EFFECTIVENESS OF INSERVICE INSPECTION REQUIREMENTS OF PRESRESSED CONCRETE CONTAINMENTS - U.S. EXPERIENCE

H. Ashar and D. Jeng *

ABSTRACT

In the United States, the prestressing tendon components of all the prestressed concrete containments are required to undergo periodic inspections. The paper describes various provisions of these inspections, and the changes thereof which have been implemented since the beginning of the use of prestressed concrete in containments of the commercial nuclear power plants. The paper discusses, in some detail, the regulatory concerns and the impact of public input in promulgating the provisions of the inspections. It describes briefly the provisions developed for inspecting the containments whose prestressing tendons are proetected from corrosion by means of cement grout. It describes the effectiveness of these provisions in terms of assessing the continued integrity of the containments. It also describes some of the difficulties associated with the inspection of greased prestressing tendons.

In addition, the authors have indicated how new designs can benefit from the experience with the use of prestressed concrete in U.S. containments.

* U. S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation
Washingon D.C. 20555.

Note: The opinions expressed in this paper are those of the authors, and do not necessarily reflect the position of the agency.

EFFECTIVENESS OF INSERVICE INSPECTION REQUIREMENTS OF PRESTRESSED CONCRETE CONTAINMENTS - U.S. EXPERIENCE

H. Ashar and D. Jeng

INTRODUCTION

The principal use of prestressed concrete in U.S. nuclear power plants(NPPs) is in the construction of their containments. The containment, a vital engineering safety feature of an NPP, is designed to withstand the postulated accident loadings as well as the loadings from low probability (i.e., <10E-4) environmental events, such as earthquakes, tornadoes, floods, seiches and tsunamis. The prestressing of a containment plays a significant role in resisting the effects of the postulated loadings. Also, the precompression provided by prestressing keeps the cracking of concrete to a minimum level, thus reducing the ingress of potentially harmful environmental elements. The hardware (tendon wires, strands, and bars; anchorage components; bearing plates; and corrosion inhibiting medium), providing prestressing to the conainment, is thus considered as the principal strength element (along with the concrete and reinforcing bars) of a prestressed concrete containment (PCC). Its integrity need to be monitored on a periodic basis. In the United States, all PCCs are required to have their inservice inspection (ISI) at scheduled intervals.

There are 44 PCCs in the United States, that is approximately 35% of the total number of containments. Two PCCs are prestressed in the vertical direction only. The vertical prestressing tendons of one of these PCCs is coupled to the grouted rock anchors in the tendon gallery. The prestressing tendons (consisting of bars wih swaged anchors) of the second PCC are grouted. This is the only PCC of an operating reactor that has grouted tendons. The tendons of the containment at Three Mile Island, Unit 2 are also grouted, but the reactor has not been in operation since the accident in 1979. The tendons of all the other PCCs are protected against corrosion by means of corrosion-inhibiting grease.

The tendon configuration in a typical PCC consists of vertical and hoop tendons in the cylinder, and of dome tendons in the shallow dome. In some later designs, the vertical and dome tendons are replaced by inverted-U tendons. In one design, the vertical and hoop tendons in the cylinder are replaced by helically wound tendons in two perpendicular directions. Figure 1 shows some of the common configurations.

DEVELOPMENT OF ISI PROVISIONS

Grouted Tendons

Because grouted tendons cannot be inspected directly, a number of alternative methods of assessing the integrity of the containments with grouted tendons were investigated in the early 1970s, when some utilities were exploring the use of grouted tendons for their PCCs. Some of the alternatives considered were the following: (1) provision of instrumentation for reinforcing bars, tendons, and concrete to monitor stresses and strains; (2) use of load cells on tendons to directly monitor the changes in prestressing forces; (3) use of strategically located ungrouted tendons to monitor general prestressing level in the PCC; and (4) pressure testing of containments to monitor the changes in their deformation characteristics. After a number of public meetings and discussions among knowledgable professionals, the final provisions for inspecting the PCCs with grouted tendons were promulgated in Revision 1 of Regulatory Guide (RG) 1.90 (Ref. 1). Two distinct alternatives are provided in the guide. The first alternative would require the monitoring of prestress level by means of strategically located instrumentation (strain gages, stress meters, load indicators, etc.). The second alternative would require the monitoring of deformations of the PCCs at critical locations under prescribed pressures. The monitoring of prestressing forces in strategically located ungrouted tendons, and visual examination of tendon-anchorage areas and structurally critical areas are the common inspection provisions for both the alternatives. It was also recognized that filling the long, tightly packed, curved tendon ducts with quality grout would require careful planning and utmost attention in proportioning, mixing and injecting the grout. Regulatory Guide 1.107 (Ref. 2) was issued to provide guidance that would be useful in developing appropriate grouting procedures. The objective of such procedures would be to ensure that the tendon ducts were properly filled with quality grout.

Except for the two PCCs mentioned previously, none of the PCCs in the United States have been grouted or inspected using these provisions.

<u>Greased Tendons</u>

The inservice inspection requirements for the earlier PCCs (i.e., licensed before 1973) with greased tendons were developed on a case-by-case basis. In general, however, the inspection would consist of (1) monitoring nine preselected tendons and (2) visual examination of the exterior of the containment. The inspections are to be performed more frequently during the earlier years (typically the first five) and less often during the later years. The practice of fixed-tendon inspection was a subject of considerable discussion in the early 1970s. A number of industry professionals and the regulatory staff members felt that monitoring the same 9 tendons out of approximately 1300 tendons would not provide confidence in the condition of the entire tendon population. It was also recognized that repeatedly tensioning and detensioning the same tendons during all inspections would result in the deterioration of the condition of these tendons. The consensus was that to have an effective inspection program, it is necessary to inspect the tendons in a random but representative basis. The relevant question was, "What would be the size of the random sample that would ensure a reasonable confidence in the integrity of the tendons?" A crude and purely statistical consideration to ensure 95% confidence that no more than 5% of the tendons could be defective (defined here as tendons whose measured prestressing forces are lower than the predicted values) required the inspection of 63 tendons selected randomly during each inspection. This was considered as too costly a proposal for the relatively passive (as compared with for example, pumps and valves) component of the containment. After a number of discussions with industry groups and after taking into consideration the performance of prestressing systems in other civil engineering structures, it was decided to inspect 21 tendons during the first three inspections. If no significant problems were found with the integrity of the prestressing system during these inspections, the subsequent inspections were to be performed with a reduced sample size. The first effective issue, i.e., Revision 1 of Regulatory Guide 1.35 (Ref. 3) incorporated the concept in which 21 tendons (10 hoop, 5 vertical, and 6 dome) were to be inspected during the first three inspections, and 9 tendons (3 from each group) during the subsequent inspections. Additionally, the regulatory guide provided for (1) the inspections of tendon-anchorage areas, (2) checking for grease coverage in the selected tendons, and (3) testing for the material properties of the prestressing elements removed from the tendons. The chemical and physical properties of grease samples were to be checked against the construction specification. The visual examination of the exterior containment surfaces was to be performed during the periodic integrated leakage rate testing, when the containment is at its maximum test pressure. These provisions were formulated for shallow-dome containments where the tendons are distinctly grouped as hoop, vertical, and dome tendons.

In the mid-1970s, a new concept (Type III, Figure 1) with regard to the containment tendon configuration was developed. The tendons consisted of two groups: the hoop tendons and the inverted-U tendons. A typical inverted-U tendon is anchored at diametrically opposite ends in the tendon gallery, and approximately follows the configuration of the containment in the vertical plane passing through the anchor points. The concept eliminated the need for a ring girder required for the transition from shallow dome to cylinder and for anchoring the dome tendons. The concept also incorporated two other changes: (1) the hoop tendons were made longer, anchoring them at 240 degrees rather than at 120 degrees, thus reducing the number of buttresses required to anchor the hoop tendons from six to three, and (2) large tendons with ultimate capacities approximately twice those of the tendons in the older configuration were developed. The combined effects of the development was to reduce the required number of tendons to about one-third of that required in the older configuration. To accommodate this development in the ISI provisions, Revision 1 of RG 1.35 was modified to include the sample-size requirement for the new configuration based on the percentage of tendons in the group population. Revision 2 of the guide (Ref. 3) includes such provisions.

IMPLEMENTATION OF ISI

An inspection of a typical tendon consists of removing the grease caps at two ends, collecting the grease for examination and testing, measuring the existing prestressing forces at the two ends, detensioning the tendon, removing a prestressing element (wire or strand) for examination and testing, examining anchor heads and bearing plates, reinstalling the tendon at the required prestressing levels, installing the grease caps, and injecting the required amount of grease. Additionally, the inspection includes a thorough visual examination of the concrete around the anchorages.

In implementing Revisions 1 and 2 of RG 1.35, a number of issues related to the appropriateness of some of the provisions in the guide became apparent. The issues and their resolution are discussed in the following paragraphs.

Tendon-Sampling Criteria

Because of the new developments in regard to tendon capacity and tendon configuration (i.e., Type II and Type III in Figure 1), the applicability of the sample size based on the Type I configuration needed reevaluation. Various proposals were considered. In one proposed concept (Ref. 4), the variable sampling procedure of Reference 5 was used. The proposed procedure consisted of (1) selecting a sample size 'n'; (2) estimating the percent defective 'p', based on sample statistics; and (3) comparing 'p' with the maximum allowable percent defective 'M'. If 'p' is less than or equal to 'M', all the tendons represented in the sample are acceptable. After studying this proposal, the regulatory staff, and the industry group (American Society of Mechanical Engineers) working on the rules for ISI of containments felt that the proposal incorporated a number of new elements which may not be quite adaptable to the tendon evaluation. Finally, a consensus was reached, whereby the sample size based on the percentage of the tendon population was accepted. Thus, for the first three inspections, 4% of the tendons in each group would be inspected, with a minimum of four tendons, but the number need not exceed ten. For the subsequent inspections, a reduced sample of 2%; with a minimum of three tendons was accepted. This position is reflected in proposed

Revision 3 of RG 1.35 (Ref. 3) and in Subsection IWL of the ASME Boiler and Pressure Vessel Code, Section XI (Ref. 6).

Detensioning of Tendons

Revisions 1 and 2 of RG 1.35 recommend that all the selected tendons be detensioned, and that a sample wire or strand from one tendon in each group be removed and tested for its physical properties. The experience with this aspect of the inspection indicated that the process of detensioning and retensioning of tendons is expensive, time consuming, and probably detrimental to the integrity of the tendons. However, it was necessary to assess the change in the physical properties of the tendons as a result of various exposures. Thus, Revision 3 of RG 1.35, and Reference 6 require that one tendon in each group be detensioned during each inspection.

ISIs of Two PCCs at the Same Location

During the development of the ISI provisions in Revisions 1 and 2 of the guide, it was stipulated that if two PCCs of similar characteristics were built at a site using the same type of hardware, and by the same contractor, the tendons in both the containments could be considered to constitute one single population. In that case, the sampled tendons of one containment were required to be fully inspected as provided in the guide. The sampled tendons of the second containment were required to have a thorough visual examination without dismantling the load-bearing components of the tendons. Experience, however, indicated that although the concept of tendons being from the same population had validity, the assumption that any significant problem in the second containment could be detected by the guide's provision was questionable. Thus, in proposed Revision 3 of the guide, when there are two containments at a site, both the containments are required to be subjected to complete inspections on an alternating basis. Figure 2 shows the schedule of inspection for each containment.

Comparision of Measured Prestressing Forces

In reviewing the procedure by which the licensees were implementing the provisions of the older versions (Revisions 1 and 2) of the guide in accepting the adequacy of the measured prestressing forces, it was found that the average of all measured forces were compared against the minimum required prestressing forces for the specific group of tendons. This practice is considered as unacceptable. To understand the behavior of the tendon population from the evaluation of a small number of sampled tendons, it is necessary to evaluate each tendon on the basis of its own predicted prestress force at the time the comparision is made. Determination of the predicted prestressing force in a tendon requires (1) documentation of its seating forces (at two ends), (2) calculation of its elastic shortening loss, (3) Calculation of its time-dependent losses, and (3) an estimation of uncertainties in the calculations. To provide guidance in determining the predicted forces in tendons, the NRC staff developed Regulatory Guide 1.35.1 (Ref. 7). The procedure recommended in the guide requires the construction of a tolerance band based on the estimated uncertainties in the loss calculations. If the measured prestressing force of a tendon falls within the established tolerance band, the tendon behavior can be considered as expected. The detailed acceptance criteria related to the measured prestressing force are delineated in Revision 3, of RG 1.35 and Reference 6.

Examination and Testing of Grease

The earlier versions of RG 1.35 (Revisions 1 and 2) basically required a general examination of the grease samples and testing them to ensure compliance with the original grease specifications. In some of the reported incidents, the original grease specifications differed appreciably from plant to plant. At least three types of grease formulations are used in the PCCs. To provide consistent criteria against which the results of the testing of the grease samples can be compared, Revision 3 of RG 1.35 delineated the acceptance criteria related to the contaminants and water in the grease. It also was reported that the exterior surfaces of some PCCs had indications of grease leakage through concrete. Such grease leakage is of concern because in a significant quantity grease in concrete can contribute to the reduction in the concrete strength and bond strength of reinforcing bars. To monitor such grease leakage from tendon sheathing, the revised guide requires the monitoring of grease voids (i.e., the difference in the quantities of the grease removed and that reinjected).

REPORTED INCIDENTS AS A RESULT OF ISIs

In general, the material and construction procedures are well scrutinized during the development of the prestressing systems to be used for PCCs. However, there were occasions when either because of the breakdown of quality control or because of construction activities that were not scrutinized, significant component failures had occurred and were discovered during the construction of PCCs. These incidents are summarized in Reference 8.

The incidents reported as a result of inservice inspections of PCCs are discussed below.

Low Prestressing Forces

In one case, the measured prestressing forces in hoop tendons consistently showed lower prestressing forces than those predicted to occur at forty years. The occurrence took place only about three years after the post-tensioning of the containment. A number of contributing factors were identified: (1) improper calibration of jacks during initial post-tensioning operation, (2) higher-than-assumed losses resulting from the concrete creep and steel relaxation, and (3) general breakdown of quality-control during the post-tensioning operation. A large number of hoop tendons were found to be affected by this occurrence. All the affected tendons were examined for evidence of broken and nontensioned wires. The tendons were reseated to the required prestressing forces.

In another case, vertical greased tendons coupled to the grouted rock anchors consistently showed lower prestressing forces than the predicted. A further investigation of the cause of this occurrence indicated that the tendon wires were relaxing to a greater degree than that assumed in the design. The tendons were retensioned to the required prestressing force levels and monitored thereafter at a shorter interval than the scheduled interval.

In a few other cases, the measured prestressing forces indicated higher than assumed losses. When the measured prestressing forces from all (the first three) inspections were extrapolated, the trend indicated that the life-time (generally 40-years) losses would occur in the first 10 years. In each of these cases, when the measured prestressing forces were adjusted to allow for 2% measurement error, the extrapolated trends improved significantly. In all these cases, the average of the measured prestressing forces had sufficient margins over the required. The licensees, however, were requested to monitor these trends carefully during subsequent inspections.

Buttonhead Deficiencies

During a number of inspections, tendons with ineffective wires have been found due to the buttonhead deficiencies, such as (1) missing buttonhead, (2) protruding buttonhead, (3) cracked load bearing buttonhead, or (4) offsize malformed buttonhead. Systematic procedures are set up to identify these deficiencies during inservice inspections and to evaluate their effect on the integrity of the affected tendons. Most designers allow for ineffective wires (between 1% and 2%) in the PCC design. However, if the cracking or other indications are related to corrosion or potentially progressive corrosion, the occurrence is investigated in order to understand the cause and extent of such corrosion. One important consideration, when more than allowable number of wires are found to be ineffective, is to ensure that the remaining wires are not overstressed [i.e., stressed to a level that is more than 70% of the guaranteed ultimate tensile strength (GUTS) of the wires].

Grease Deficiencies

In general, the greases (various formulations) used in PCCs have performed well. However, grease contamination has been reported in a few plants. The main contaminant is chloride ion. Generally grease used in PCCs contains less than 5 parts per million (ppm) of chloride ion. However, in the reported cases, the choride ion was twice the allowable value of 10 ppm. In these instances, the contamination was attributable to the presence of rain water in the grease caps. Neither the tendon wires nor the tendon anchorages showed any adverse effects.

Low Strengths of Tendon Wires

Three separate incidents have been reported where the stressed wires removed from the inspection tendons, when tested for yield strength and ultimate strength, showed ultimate strength that was lower than the corresponding GUTS. In all the cases, the low strengths could be attributed to (1) the handling of wires while they were being removed from the tendons, (2) the additional stresses induced by coiling, and (3) an eccentricity in the testing machine. The deviation from GUTS was less than 3%. Also, wires of other groups of tendons tested during the same inspection did not exhibit low strengths. The deviations reported thus far are not considered significant enough to affect the integrity of the PCCs.

Grease Leakage in Concrete

Grease streaks on the exterior concrete surfaces of PCCs have been found at a few Plants. The leakage of grease from tendon sheathing or from the joints between the sheathing lengths could be conceived as the only reason for such occurrences. The grease leaking through the sheathing (or its joints) could find its way to the exterior or interior surfaces of the containment through cracks and crevices in the concrete. The most likely period when the grease could be extruded from the sheathing would be during the injection or reinjection of the grease under significant pressures. This is an area of concern for the NRC regulatory staff. To reduce the adverse impact of reinjection of the grease during an ISI, Revision 3 of RG 1.35 recommends the use of low reinjection pressures. The guide also recommends the monitoring of the amount of grease removed and that reinjected. An excessive difference in these quantities (defined as % of voids in Revision 3 of the guide) could be indicative of grease leakage through the sheathing. Better methods of monitoring internal grease leakage, its causes and the potential impact of such leakage require further studies. At present, however, the PCCs with such problem are closely monitored.

OTHER SIGNIFICANT EVENT

In addition to the incidents reported as a result of inservice inspection, a significant event was reported in January 1985. During a routine visual examination before the integrated leakage rate testing of the Unit 2 containment at Farley Nuclear Power Plant, it was discovered that the grease cap of the shop-end of a vertical tendon was deformed. When the other end (the field-end) of the tendon in the tendon gallery was opened for inspection, it was found that the anchor head was broken, allowing the tendon to detension completely. An extensive investigation conducted to understand the cause and extent of the occurrence showed that two additional anchor heads were broken, and the tendons were completely detensioned. The anchor heads of 23 other tendons (17 in Unit 2, 6 in Unit 1) were found to have cracks. The factors contributing to this event can be summarized as (1) high hardness material of the anchor heads, (2) free water in the grease caps, and (3) high stresses in the anchor heads. All the broken and cracked anchor heads were replaced with new anchor heads, and the tendon inspections were performed at shorter intervals. Similar incidents were reported during construction at other two plants (Ref. 8).

The following actions are taken as preventative and monitoring measures.

1. Regulatory Guide 1.136 limits the hardness of the material used for highly stressed elements, such as anchor heads, wedges, and wedge blocks.

2. Free water found in the grease caps during an ISI would require further evaluation according to Revision 3 of RG 1.35.

3. Bottom grease caps of all the vertical anchorages need to be visually examined to detect significant grease leakage or grease cap deformation in accordance with Revision 3 of RG 1.35.

CONCLUSION

The above discussion validates the basic premise that the ISI program as implemented at U.S. Plants with PCCs serves its purpose of identifying potential significant problems with prestressing tendons and the PCCs. It can be debated whether a specific program is "too much" or "too little." However, the program delineated in Revision 3 of Reference 3 is based on a thorough scrutiny by knowledgable professionals in industry and in the regulatory staff.

On the basis of the experiences related to the use of prestressed concrete in U.S. containments, the authors make the following recommendations regarding the future designs of prestressed concrete containments.

1. Although the use of large-size (>9MN) tendons reduces the number of tendons and anchorages, which is a distinct advantage, it should be recognized that the components of the tendon anchorage (wedges, wedge blocks, and anchor heads) are likely to have areas of sustained high (>yield) stress concentration. The use of high hardness material should be avoided in designing these components.

2. Tendon sheathing and its joints should be carefully designed to ensure that under the maximum anticipated grease injection pressure, the grease will not leak into the surrounding concrete.

3. At least one tendon in each group of tendons should be provided with reliable load cells for continuous monitoring of the prestressing forces.

4. Procedures similar to those in Reference 7 should be used during the design process to determine the predicted band of prestressing forces in tendons for use during ISIs.

REFERENCES

1. U.S. Nuclear Regulatory Commission, "Inservice Inspection of Prestressed Concrete Containment with Grouted Tendons," Regulatory Guide 1.90, Revision 1, August 1977.

2. U.S. Nuclear Regulatory Commission, "Qualifications of Cement Grouting for Prestressing Tendons in Containment Structures," Regulatory Guide 1.107, February 1977.

3. U.S. Nuclear Regulatory Commission, "Inservice Inspection of Ungrouted Tendons in Prestressed Concrete Containments," Regulatory Guide 1.35, Revision 1, June 1974; Revision 2, January 1976; Proposed Revision 3, April 1979; Revision 3, May 1990.

4. M. P. Singh and A. Walser, "Statistical Aspects of Containment Tendon Surveillance," Journal of the Power Division, ASCE 101, 22-34, July 1975.

5. Mil-Std-414, "Sampling Procedures and Tables for Inspection by Variable for Percent Defective," Superintendent of documents, U.S. Government Printing Office, Washington D. C., June 1957.

6. American Society of Mechanical Engineers, "Requirements for (ISI of) Class CC Concrete Components of Light-Water Cooled Power Plants," Subsection IWL of ASME Boiler and Pressure Vessel Code,

Section XI, Division 1, July 1989.

7. U.S. Nuclear Regulatory Commission, "Determining Prestressing Forces for Inspection of Prestressed Concrete Containments," Regulatory Guide 1.35.1, May 1990.

8. H. Ashar and D. J. Naus, "Overview of the Use of Prestressed Concrete in U.S. Nuclear Power Plants," Nuclear Engineering and Design, North Holland Publishing Company, Volume 75, June 1983.

9. U.S. Nuclear Regulatory Commission, "Materials, Construction and Testing of Concrete Containments," Regulatory Guide 1.136, Revision 2, June 1981.

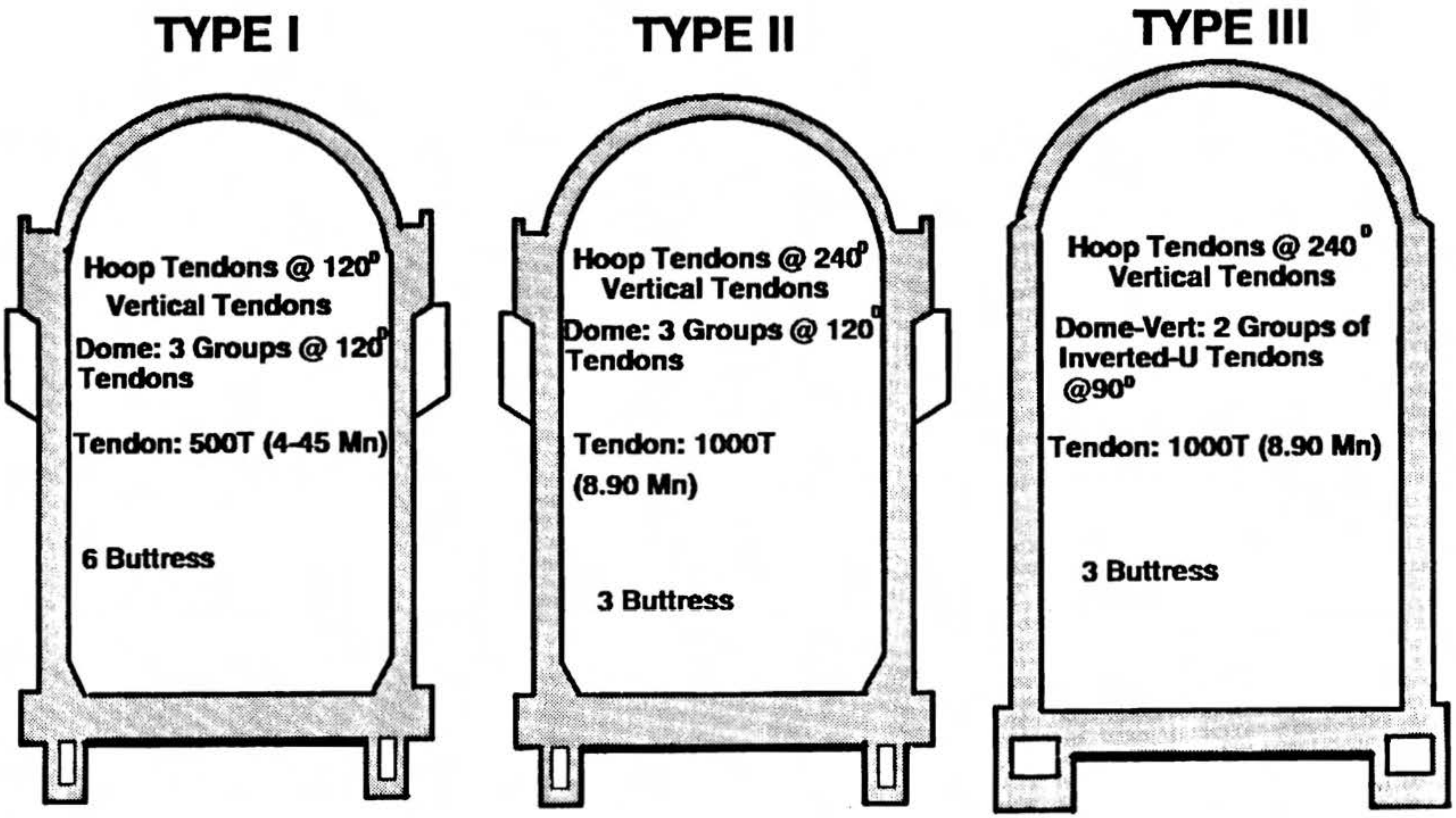

Figure 1. Generic types of prestressed concrete containments

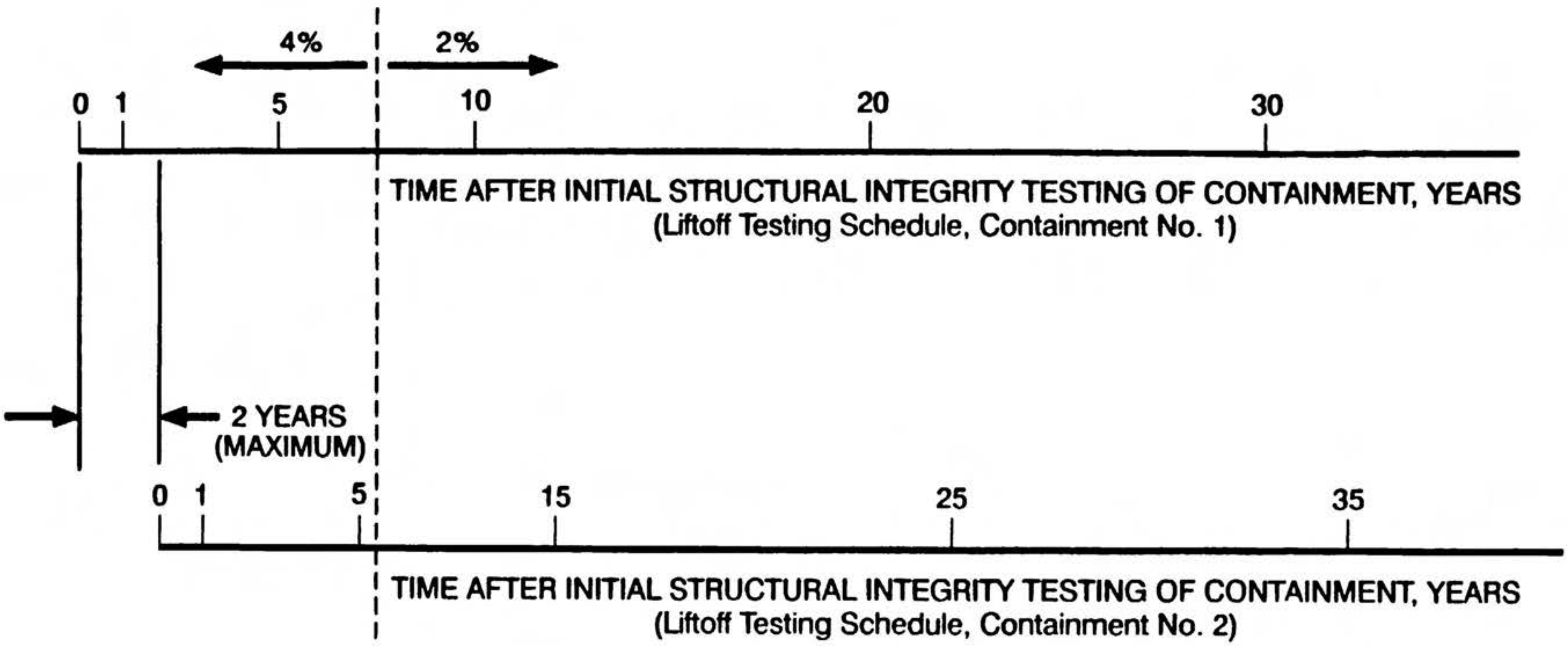

Figure 2. Schedule of Liftoff Testing for Two Containments at a Site