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Division of Reactor Safety
Region I

THRU: Michael L. Marshall, Chief
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SUBJECT: POSITION PAPER: IN SITU MONITORING OF ALKALI-SILICA REACTION (ASR) AFFECTED CONCRETE: A STUDY ON CRACK INDEXING AND DAMAGE RATING INDEX TO ASSESS THE SEVERITY OF ASR AND TO MONITOR ASR PROGRESSION

The purpose of this position paper is to provide the Alkali-Silica Reaction (ASR) Working Group and inspection team with a basis to assess the adequacy of using crack indexing and the damage rating index methods to (1) determine severity of ASR and (2) monitor the progression of degradation in reinforced concrete structures at Seabrook Station. Further, the paper provides the basis for a recommendation that using the method of combined crack indexing alone to characterize the extent of ASR damage to-date and monitor the progression is not adequate, and that additional measures should be taken to provide a baseline understanding of the ASR affect on structures before crack indexing measurements can be correlated to anticipated structural performance.

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Key Messages:

1. Surface cracking may not be indicative of the conditions of the concrete through the full section of the concrete member, and crack indexing measurements may not consistently indicate the level of ASR severity from one structure to another. For each group of similar (i.e., reinforcement details, size, environmental conditions) structures, additional examinations are necessary to correlate crack measurements to severity of ASR degradation.

2. Crack mapping results should be correlated to actual stresses and strains in the concrete and rebar in order to accurately represent the effect of ASR in engineering evaluations for structural behavior.

3. Damage rating index (DRI) is a more accurate measure of ASR severity than crack indexing, and alleviates many of the pitfalls of the crack indexing method. DRI should be considered as a method to assess damage related to ASR. However, since there is no standard on performing the DRI, one would need to be developed to ensure consistency.

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Position Paper: In situ Monitoring of Alkali-Silica Reaction Affected Concrete: A Study on Crack Indexing and Damage Rating Index to Assess the Severity of Alkali-Silica Reaction and to Monitor Alkali-Silica Reaction Progression

Recommendation: Using the method of crack indexing alone to characterize the extent of alkali-silica reaction (ASR) damage to-date and monitor the progression is not adequate. Additional measures should be taken to provide an understanding of the ASR affect on structures before crack indexing can be correlated to anticipated structural performance.

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1. Surface cracking may not be indicative of the conditions of the concrete through the full section of the concrete member, and crack indexing measurements may not consistently indicate the level of ASR severity from one structure to another. For each group of similar (i.e., reinforcement details, size, environmental conditions) structures, additional examinations are necessary to correlate crack measurements to severity of ASR degradation.

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3. Damage rating index (DRI) is a more accurate measure of ASR severity than crack indexing, and alleviates many of the pitfalls of the crack indexing method. DRI should be considered as a method to assess damage related to ASR. However, since there is no standard on performing the DRI, one would need to be developed to ensure consistency.

Background:

Alkali-Silica Reaction (ASR)

ASR is a chemical reaction that occurs in concrete between alkali hydroxides dissolved in the concrete pore solution and reactive silica phases in the aggregates. The product of the reaction is an expansive gel around the aggregate particles, which imbibes water from the pore fluid, and, having much larger volume than the reacting components, triggers a progressive damage of the material (Winnicki and Pietruszczak 2008). The pressures imparted by the gel onto the concrete can exceed the tensile strength of the aggregates and the cement paste and cause microcracking and macrocracking in the aggregate and surrounding paste. With the presence of moisture, the gel expands and can cause destructive cracking and deleterious expansion of the concrete. The extent of the concrete deterioration depends on aggregate reactivity, high levels of alkalinity, availability of moisture, temperature, and structural restraint (Williams, Choudhuri, and Perez 2009). Concrete expansion and cracking can lead to serious operational and serviceability problems in concrete structures (Rivard et al. 2002).

Surface Cracking and Expansion

The Federal Highway Administration (FHWA) Report on the Diagnosis, Prognosis, and Mitigation of Alkali-Silica Reaction in Transportation Structures states that "in concrete members undergoing internal expansion due to ASR and subject to wetting and drying cycles (cyclic exposure to sun, rain, wind, etc.), the concrete often shows surface cracking because of induced tension cracking in the 'less expansive' surface layer (because of variable humidity conditions and leaching of alkalis) under the expansive thrust of the inner concrete core (with more constant humidity and pH conditions)." Cracks first form as three or four-pronged star patterns resulting from expansion of the gel reacting with the aggregate. If the concrete is not subject to directional stress, the crack pattern developed forms irregular polygons, commonly referred to as map cracking (Swamy 1992). This cracking is usually enough to relieve the pressure and accommodate the resulting volume increase (Figg 1987; reported by Farny, et al. 2007).

Map cracking is one of the most commonly reported visual signs associated with ASR. The pattern and severity of cracking vary depending on the type and quantity of reactive aggregate used, the alkali content of the concrete, exposure conditions, distribution of stresses, and degree of confinement in the concrete (Smaoui et al. 2004). ASR can also be characterized by longitudinal cracking, surface discoloration, aggregate pop-out, and surface deposits (gel or efflorescence) (Williams, Choudhuri, and Perez 2009). Although pattern cracking is a characteristic visual indication that ASR may be present in the concrete, ASR can exist in concrete without indications of pattern cracking. Newman (2003) noted that "while superficial cracking patterns can often be reminiscent of ASR, it is important to be aware that reliable diagnosis can never be adequately based on the appearance of surface cracking alone." This is also emphasized by Hobbs (as reported by Bensted and Barnes, 2001), whose research cites examples where cracking from other mechanisms was diagnosed as ASR, and also examples in which ASR gel and associated cracked aggregate particles were found in concrete that was uncracked. In addition, in ASR-affected structures with reinforcement close to the surface or in heavily reinforced structures, surface cracking may be suppressed while internal damage exists throughout the section. The presence and extent of surface cracking is not a conclusive indication that ASR is present, nor is it a conclusive measure of concrete degradation due to ASR. Conversely, the absence of surface cracking does not conclusively indicate the absence of ASR.

Crack Mapping/Indexing Review:

In order to determine the effect of ASR on the performance of a concrete structure, it is important that there be an understanding of current concrete condition (ASR damage reached to-date) and the rate of ASR expansion. Crack indexing is a method that is proposed to measure crack widths and expansion of cracks over time. For this type of visual examination individual crack widths are measured over a defined grid and the total amount of cracking is quantified. The examination is repeated at regular intervals and the results are compared over time, with a goal of establishing a rate of ASR progression. The Institute of Structural Engineers

(ISE 1992) proposed a method for crack mapping that consists of measuring the ASR crack widths along five parallel lines that are each 1 m long. Lines are traced directly onto the concrete structure. The total width of intersecting cracks along each line is summed and divided by the length over which they were measured, to determine the severity of ASR cracking, and then over time to determine the rate of expansion. Another method, suggested by Laboratoire Central des Ponts et Chaussees (LCPC 1997), consists of measuring the widths of all cracks intersecting two perpendicular 1m lines originating from the same point and their two diagonals 1.4 m long. The total crack index is determined as a value in millimeters per meter and compared to criteria that correspond to action levels.

Summary of General Discussion on Crack Mapping

It is stated throughout published ASR research that crack mapping is somewhat limited in its applicability to understanding ASR degradation in concrete. Saint-Pierre et al. (2007) note that compared to other non-destructive methods developed for assessing the damage induced by ASR, the semi-quantitative surface methods like crack mapping appear to be less effective. It is generally agreed that while results of crack indexing can potentially give some indication of how ASR is progressing over time, establishing an absolute trend that directly correlates expansion levels to ASR progression may not be a reliable practice. Much of the published ASR research also indicates that using crack measurement alone to characterize the current state of ASR degradation would not be advised, since the practice relies on the assumption that the surface cracking on the face of a structure is wholly congruent to ASR severity. In the 2010 Addendum to its report titled "Structural Effects of Alkali-Silica Reaction - Technical guidance on the Appraisal of Existing Structures," ISE stated that the crack summation procedures for estimating expansion to date work well in directions where there is little restraint from structural stress, reinforcement, or prestress. This suggests that in structures with higher restraint, this would not be the case. In addition, crack mapping is limited in that it can only give data on two-way crack measurements and does not capture cracking in the out-of-plane direction. It is suggested that further activities be carried out for assessing current condition of the concrete and current expansion rate, as well as correlating the expansion to structural integrity.

In addition, crack indexing evaluation criteria should not be universally applied to all structures because surface cracking may not give a reliable indication of the ASR degradation to the structure. Due to variability in size, location, environment, reinforcement detailing, and relative severity of ASR damage, it may be necessary to obtain an understanding of the ASR effects for each individual structure or group of structures with similar physical properties and environments. Indeed, Newman (2003) stated "it is important to relate cracking patterns variously to structural geometry and/or design, apparent concreting sequence, localized detailing (especially where cracking may be coincident with water leakage) and both environmental and in-service conditions." Deschenes et al. (2009) also state that research into the method highlighted that a number of factors (size and shape of member, restraint present, depth of cover, etc.) leading to poor correlation between crack indexing and measured expansions.

Surface Cracking vs. Internal ASR Damage

The correlation between surface cracking and ASR deterioration may be closer to unity for specimens used in the laboratory that are only allowed to deteriorate due to ASR conditions. However, for concrete in the field, the surface indications sometimes poorly correlate to the extent of ASR degradation within the concrete. Since conditions are so variable from one region to another, and even from one location to another in the same structure, poor correlations are often observed between the severity of surface cracking and the presence of the internal signs of ASR (i.e., reaction products, micro-cracking, and expansion) (Nishibayashi et al. 1989 and Stark 1990 reported by Smaoui et al. 2004). Development of cracking on the surface depends strongly on the amount of reinforcement close to the surface (Smaoui et al. 2002) and also depends on external environmental conditions such as wetting-drying, freezing-thawing, and exposure to saline solutions (Smaoui et al. 2002). Two examples of situations in which external conditions can affect the surface cover concrete such that the surface features are not indicative of the actual ASR degradation of the structure are presented here for consideration. In one case, presence and extent of surface cracking can depend on the pH of the surface which can be affected by leaching and carbonation. As such, wetting-drying cycles can affect the features of ASR, as conditions at the surface layer could be less favorable to the development of ASR, due to the [lower] humidity during the drying periods and the leaching of alkalis during the wetting periods (Poitevin 1983 and Swamy 1995, reported by Smaoui et al. 2004). In other words, if the outer surface layer of concrete is exposed to conditions that would cause the ASR severity or development to be lower, but conditions inside the concrete remain conducive to ASR development (i.e., high relative humidity); surface conditions would not be representative of the ASR within the concrete section. Crack indexing efforts could incorrectly characterize the level of ASR degradation as minor, when within the section the ASR degradation might be more severe.

Another example in which environmental conditions have caused surface conditions to be different than conditions within the concrete is the subject of a study done (Berube et al. 2002). In this study, an attempt was made to correlate ASR expansion with a type of exposure to moisture. Results showed that specimens exposed to wetting-drying cycles saw more surface cracking but less actual expansion than specimens that were always exposed to humidity. In this case, the larger amount of surface cracking evident in the specimens exposed to wetting-drying cycles did not show to correlate well to the actual expansion due to ASR, with the ASR expansion being less severe than the cracking would indicate. Conversely, the specimens that showed less surface cracking saw a greater expansion due to ASR, which shows that visual examination of surface cracking alone may not be adequate.

Smaoui et al. (2004) stated that although the intensity of surface cracking on ASR-affected concrete in service can help to assess the severity of ASR, quantitative measurement of this intensity [i.e., crack mapping] [could] lead to values that generally underestimate the true expansion attained, except maybe when the surface concrete layer does not suffer any ASR expansion at all. If the concrete surface layer undergoes ASR expansion that is less than that of the inner concrete, according to Smaoui et al. (2004), "the measurement of surface cracking will tend to give expansion values lower than the overall expansion of the concrete element under study." This research indicates that the degree of correlation between surface cracking and actual ASR expansion or degradation tends to vary with the level of exposure, which means that crack indexing over a number of structures with varying environmental conditions may not conclusively measure the extent or severity of ASR degradation.

ASR-Induced Stresses

The ISE (2010) noted that for some structures exposed to ASR, internal damage occurs through the depth [of the section] but visible cracking is suppressed by heavy reinforcement. In reinforced concrete structures, expansion of ASR cracks generates tensile stresses in the reinforcing steel while also causing compressive stresses in the concrete surrounding the rebar (this phenomenon is often likened to prestress in the concrete and noted to temporarily improve structural behavior). According to Smaoui et al., 2004, the most useful information in the structural evaluation of an ASR-affected concrete member is the state of the stresses in the concrete, but more importantly in the steel reinforcement. The ASR-induced stresses increase the structural demand on the steel and concrete, but this has likely not been accounted for in the original design or in further structural evaluations. According to Multon et al. (2005), "assessment models have to take into consideration the property of stresses to modify ASR-induced expansions and their effect on the mechanical response of ASR-damaged structures..." The expansion reached to date, the current rate of expansion, and the potential for future expansion of the concrete are particularly critical pieces of information to determine whether or not the reinforcing steel has reached or will at some point reach its plastic limit, thus creating risk of structural failure (FHWA 2010).

Crack mapping alone to determine ASR effects on the structure does not allow for the consideration of rebar stresses. Visual examination and measurement of crack growth need to be correlated to strain measurements taken of ASR-affected concrete and the reinforcing steel. In similar structures, then, the visual indications of expansion due to ASR can relate to stresses in the concrete and reinforcing steel in order to apply ASR-induced stress in structural evaluations. Smaoui et al. (2004) propose that if it is not possible to do a destructive examination (i.e., exposing the rebar or taking deep cores) of the structure in question, "an indirect method is based on the expansion accumulated to date...[a]ssuming that this expansion corresponds to that of the reinforcement steel, the stresses within the reinforcement and the concrete could thus be determined from the modulus of elasticity of the steel and the corresponding sections of the concrete elements under investigation." For determining added stresses in in-situ structures, once correlation has been made with respect to size and rebar configuration between the in situ structure and a test specimen, it would be appropriate to use crack mapping as a measure of ASR degradation when introducing the additional ASR-induced stresses on concrete and reinforcing steel in structural evaluations.

Discussion on Applicability of Crack Indexing

This report is not intended to present the position that crack indexing and resulting data should not be part of a structural monitoring program to assess the ongoing effects of ASR in concrete. In fact, crack indexing is recommended by the FHWA (FHWA 2010) "to obtain a quantitative rating of the 'surface' deterioration of the structure as a whole" (it should be noted that in the FHWA document, the word "surface" is emphasized with quotation marks, which implies recognition that crack indexing measurements alone provide information limited only to what is occurring at the concrete surface). NRC staff position is that crack mapping can only be useful once there is an understanding of how the conditions inside the concrete, (i.e., relative humidity, presence and severity of cracking, and added stresses in the concrete, reinforcing detail) correlate to the cracking observed at the surface. The FHWA (2010) document agrees, indicating that to obtain an understanding of the current state of ASR degradation and in order to correlate the surface cracking to the actual effects of ASR-induced expansion on the structure, other investigations of the in-situ structure are necessary. In addition to crack indexing, some FHWA recommendations for transportation structures that can be appropriately applied to nuclear structures include taking stress [strain] measurements in reinforcing steel, obtaining temperature and humidity readings, and performing non-destructive testing such as pulse velocity measurements (the recommendation to use pulse velocity measurements is in agreement with the experimental findings of Saint-Pierre et al. 2007). The ISE (ISE 2010) suggests that expansion to date and severity of ASR should be evaluated using examination and testing of cores for changes in modulus of elasticity and development of hysteresis (stiffness deterioration). It is also proposed that strain sensors be used as a method of monitoring ASR progression in order to monitor and quantify out-of-plane expansion.

In addition to provisions for monitoring (or predicting) progression of ASR, it is recommended that each structure or group of similar structures undergo petrographic analysis to determine the current state of ASR damage, in order to provide an accurate baseline from which to understand the current severity level and monitor ASR progression.

Damage Rating Index Review:

The DRI was developed by Grattan-Bellew and Danay in 1992 (Reported by Smaoui et al. 2004) as a method to determine the extent of internal damage in concrete affected by ASR (Rivard et al. 2002). The DRI is a method for quantifying both qualitative and quantitative observations and determining severity of ASR using petrographic analysis of polished sections of concrete. It is based on the recognition of a series of petrographic features that are commonly associated with ASR (Rivard et al. 2002). The DRI accounts for defects observed in the concrete, such as the presence and distribution of reaction products, existence of internal microcracking, and location of microcracking (within the aggregate vs. through the cement paste) by assigning a weighting factor to each and quantifying overall damage. When the factors are normalized to an area of 100 cm^2, and the resulting number is the DRI. Rivard et al. (2000) noted that the abundance of individual defects and the overall DRI values increased with regularity with increased ASR expansion.

It should be noted that the specimens used by Rivard et al. were comprised of reactive aggregates with different reaction mechanisms, but ASR expansion indeed correlated with DRI measures of ASR severity.

Smaoui et al. (2004) performed damage rating indexing on specimens from five concrete mixes using different reactive aggregates to determine if there was a reliable and accurate correlation between ASR damage determined by DRI and ASR expansion measurements. They noted that there exists a potential error in estimating expansion of ASR concrete in the field and establishing a DRI-expansion relationship with laboratory testing. In some of the lab specimens, relatively similar DRI values were obtained for very different expansion levels for cylinders which had been cast with the same concrete mix (and progressed ASR over time). The tests indicated that expansion levels (of in situ structures compared to laboratory specimens) may not be the best indication of ASR degradation. For example, the presence of air bubbles in the proximity of reactive aggregates [in field concrete] usually has the effect of reducing the expansion due to ASR (Landry 1994, Reported by Smaoui et al. 2004). In other words, air bubbles that exist in the in situ concrete structure could result in a smaller expansion of the structure as concluded under crack mapping activities while more severe ASR damage could be present in the structure because ASR features have "room" to grow inside the existing structure before extensive cracking is notable on the concrete surface. Smaoui et al. (2004) concluded that "for evaluating the expansion attained to date by ASR-affected concrete, it may be necessary to reconsider the relevant defects and their respective weighting factors and take into account a certain number of factors such as the presence or absence of entrained air and preexisting cracks and alteration rims" to assess the severity of ASR in structures. It is notable that the research done by Rivard et al. (2000) showed that DRI correlated well with actual ASR expansion, while subsequent work done by Smaoui et al. (2004) proposed that in some cases lack of gross expansion did not correlate to low ASR degradation, and that air bubbles prevented macro-level expansion even though ASR effects were severe. Crack indexing would not have identified this severe ASR progression since that method only measures expansion of surface cracks.

Rivard et al. noted a possible limitation of the DRI method: that weighting factors assigned to each defect may not universally apply to all types of reactive aggregates (reported by Smaoui et al. 2004) and that weighting factor adjustments may be needed depending on the type of reactive aggregate being examined. In other words, DRI results (and their correlation to concrete expansion) should not be applied universally between concretes with different aggregates (with different types of siliceous materials). However, the FHWA (2010) notes that the DRI method can be useful for quantitative assessment of ASR damage for concretes with the same constituents (i.e., same type of reactive aggregate and cement mix design), and can provide useful relative information when cores are taken and a damage rating developed for each structure by the same experienced technician.

Conclusion/Recommendations:

In order for the effects of ASR on concrete to be assessed, the parameters that need to be understood are (1) the amount of cracking inside the concrete, (2) ASR-induced expansion-to-date and rate of expansion, and (3) effects of ASR on concrete and rebar stresses. To understand the affects of ASR on structural behavior, the effects of ASR damage inside the rebar cage should be applied to engineering analyses or laboratory testing of an equivalent structure for each group of similar structures.

Visual examination of the concrete surface, without any other information about the concrete beneath the surface, is not recommended for either determining the current level of ASR degradation or projecting the future effects of ASR in concrete. Crack indexing would be an adequate and reasonable method of monitoring ASR progression once surface cracking can be correlated to actual ASR degradation, including cracking, expansion, and corresponding stresses (strains) in the concrete and rebar. Laboratory and in-situ testing must be performed to correlate surface cracking with loss of mechanical properties because cracking patterns may vary for different structural geometry and/or design, apparent concreting sequence, localized detailing (especially where cracking may be coincident with water leakage) and both environmental and in-service conditions (Newman et al. 2003).

At a minimum, for each set of structures with the same environmental conditions (e.g., chronically wetted, exposed to freeze-thaw action, constant wetting/drying) and section properties (e.g., wall thickness, rebar layout), an initial petrographic analysis should be done to establish the current state of ASR degradation. The severity of ASR damage on the inside of the structure should be correlated to the surface cracking found on the face of the concrete. The expansion measured by subsequent periodic crack indexing can then be assessed on a structure by structure basis depending on that correlation. Also, depending on the correlation between the surface and interior indications for each set of structures, it may be appropriate to adjust the individual crack width and cracking index acceptance criteria for different groups of structures. An added benefit to doing an initial petrographic analysis is that the cores removed from the structure could be studied for subparallel microcracking that would not be detected from crack mapping efforts, which only show cracks on the surface face. This is the minimum effort that should be undertaken to gain at least a more informed understanding, for each set of similar structures (physical attributes and environmental conditions), of the ASR expansion reached to date and rate of expansion. The ability to correlate in-situ conditions with laboratory testing would strengthen the reliability of the crack indexing method.

A recommended approach to monitoring ASR progression would be the use of embedded strain gauges and other sensors in the concrete to provide a measure of expansion in the concrete. This would provide the most accurate measure of expansion due to ASR and would provide the benefit of understanding expansion due to cracking in the third direction. The application of strain instrumentation would also be able to quantify strains (stresses) on the rebar and concrete in order to apply the additional demand due to ASR to a structural engineering evaluation. Finally, this method would help to establish a rate of expansion in the concrete, and could provide insights into understanding the ASR degradation mechanism, including relating environmental conditions specific to a structure to the rate of change of ASR progression, in order to characterize the potential and extent of continued degradation over time. The data could also be used in engineering analyses to predict the effects of ASR on structural behavior.

The DRI method has been shown to be an effective method for assessing the damage level of ASR-affected structures. However, due to the limitation of this method in being able to apply weighting factors consistently between various types of aggregates, practical implementation of this method would mean that site-specific criteria for severity ratings and weighting factors for ASR indications may need to be established in accordance with the reactivity of the aggregate used on site. Also, since there is no standard test procedure available and thus the DRI method results could be variable from one petrographer to another, it would be important to ensure quality and consistency in the implementation of the method. If consistency could be ensured through quality of the technician performing the initial examination and subsequent examinations, the DRI would provide a beneficial and useful understanding of current ASR degradation and degradation over time.

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