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MEMORANDUM FOR: Richard H. Vollmer, Director
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THRU: William V. Johnston, Assistant Director
Materials, Chemical & Environmental Technology

FROM: B. D. Liaw, Chief
Materials Engineering Branch

SUBJECT: BOLTING DEGRADATION OR FAILURE IN NUCLEAR POWER PLANTS
PROGRAM ACTION PLAN (PROPOSED GENERIC ISSUE NO. 29)

There are numerous bolting applications in nuclear power plants. The most crucial bolting applications are those constituting an integral part of the primary pressure boundary such as closure studs and bolts on reactor vessels, reactor coolant pumps, and steam generators. Failure of these bolts or studs could result in loss of reactor coolant and thus jeopardize the safe operation of nuclear power plants. Other bolting applications such as component support and embed anchor bolts or studs are essential for withstanding transient loads created during abnormal or accidental conditions.

In recent years, the number of bolting-related incidents reported by the licensees of operating reactors and reactors under construction has increased. A large number of the reported bolting incidents are related to primary pressure boundary applications and major component support structures. Therefore, there is increasing concern regarding the integrity of the primary pressure boundary in operating nuclear power plants and the reliability of the component support structures following a LOCA or earthquake. A report summarizing bolting failure experience has been issued.

Because bolting has a wide range of application in nuclear power plants, there is no simple solution to the problem. Therefore, in order to minimize the potential bolting problems in new power plants and to assure adequate performance of essential bolting in operating nuclear power plants, improvements in one or all of the five following areas could be recommended: design, materials, fabrication, installation and inspection.

Many, if not all, of the bolting failures could probably have been prevented if guidelines for design material selection, fabrication, installation and inspection were available and enforced. The anticipated product of this program would be to make available such guidance in the form of a staff technical position paper.

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NUREG-0943 (dated 1/83) reviews a total of 44 bolting incidents reported by licensees of PWR nuclear power plants. A total of 19 bolting incidents were identified as resulting from stress corrosion which, as it turns out, is the most common type of bolting failure. Three bolts failed by fatigue and all were within reactor vessel as part of the internals.

Boric acid corrosion was the second most common type of bolting failure or degradation reported and occurred only in the pressurized water reactor (PWR) because the boric acid is not normally used in the boiling water reactors (BWRs). A total of 12 bolting incidents resulting from boric acid corrosion has occurred. Two bolting incidents resulting from erosion corrosion by boric acid solution have been reported.

A total of eight bolting incidents cannot be classified into the previous categories due to lack of information. A total of 16 of the reported 44 incidents are related to primary pressure boundary bolting applications such as various closure studs in reactor vessels, pressurizers, and steam generators, and holddown bolts in various types of valves. Three of the failures have been reported in BWRs.

The 44 bolting failures identified above have occurred in about 350 reactor-years of experience. Thus, the frequency of corrosion initiated events is 44/350 or 1.3×10^{-1} events/reactor-year.

Based on experience, there is a good chance that the corrosion will be discovered and the studs replaced. However, to be conservative, it is assumed that 10% of the bolts or studs will not be discovered before they fail and result in an (S2) LOCA. Therefore, the frequency is $F = 1.3 \times 10^{-2}$ S2 events/reactor-year.

Most of the 44 reported bolting incidents of NUREG-0943 were discovered either during refueling outages or scheduled inservice inspections or maintenance/repair outages. Therefore, such reported incidents have no immediate impact on public health and safety and the bolting incidents so far have not resulted in accidents. Degradation or failure of such studs and bolts constitutes a reduction in the integrity of the primary pressure boundary. Concern is compounded by the fact that there is currently no reliable NDE method (other than visual) to detect in situ the cracking or degradation of such bolts or studs resulting from the principal modes of failure which are stress corrosion, fatigue, erosion corrosion, and boric acid corrosion.

Visual examination is currently the only reliable method to discover bolting degradation by boric acid corrosion or erosion corrosion. In many cases this requires disassembly of the component in order to inspect the bolting. If there is no clear evidence of boric acid leakage in the surrounding, bolting degradation by boric acid corrosion can potentially be undetected until the bolts or studs completely fail. Under the present in-service inspection program, visual inspection of bolts is a mandatory requirement. However, Section XI of the ASME Code exempts inspection of bolting if insulation must be removed solely for the purpose of performing the inspection. UT inspection is not required on pressure-retaining bolts or studs with diameters less than 2 inches. A major accident such as a LOCA could conceivably occur due to undetected extensive bolting failure of the primary pressure boundary because much pressure boundary bolting is less than 2" diameter.

A total of 13 bolting incidents related to component support structure such as the column support or embed anchor bolts or studs of steam generator, reactor vessel, reactor coolant pumps, and piping restraint have been reported. Although failure of such bolts or studs will not normally impair the normal operation of the plant, extensive failure of such bolts or studs could cause component damage or multiple piping failure under abnormal or accident conditions such as a LOCA or an earthquake.

Failure of bolted connections of pressurized systems is not currently analyzed, although in special situations such as ATWS an analysis was made with one failed stud to see if complete failure would occur. The MEB has stated its belief that the instantaneous unzippering of a series of studs or bolts as used in primary system pressurized bolted connections such as the reactor pressure vessel head, steam generator manways, or on valves or other closures resulting in the closure becoming a missile and the system blowing down through the opening is of a sufficiently low probability so as not to warrant consideration as a design basis accident for the following reasons:

a) Current primary system design practice requires a large margin to failure in each stud. Current criteria for setting allowable stress intensity values are based on 1/3 of the yield strength at temperature. In general, joints can withstand the failure of a large number of studs before the next sound stud exceeds yield. In an analysis performed by CE, it was stated that a symmetrical failure of 3/4 of all studs in a particular steam generator manway cover installation could fail and the cover would remain in place. With random failures, the number would be lower but the cover would remain in place. A similar situation occurs in the case of ATWS on the RPV closure studs and complete unzippering does not occur.

b) In most situations in non-support applications, preload is generally established to produce a stress of about 40% of the yield stress provided the joint is properly made up in accordance with the design specifications. (The design specifications rarely define the method of attaining the desired preload nor do they identify a thread lubricant.)

c) Current design against the effects of postulated pipe break affects the environmental protection of equipment in containment and requires that specific targets be protected from the effects of jet impingement and pipe whip. The postulated failure of a bolted connection would provide another source of blowdown loads and a cover missile.

It is not recommended that this become a design basis accident but it is suggested that attention be focused on the fact that it is vital that plant maintenance personnel follow instructions to be sure that proper gasket material, shape and location is used to prevent the introduction into the joint of undesigned-for bending loads, that lubricant instructions be followed to assure proper joint coefficient of friction and to minimize the stress corrosion initiating effects of certain lubricant elements, and that the proper value of preload is confirmed. Torque wrenches are not usually used on RPV closures. Instead stud tensioners and other methods are employed. It may be advisable to use other methods for establishing preload for large openings such as manways or more closely monitor field situations to verify that proper values of preload can be adequately established with the use of torque wrenches at specific sites. This would not be necessary for smaller bolted connections.

Bolting considered to be essential for plant integrity would be identified by the MEB. Boric acid corrosion of bolting has been investigated by Brookhaven National Laboratory on a contract sponsored by the Chemical Engineering Branch which culminated in NUREG/CR 2827 "Boric Acid Corrosion of Ferritic Reactor Components." ("Ferritic" in this title is, strictly speaking, a misnomer as most nonstainless bolting is Martensitic.)

Development of the technical bases for prevention of stress corrosion failure of bolting application requirements is currently underway by MTEB through its contractor at BNL. This work is being performed to produce a position on the materials, installation and inspection of bolting. Included in this work is consideration of deleterious environments such as embedment in concrete and exposure to various other environments. It is anticipated that materials, installation and inspection would be, to some extent, interrelated and that the position produced would reflect these interrelationships. The work is currently being performed and is divided into tasks or milestones as follows:

1. Convert the information presented in NUREG/CR 2467 to yield strength equivalent (hardness) vs. preload. Such resulting curves would serve to limit preload for a given yield strength. Provide lower limits to preclude plastic tensioning. The curves are self limiting on the upper end.

2. Perform a literature search for information on internals bolting (A286 and Inconel X750) similar to that reported in NUREG/CR 2467 on low alloy and maraging steels. This information need be provided only for air and reactor grade water for PWR and BWRs, but should include oxygen saturation at low temperatures and effect of temperature for operating water conditions.

3. Provide verification that information presented in NUREG/CR 2467 for chlorine is representative of environment of bolting embedded in concrete (i.e., high pH).

4. Review test sample requirements of frequently used fastener specifications and provide recommendations on statistical sampling of fasteners.

5. Provide recommendations for receiving and inservice inspection of bolting. This should include but not be limited to type of inspection, slimness ratio limit for UT inspection.

6. Provide written recommendations for acceptable methods of cottering that would not defeat primary purpose of fasteners.

7. Provide recommendations for writing improvements in bolting and bolting materials specification.

8. Provide a final technical report incorporating the above tasks into a technical position on bolting application requirements, to be issued as a NUREG report by the NRC.

The NRC bolting position will provide guidance in the following areas:

1. Applicability. Guidance will be provided to identify what bolting is required to adhere to the guidance provided.

2. Material. Much of the information on material will be in the form of limit curves plotting bolting material strength against preload in various environments. Additionally, such presentation will accommodate various heat treatments of those alloys that are enhanced by heat treatment because of the plotting by strength.

3. Preload control. Guidance will be provided for various methods of bolting preload control, including the design modifications to bolting which may be necessary to incorporate upgraded preloading techniques.

4. Testing. Guidance will be provided for acceptable sample size for representative testing.

5. Specifications. Guidance will be provided for improvements in specifications of bolting and bolting materials in addition to testing.

6. Cottering. Guidance will be provided on cottering methods that would not defeat the primary purpose of fasteners.

7. Inspection. Guidance will be provided for inspection of bolting and bolting materials . Such inspection would be both upon receipt and inservice. Specific inspection methods would be provided together with possible design modifications to permit improved inspection.

The NRC bolting position will be submitted for review by CRGR with the necessary supporting documents. These supporting documents will consist of the NUREG, the value impact statement, and the risk assessment.

Upon approval of the package and issuance of the bolting position and the implementation plan, proper enforcement of the provisions of the NRC bolting position should radically reduce the problem of bolting degradation or failure in nuclear power plants by providing information on design, material, selection, fabrication, installation and inspection of designated bolts.

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