on page 4-5 at two places.

- On page 4-4, a proposed category is defined by "the range of 120 ksi to 150 ksi specified minimum yield strength" showing that the use of S_y on page 4-3 was not to be taken literally.

- In Vol. 1, Section 11, "Conclusions and Recommendations," page 11-5, the words "minimum specified" are used again.

- On the next page (p. 11-6) one finds "specified yield strength." An inconsistency arises in EPRI NP-5769, Vol. 2, Section 1, page 1-17 because the reader is advised to consider materials vulnerable to SCC if the minimum specified ultimate tensile strength (UTS) is greater than 150 ksi or if the actual UTS is greater than 170 ksi.

- Then, in NP-5769 Vol. 2, Section 7, page 7-2, we find: "...the proposed screening limit of $S_y \leq 150$ ksi (1034 MPa)" although in the preceding paragraph the words "specified minimum yield strength" were used to describe the strength range of 120-150 ksi (827-1034 MPa).

A more careful reading might reveal more discrepancies or inconsistencies. For the reasons previously given, the criterion of actual yield strength, $S_y \geq 150$ ksi should be used as the level for consideration of SCC vulnerability.

Third, the data listed in Table 2-1, Vol. 2, EPRI NP-5769 are questionable. Indexing off the values of Rockwell C-scale hardness as given, the corresponding values of Vickers hardness numbers do not agree with those given in the ASTM Standard E 140. From the same R_C start, the corresponding values of tensile strength do not agree with values given in the ASTM Standard A 370. Such errors (there are typographical mistakes, as well) also make the hardness conversions listed in Table 11A-1 of EPRI NP-5769 suspect; they should be audited. Accepting the ASTM standards as the authority, the hardness conversions and hardness-tensile conversions in EPRI NP-5769 should be treated skeptically. Since Table 2-1 was to be part of a draft ASTM standard, the responsible ASTM committee can be expected to make such corrections as may be necessary. Until Leeb hardness values and conversion tables have been incorporated in a standard test method by the ASTM, they should be used "for information only" and not be accepted as evidence in licensing actions or in safety evaluations.

Fourth, the indictment against MoS_2 as a lubricant (found on page 3-5 of EPRI NP-5769, Vol. 2) deserves more emphasis. Facts gleaned from some service failures and from laboratory examinations (Ref. 12) clearly show that MoS_2 is a potential contributor to SCC, especially when applied to high-strength bolting steels. One of the problems posed by MoS_2—difficulty in removing it from parts that have been in service (see page 8-3, Vol. 1., Ref. 5)—may be close to being resolved. Whereas Czajkowski (Ref. 12) found that CS_2 will remove MoS_2, handling CS_2 poses some problems. More recently, tests by Czajkowski of samples of "citrus-based cleaners" were subjected to a cleaning task similar to that reported in Ref. 12, and it was evident that the sulfur component (the active SCC ingredient) had been effectively removed (Ref. 15). Providing that the citrus-based cleaners, themselves, are not SCC promoters, an answer to the MoS_2 cleaning problem may be at hand.

Fifth, although the fracture mechanics analyses by Cipolla cited in Section 9, Vol. I, EPRI NP-5769, are useful and could well be employed in engineering problems where values for the stress intensity factor, K_I, are needed, other more recent results are available. In a report published in 1988, "Review and Synthesis of Stress Intensity Factor Solutions Applicable to Cracks in Bolts" (Ref. 16), values for K_I for cracks in round bars, both threaded and unthreaded, subject to either tension or bending, were reviewed. Available solutions were synthesized into forms appropriate to analyses of bolts and studs. The K_I solutions published in Reference 16 should be used in fracture mechanics analyses of threaded fasteners.

The importance of maintaining adequate traceability* and control of material of fasteners at nuclear power plants was set forth in IE Information Notice No. 86-25 (Ref. 17). Because plant-specific bolting integrity programs should include steps to ensure bolting traceability and material control and to prevent introduction of incorrect or defective materials or components, the central ideas from this notice follow:

Awareness of 10 CFR Part 50, Appendix B, Criterion VIII, "Identification and Control of Materials, Parts, and Components," and applicable codes and specifications is important. Measures have been established and implemented by the NRC for identification and control of materials, parts, and components and for traceability both to the approved design basis and to the source. It is important that required identification of items be maintained by heat number, part number, serial number, or other appropriate means, either on the item itself or on records traceable to the item as required, and that required markings be on the item.

*In Attachment 2 to NRC Bulletin No. 88-10, November 22, 1988, verifiable traceability was defined as (with minor editing for this report): Documented evidence such as a certificate of compliance that establishes traceability of purchased equipment to the manufacturer. If the certificate of compliance is provided by any party other than the manufacturer, the validity of the certificate must be verified by the licensee or permit holder through an audit or other appropriate means.

It is the licensee's responsibility to use qualified individuals to examine markings on material and equipment and to verify that the markings represent material and equipment as specified by the design drawings and specifications. In the case of fasteners, compliance with the applicable material specification (e.g., ASTM or ASME material and grade) is verified by required markings on bolts and nuts and certified material test reports or certificates of conformance as required by procurement drawings and orders and by applicable codes and specifications. When vendor-supplied equipment assemblies contain fasteners, it is important to verify compliance with approved vendor drawings and specifications and such other information as materials used for equipment qualification tests analyses. The required markings on material and equipment, including fasteners, not only must exist, but the markings must indicate the correct material and grade as specified.

The NRC staff resolved GSI 29 based on the findings presented herein, including the following three conditions.

First, all earlier NRC notices, bulletins, and generic letters that bear on the issues involved in bolting, degradation or failure, some of which were noted earlier in this section, should remain in effect.

Second, it was concluded that an effective means of ensuring bolting reliability, as recommended in Ref. 5, would be through development and implementation of plant-specific bolting-integrity programs. These programs should be comprehensive and include all relevant NRC requirements and guidance and the recommended positions of the industry-sponsored programs.

Third, it is recommended that a new section of the Standard Review Plan (SRP) be prepared to provide guidance to the staff for the review of future plants. The elements of the review would include all safety-related joint design, threaded fastener material selection, and programatic aspects dealing with bolting integrity during construction, operation, and maintenance, except for closure studs which are addressed in SRP Sections 5.3.1 and 5.2.3.

In light of the facts that many safety-related systems and components rely in large measure on fastener integrity and that there have been numerous reported instances of degradation or failure of threaded fasteners, completion of the studies under GSI 29 has led to the conclusion that fastener integrity needs to be procedurally controlled. The information reviewed in this report showed that the safety issue related to fastener integrity involves a very large number of parts in each plant, a number of potential failure mechanisms (therefore, a corresponding number of protective or corrective actions), and several technical and engineering disciplines. Although the resolution of GSI 29 was found to be rather complex, sufficient guidance is available to resolve this issue, mainly from EPRI NP-5769 (Ref. 5). Specifically, the NRC staff concurred with the recommendations and guidelines provided in Section 1*, Vol. 2, of EPRI NP-5769. The recommendations and guidelines apply to threaded fasteners with regard to certification, identification, nondestructive examination, storage and tightening procedures, except when storage and tightening procedures are specified in other design documents or drawings. Implementing Section 1 and other technical guidelines in the EPRI report would help ensure fastener integrity.

A comprehensive bolting integrity program for a nuclear power plant would include all safety-related bolting, especially bolting used to close the primary pressure boundary and used for component support.

Of particular importance to safety are component support fasteners in the onsite power distribution system, including those power sources, distribution systems, and vital supporting systems provided to supply power to safety-related equipment and capable of operating independently of the offsite power system. The onsite power system includes an ac distribution system, a dc power system, an uninterruptible ac power system, and the emergency (diesel generator) power system. Fasteners in the auxiliary feedwater system and its support systems are also important to safe operation of a plant.

The work done to resolve GSI 29 has shown that (1) existing requirements, (2) the implementation of leak-before-break criteria for RCPB joints (proposed in EPRI NP-5769, Volume 1, Section 3), and (3) the ongoing programs (e.g., implementation of USI A-46 and the development of individual plant examinations for external events) should adequately limit the risk resulting from, and minimize the severity of, the failure of safety-related bolting in current plants. However, licensees with operating plants could avoid many of the problems recorded in the past by developing and implementing plant-specific bolting-integrity programs that include current requirements and reflect the information and recommendations made by the industry-sponsored program managed by EPRI (with NRC staff exceptions as discussed in Section 3 of this report). New plant licensees, however, could meet stringent bolting requirements with only a very small cost increase if established before they begin operating their plants.

Guidance regarding bolting for staff reviewers in the NRC Office of Nuclear Reactor Regulation (NRR) performing safety reviews of all new nuclear power plants could be provided by a new section in the NRC Standard Review Plan. Such a section, entitled, for example, "Safety-Related Bolting," would expand the limited coverage on fasteners now included in the SRP and provide a

*The Section 1 title is: "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."

systematic method for implementation of the staff position regarding the basis for resolution of GSI 29. As part of the resolution of GSI 29, the staff noted the absence of an SRP section on general reviews of bolting and recommended that one be prepared and issued.

4 REFERENCES

1. U.S. Nuclear Regulatory Commission, "Potential for Low Fracture Toughness and Lamellar Tearing in PWR Steam Generator and Reactor Coolant Pump Supports," NUREG-0577, October 1983.

2. U.S. Nuclear Regulatory Commission, Office of Inspection and Enforcement, "Degradation of Threaded Fasteners in the Reactor Coolant Pressure Boundary of PWR Plants," IE Bulletin No. 82-02, June 2, 1982.

3. U.S. Nuclear Regulatory Commission, "A Prioritization of Generic Safety Issues," NUREG-0933, Rev. 0, November 10, 1982.

4. U.S. Nuclear Regulatory Commission, "Threaded-Fastener Experience in Nuclear Power Plants," NUREG-0943, January 1983.

5. The Electric Power Research Institute, R. E. Nickell, Principal Investigator, "Degradation and Failure of Bolting in Nuclear Power Plants," EPRI NP-5769, Vols. 1 and 2, Palo Alto, California, April 1988.

6. E. I. Landerman et al., "Assurance of Primary Boundary Bolting and Closure Integrity," Westinghouse Owners' Group, Material Subcommittee, Program MUHN 1072, December 1985.

7. R. Rungta and B. S. Majumdar, "Materials Behavior Related Issues for Bolting Applications in the Nuclear Industry," in *Improved Technology for Critical Bolting Applications*, E. A. Merrick and M. Prager, eds., *MPC-Vol. 26*, pp. 39-48, American Society of Mechanical Engineers, New York, 1986.

8. R. Rungta and B. S. Majumdar, "Stress-Corrosion Cracking of Alternative Bolting Alloys," Final Report RP 2058-12, Electric Power Research Institute, Palo Alto, California, March 1986.

9. The Institute of Nuclear Power Operations, "Bolting Degradation or Failure in Nuclear Power Plants," SOER No. 84-5, September 20, 1984. Proprietary Information. Not Publicly Available.

10. U.S. Nuclear Regulatory Commission, "Lower-Bound K_{ISCC} Values for Bolting Materials—A Literature Study," NUREG/CR-2467, February 1982.

11. U.S. Nuclear Regulatory Commission, "Examination of Failed Studs From No. 2 Steam Generator at the Maine Yankee Nuclear Power Station," NUREG/CR-2793, February 1983.

12. U.S. Nuclear Regulatory Commission, "Testing of Nuclear Grade Lubricants and Their Effect on A540 B24 and A193 B7 Bolting Materials," NUREG/CR-3766, March 1984.

13. U.S. Nuclear Regulatory Commission, "Bolting Applications," NUREG/CR-3604, May 1984.

14. U.S. Nuclear Regulatory Commission, "Preloading of Bolted Connections in Nuclear Reactor Component Supports," NUREG/CR-3853, October 1984.

15. C. J. Czajkowski, Brookhaven National Laboratory, letter to Richard E. Johnson, U.S. Nuclear Regulatory Commission, August 4, 1988.

16. L. A. James and W. J. Mills, "Review and Synthesis of Stress Intensity Factor Solutions Applicable to Cracks in Bolts," *Engineering Fracture Mechanics*, Vol. 30 (No. 5), pp. 641-654, 1988.

17. U.S. Nuclear Regulatory Commission, Office of Inspection and Enforcement, "Traceability and Material Control of Material and Equipment, Particularly Fasteners," IE Information Notice No. 86-25, April 11, 1986.

NRC FORM 335
(2-89)
NRCM 1102,
3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG-1339

2. TITLE AND SUBTITLE

Resolution of Generic Safety Issue 29: Bolting Degradation or Failure in Nuclear Power Plants

3. DATE REPORT PUBLISHED

MONTH	YEAR
June	1990

4. FIN OR GRANT NUMBER

N/A

5. AUTHOR(S)

Richard E. Johnson

6. TYPE OF REPORT

Technical

7. PERIOD COVERED (Inclusive Dates)

N/A

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

Division of Safety Issue Resolution
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)

Same as above

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This report describes the U.S. Nuclear Regulatory Commission's (NRC's) Generic Safety Issue 29, "Bolting Degradation or Failure in Nuclear Power Plants," including the bases for establishing the issue and its historical highlights. The report also describes the activities of the Atomic Industrial Forum (AIF) relevant to this issue, including its cooperation with the Materials Properties Council (MPC) to organize a task group to help resolve the issue. The Electric Power Research Institute, supported by the AIF/MPC task group, prepared and issued a two-volume document that provides, in part, the technical basis for resolving Generic Safety Issue 29. This report presents the NRC's review and evaluation of the two-volume document and NRC's conclusion that this document, in conjunction with other information from both industry and NRC, provides the bases for resolving this issue.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

Bolting; Degradation; Failure; Generic safety issue; Resolution; Fastener integrity; Fracture; Fracture mechanics; Corrosion; Stress-corrosion cracking; Nuclear power plants.

13. AVAILABILITY STATEMENT

Unlimited

14. SECURITY CLASSIFICATION

(This Page)
Unclassified

(This Report)
Unclassified

15. NUMBER OF PAGES

16. PRICE