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REVIEW OF INSERVICE INSPECTIONS OF GREASED TENDONS IN PRESTRESSED-CONCRETE CONTAINMENTS*

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Abstract

Prestressed-concrete containments in the United States using greased prestressing tendons are inspected periodically to ensure structural integrity and to identify and correct problem areas before they become critical. Currently, these inspections are conducted in accordance with the Nuclear Regulatory Commission (NRC) Regulatory Guide 1.35 (Rev. 2), which contains guidelines for sample selection, visual inspection of anchorage components, monitoring of prestress force, analysis of the grease for impurities, and tensile testing of the tendon material. Due to varying interpretation by the utilities of the current version of the Reg. Guide, the NRC has developed a proposed third revision to Reg. Guide 1.35 along with a proposed companion guide, Reg. Guide 1.35.1. The American Society of Mechanical Engineers (ASME) also has been developing a proposed set of rules for examination of prestressed-concrete containments with unbonded tendons for inclusion in Section XI of the ASME Boiler and Pressure Vessel Code.

In the study, an analysis of the available utility inspection data and an evaluation of the current and proposed guidelines were conducted to provide a measure of the reliability of the inspection process. Comments from utility and industry personnel were factored into the analysis. The results indicated that the majority of the few incidences of problems or abnormalities which occurred were minor in nature and did not threaten the structural integrity of the containment. All of the available inspection reports concluded that the respective containments were in good condition. However, the reports did reveal discrepancies between utilities in the interpretation of the results. Evaluation of the proposed guidelines also revealed areas that could be modified to provide improved results; that is, some consideration should be given to modifying the sample size, the tendon force levels should be evaluated both as a group and individually, and the acceptable levels of impurities in the grease should be re-examined as more data become available. Additional research on the long-term effects of the impurity levels and grease degradation due to aging on the effectiveness of the grease could help identify potential problems. Furthermore, because only a limited amount of data was available during this study, perhaps the most-important suggestion is that more data should be examined before firm conclusions are drawn. And there should be a continuing effort to utilize the information gained through containment-inspection experience.

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1. Introduction

A large percentage of operating nuclear power plant stations in the United States use a prestressed concrete containment structure. Virtually all of these structures make use of post-tensioned unbonded prestressing tendons coated with some type of corrosion inhibitor. The principal functions of these structures are to (1) provide the reactor coolant system with protection for such potentially disastrous events as aircraft impact, wind-generated missiles, and earthquakes, and (2) prevent the release of radioactivity in the event of a loss-of-coolant accident [1]. Because these functions are safety related, the *Code of Federal Regulations* requires in part that the containment be designed to permit a periodic inspection of all important areas and that an appropriate inspection program be developed [2].

To aid in the development of an inspection program, the U. S. Nuclear Regulatory Commission (NRC) issued a Regulatory Guide that described the basis of an acceptable program. The guide sought to examine all sources of potential problem areas such as tendon corrosion, anchorage failure, and material defects before they became critical. As experience with the inspections mounted, the guide was revised to keep pace with technological advances in containment design, to reflect the knowledge gained through experience, and to eliminate points of confusion concerning interpretation and implementation of the guide. The version of the guide currently in effect is Regulatory Guide 1.35 (Rev. 2) [3].

A third revision to the guide [4] has been proposed in order to update the guide based on experience and to clarify recurring points of confusion. In fact, various interpretations of the prestress force acceptability prompted the NRC to propose a companion guide, Regulatory Guide 1.35.1 [5]. In addition, an industry-generated standard concerning inservice inspection of prestressed concrete containments is under development in the form of a proposed draft subsection of Section XI of the "American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code" [6].

The basic aspects of an inspection include: (1) the selection of a random sample of tendons to be inspected, (2) a visual inspection of the anchorage components, (3) the measurement of the prestressing force, (4) obtaining a sample of the corrosion inhibitor for analysis for impurities, and (5) the removal of a wire sample for material property determinations. Allowable limits are indicated in each of the guidelines to determine the acceptability of an inspection.

Inspection data were obtained through the NRC for a limited number of plants. Only three utilities provided reports thorough enough to permit a detailed evaluation. These data were analyzed, and both the industry and government guidelines (proposed and existing) were reviewed to determine the reliability of the inspections [7].

2. Sample Size

Under Reg. Guide 1.35 (Rev. 2), the sample size during the first three inspection periods for a typical (shallow dome) containment is composed of six dome tendons (two from each 60° group or three from each 90° group), five vertical tendons and ten hoop tendons. For a hemispherical dome containment, the criteria are 4% of the inverted-U tendon population but not less than four, and 4% of the hoop tendon population but not less than nine. Both the ASME Section XI draft and Reg. Guide 1.35 (Rev. 3) proposed criteria for the first three inspections are 4% of the total tendon population of each tendon family with a minimum of four and a maximum of ten from each family. No distinction is made in the proposed criteria between typical and hemispherical dome containments. In all instances, the sample size may be reduced (to approximately 2%) after the third inspection, provided no problems were found.

The information reviewed during this study indicates that, for the most part, the utilities are following the recommended sample size criteria. One problem, however, has been the practice of using the same tendons in each inspection rather than selecting a new sample. This practice defeats the intent of random sampling the entire tendon population (or as much as possible) over the life of the plant.

2.1 Statistically Based Requirements

To examine the suitability of the sample sizes recommended by the NRC, a statistical analysis of the available data was undertaken. Two questions were posed at the outset of the analysis: (1) are enough tendons being sampled for the containment prestressing level to be known with a high degree of confidence and (2) given that several defective tendons exist in the population, what is the probability that at least one will be included in a sample of the specified size? A defective tendon is defined here as any tendon that is unacceptable according to Regulatory Guide 1.35.

To answer the first question, the mean and standard deviation for each sample was calculated for the available inspection force data. A 95% confidence interval was defined for the mean of the population from which each sample was drawn, and a measure of the precision of the confidence interval was defined as one-half the width of the interval divided by the sample mean and expressed as a percentage. A small percentage indicates a high level of precision or a narrow confidence interval which, in turn, indicates a high degree of confidence in the information obtained from the sample. The results for various sample sizes are shown in Table I and in all but one case, the precision is very high. Thus, the sample sizes employed were adequate for determining the containment prestressing level with a high degree of confidence.

To answer the second question, the hypergeometric distribution [8] was used to calculate the probability of including at least one defective in the sample for sample sizes 2, 4, and 8% drawn from populations containing 5, 10, and 20 randomly scattered defectives. The probabilities varied slightly depending on the population size chosen, with the larger population sizes having lower probabilities than the smaller sizes. Therefore, an upper bound on the probabilities was defined as the value computed for the smallest population size considered, which was 100. The results are tabulated in Table II and indicate low probabilities for all cases except the sample size of 8% with 20 defectives.

Another aspect of this problem concerns the probability of including at least one defective tendon in the sample if all of the defectives are grouped together in one area, which is a situation that is more likely in a containment. To determine this probability, a simplistic approach was adopted. A populatic size of 100 tendons was assumed. For the case of 5 defective tendons grouped together, this population was assumed to be composed of 20 groups of 5 tendons each with 19 of the groups containing none of the defectives and one group containing all of the defectives. For the sample size of 2%, two tendon selections will be made from the 20 groups. Each group has an equal probability of being selected, namely 0.05. Therefore, if two selections are made, the probability that at least one selection will be made from the group of defective tendons is 0.10. The results for sample sizes 2, 4, and 8% from populations containing 5, 10, and 20 defectives that were assumed to be to be grouped together are shown in Table II. For most cases, these results represent a significant improvement over the results for the randomly scattered defectives. However, the chances of uncovering at least one defective tendon during an inspection with the recommended sample sizes of 2 or 4% are not very good, unless a large number of defective tendons exist in the population.

2.2 Performance-Based Requirements

The statistically based requirements did not include in the analysis either the evolution of prestressed concrete technology, quality control, and quality assurance programs, or the history of proven performance of prestressing tendons in structures over the past decades. Therefore, an overview of the performance of prestressing in structures applications was conducted. Results of the overview revealed that coincidences of prestressing tendon corrosion were extremely low, on the order of 0.0007%. This result indicates that the proposed criteria of monitoring 4% of the population of each tendon family (minimum of 4 from each group) for the first three inspections, followed by a drop to 2% in future inspections if no abnormal degradation was uncovered, are reasonable. In fact, the performance of tendons has been so good that consideration could be given to a reduction in these levels. Sufficient data appear to demonstrate the proven performance of prestressing tendons to indicate that the 2% sampling criteria of future inspections, intended primarily to detect material degradation, could probably be relaxed to 1% (minimum of 2-3 tendons from each family). Because the first few inspections are conducted primarily to identify construction defects, the 4% criteria should probably remain at that level until a larger performance sample can be obtained to form a basis for a reduction of the sample size requirements. Where defects have been identified, they were generally the result of construction practices.

3. Monitoring of Prestress

The prestress level in a tendon is typically determined by measuring the force required to lift the anchor head off the shims thereby transferring all the stress to the jacking equipment. According to Reg. Guide 1.35 (Rev. 2), the containment force level is acceptable if the force levels in all the tendons in the sample are within the limits of expected behavior. Knowing the original stressing force and the stressing sequence, a reasonable approximation of the tendon force level can be made, thereby defining the limits.

Proposed Revision 3 to the Reg. Guide follows the same methodology as Revision 2 but specifies acceptable methods for calculating the expected prestress losses through proposed Reg. Guide 1.35.1. As before, only individual forces are examined in determining containment acceptability. However, the ASME approach considers both individual force levels and the average force level. The average of all the tendon forces in the sample of a certain type of tendon must be equal to or greater than the minimum required prestress level for that type.

The principal differences between the utilities' inspections concerned the acceptability of the prestress force. The data examined indicated that the utilities are attempting to determine the acceptability of the prestress forces on a fair and rational basis. However, the methods are sufficiently different as to cause some concern that the containments are being incorrectly evaluated.

3.1 Individual Force

The force level in an individual tendon at some time is acceptable if it is equal to or greater than the expected force level at that time. The expected force level is calculated from the original stressing force and the assumed losses due to creep, shrinkage, and stress relaxation. If the tendon force level is below the expected level, the indication is that the losses are greater than expected which may imply abnormal degradation of the containment. If no abnormal behavior is detected, then the containment is assumed to have adequate prestressing force. The benefit of examining individual tendon forces is that abnormal degradation will be observed more quickly than if only average force levels are examined.

3.2 Average Force

A criteria that the average of the forces be equal to or greater than the minimum required prestress force indicates that at the time of the inspection the containment can withstand the maximum design loads safely. However, it will not provide an indication of the trends in the behavior of the tendon system. The fact that some individual tendon forces may be less than their respective lower bounds is cause for some concern but may not be cause to consider the containment structurally unacceptable.

The detection of abnormal behavior of individual tendons serves to indicate that some containment tendons are not behaving as expected, but the containment may still have an adequate prestressing level to be considered safe. But more importantly, if no abnormal behavior is detected, the indication is only that the containment tendons are behaving as expected. Certainly, the implication here is that the containment has an adequate level of prestress because the tendons are behaving as expected. But in this instance, the adequacy of the containment at the time of the inspection has been implied only and not directly extablished. Therefore, evaluating the force level in a containment can best be accomplished by both computing an average value of the tendon forces for comparison with the required force level and by comparing the individual forces with their respective lower bounds.

4. Corrosion Inhibitor

Revision 2 of Regulatory Guide 1.35 recommends that a sample of corrosion inhibitor, or grease, from each tendon in the inspection sample be analyzed. The results of the analyses are to be compared with the original grease specifications to determine acceptability. Also, the presence of voids in the grease is to be noted. The limits on the impurities are 10 ppm on the quantity of water-soluble chlorides, nitrates, and sulfides.

The proposed Revision 3 to Reg. Guide 1.35 basically maintains the same criteria as Revision 2. However, the proposed ASME Section XI draft adopts the limits on the impurities of the grease as installed and proposes two additional criteria: a water content limit of 10% of the dry weight of the grease and a limit on the total base number of the grease. The total base number provides an indication of the relative amounts of acidic or basic constituents in the grease.

For a grease sample that is neutral (neither acidic nor basic), the total base number is 0 because no basic constituents are present in the grease. A total base number >0 represents a basic sample, and the higher this number, the more basic the sample. On the other hand, a number of <0 represents an acidic sample, with acidity increasing as the number becomes more negative. The ASME proposal requires that the total base number be at least 50% of the as-installed value, unless this value is ≤5. In that case, the total base number will not be <0. If the duct is filled with a mixture of materials with different as-installed base numbers, the lowest number will govern.

The available inspection data indicate that the utilities are examining the grease in a responsible manner. No significant corrosion has been reported, which implies that the grease is performing effectively. In one instance, a utility noted a large discrepancy between the amount of grease removed and the amount required to refill the duct. The subsequent investigation revealed that the problem was not confined to just one tendon and apparently was the result of incomplete initial filling of several ducts. Still, no significant amounts of corrosion were evident.

4.1 Voids

When the grease is installed, it is pumped into the duct at a temperature around 93°C (200°F) to ensure adequate coverage of the tendon wires. The temperature of the grease is much less [<46°C (115°F)] during normal plant operation; as the grease cools, it contracts and forms voids. Experiments performed under extreme temperature ranges have indicated that the voids form in the body of the grease, not against the duct or the tendons. Therefore, even for large temperature changes, the tendons remain sufficiently protected as long as the duct was completely filled with grease. Thus, the presence of voids due to thermal effects may not necessarily be critical.

4.2 Impurities

To provide an indication of the amounts of impurities being found, the results of the laboratory analyses of the grease for the inspections were combined. These results, which represent the reported amounts of water-soluble chlorides, nitrates, and sulfides, and water content, showed that the grease impurities in these instances were well within the 10 ppm limits. In fact, practically all of the impurities were found to occur in amounts <2 ppm.

Although experience with the corrosion-inhibiting greases is mounting, determination of the potential for the corrosion of a greased tendon is still a difficult problem. Laboratory studies indicate that the grease provides positive protection from corrosion when properly applied, even if impurities are present at low levels [9, 10]. Experience with existing containments further indicates that the grease is effective in inhibiting corrosion [11]. However, limiting the water content and the water-soluble chlorides, nitrates, and sulfides may not be sufficient. Because a basic environment reduces the potential for corrosion, the proposed ASME Section XI draft incorporates a limit on the total base number of the grease. Adherence to this limit will help to ensure a basic environment and therefore lessen the potential for corrosion. However, it is difficult to predict what amount of corrosion would occur as the amounts of the impurities approach the ASME-proposed limits. In short, too little information exists on the long-term effects of these impurities to make a firm decision regarding their respective limits. The major source of information regarding corrosion of prestressing tendons probably will be the containments as they are evaluated during each inspection period. Thus, it should be clear that additional research is needed in this area.

5. Anchorage Components

The anchorage components are subjected to a visual examination which entails a general examination of the components and the concrete in the vicinity of the anchorage. Both the ASME and the NRC guidelines call for visual inspection with the intent being to detect corrosion of the anchorage components, grease leakage, and excessive cracking of the concrete. In most instances, the utilities also check for missing, cracked, and off-size buttonheads.

The data available during this study indicate that the visual inspections have revealed problems. Buttonheads were found to be missing in sufficient quantity in at least one instance to require replacing the tendon. Although many comments reflect the attitude that the presence of split buttonheads is not critical because a positive anchorage is maintained due to the compressive forces acting on the buttonhead, there is no assurance that these buttonheads will allow the tendon to develop its full capability during an accident or environmental phenomena (such as an earthquake or tornado). Also, serious grease leakage has occurred in at least three instances, typically through construction joints or cracks in the concrete. Thus the visual inspections of the anchorage components have uncovered problem areas, which, if undetected, could jeopardize the integrity of the tendon system.

6. Summary

A review of available utility data indicates that the utilities are making a conscientious effort towards containment inspection. The majority of the problems or abnormalities documented were minor in nature, and all of the inspection reports concluded that the respective containments were in good condition after necessary repairs and corrections.

Concerning the existing and proposed guidelines, if sampling requirements are dictated on a purely statistical basis, the guidelines are adequate with respect to providing high confidence in the containment force level; but for the required sample sizes, the probability of including at least one defective tendon in the sample when several defective tendons exist in the population is low. Unfortunately, the statistical evaluation did not include the effects of past prestressing tendon performance that generally have been exemplary in both civil engineering and nuclear power plant structures. Experience indicates that the required sampling sizes may be cautiously reduced from the presently recommended levels. This is especially true for the inspections intended to detect material degradation, but the 4% criteria of the initial inspections designed to detect construction defects should probably remain. Also, it is beneficial to evaluate tendon-force measurements both as a group by averaging the values and individually by computing lower bounds. Voids in the grease created by thermal effects do not appear to be critical because the tendon remains coated by the grease. Additional research in the area of long-term effects of impurities on the effectiveness of the grease as a corrosion inhibitor is necessary; and some means of evaluating the relative acidity or alkalinity of the grease should be employed, such as the method of calculating the total base number of the grease.

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Table I. Measure of the precision of the confidence intervals

Tendon Family	Sample size %[a]	Precision %
Vertical	2	4.4
Vertical	4	4.3
Vertical	5	3.0
Dome	2	11.8
Dome	8	1.4
Dome	7	0.5
Hoop	1	0.8
Hoop	8	1.1
Hoop	5	2.4

[a]Sample size is expressed as an approximate percentage of the total population size.

Table II. Probability of including at least one defective in the sample.

Sample Size %[a]	Number of defectives	Probability[b] if defectives are: Randomly scattered	Grouped together
2	5	0.10	0.10
2	10	0.19	0.20
2	20	0.36	0.40
4	5	0.19	0.20
4	10	0.35	0.40
4	20	0.60	0.80
8	5	0.35	0.40
8	10	0.60	0.80
8	20	0.85	1.00

[a]Sample size is expressed as a percentage of the total population size.

[b]Based on population size of 100.