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# Through-Thickness Expansions To-Date for the First Campaign of Extensometers

This appendix includes MPR Calculation 0326-0062-CLC-04, *Calculation of Through-Wall Expansion from Alkali-Silica Reaction To-Date at Seabrook Station: First Campaign of Extensometers*, Revision 0.

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# CALCULATION TITLE PAGE

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| Title:<br>Calculation of Through-Wall Expansion from Alkali-Silica Reaction To-Date at Seabrook Station | Calculation No.<br>0326-0062-CLC-04 |

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| Amanda Card<br>Amanda E. Card<br>July 19, 2016 | [signature]<br>David Cowles<br>July 19, 2016 | C W Bagley<br>Christopher Bagley<br>July 19, 2016 | 0 |

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# RECORD OF REVISIONS

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**Note:** *The revision number found on each individual page of the calculation carries the revision level of the calculation in effect at the time that page was last revised.*

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## 1.0 PURPOSE AND BACKGROUND

This calculation determines the through-thickness expansion to-date from Alkali-Silica Reaction (ASR) for various locations in reinforced concrete structures at Seabrook Station. The current through-thickness expansion values were calculated using a correlation between through-thickness expansion and elastic modulus of concrete test specimens affected by ASR.

Seabrook Station is installing extensometers to monitor through-thickness expansion. The first set of eighteen extensometers has been installed. This calculation determines the current through-thickness expansion values for the first set of extensometer locations.

Seabrook Station will follow the process presented in this calculation to determine the current through-thickness expansion values upon installation of the remaining extensometers.

## 2.0 SUMMARY OF RESULTS AND CONCLUSION

The table below provides through-thickness expansion values to-date for eighteen reinforced concrete locations at Seabrook Station. Each of the locations corresponds to the location of an installed extensometer.

**Table 2-1.** Through-Thickness Expansion To-Date

[redacted]

**Table 2-1.** Through-Thickness Expansion To-Date

[redacted]

## 3.0 METHODOLOGY

This calculation uses the equation developed in Reference 3 to determine the current through-thickness expansion from ASR. The equation in Reference 3 uses normalized elastic modulus (i.e., current elastic modulus / original elastic modulus) to determine through-thickness expansion to-date. The key steps in the methodology used herein are (1) determination of the original elastic modulus which was not directly measured during original construction and (2) determination of through-thickness expansion using the equation in Reference 3.
The ASR-affected elastic modulus is determined using measurements of cores removed from the plant structures in the vicinity of the extensometer locations.

### *3.1 Using 28-Day Compressive Strength to Determine Original Elastic Modulus*

Section 8.5.1 of ACI 318-71 (Reference 2) states that the 28-day elastic modulus ($E_c$) of concrete can be calculated based on the density of concrete in lb/ft$^3$ ($w_c$) and the 28-day compressive strength of concrete ($f_c'$). The elastic modulus for normal weight concrete (approximate density of $144\frac{\text{lb}}{\text{ft}^3}$) can be calculated using Equation 1. Equation 1 was developed using data from a wide range of concrete and is therefore generally applicable to most concrete mixes.

$$E_c = 57{,}000\sqrt{f_c'} \qquad \text{(Equation 1)}$$

Reference 1 evaluates the applicability of Equation 1 to the concrete mix used in the test programs that MPR sponsored at Ferguson Structural Engineering Laboratory (FSEL) (i.e., the MPR/FSEL test programs). Based on the results of Reference 1, the relationship between the measured 28-day compressive strength (original compressive strength) and the 28-day elastic modulus for the test specimens within the MPR/FSEL test programs is consistent with the ACI equation.

Using Equation 1 to evaluate concrete at Seabrook Station is also appropriate. The correlation was demonstrated to apply to the concrete used in the MPR/FSEL test programs in Reference 1 and the concrete mix used in the MPR/FSEL test programs was representative of the concrete at

Seabrook Station. Accordingly, the compressive strength of concrete identified in Seabrook Station's original construction records can be used to determine the original elastic modulus ($E_c$) of the concrete of interest.

### 3.2 Determining Through Thickness Expansion from Elastic Modulus

Reference 3 determines a correlation (Equation 2) between through-thickness expansion and normalized elastic modulus of concrete test specimens affected by ASR. The correlation is based on data from test programs that MPR sponsored at FSEL. The correlation was verified against published data.

[redacted] (Equation 2)

Where:

*expansion* is the relative through-thickness expansion of the concrete specimen (e.g., 0.02 equals a 2% expansion) and
*modulus* is the normalized modulus of the test specimen after ASR.

A normalized modulus reduction factor of [redacted] was applied to Equation 2 to provide appropriate conservatism for the methodology.

## 4.0 ASSUMPTIONS

### 4.1 Verified Assumptions

There are no verified assumptions.

### 4.2 Unverified Assumptions

There are no unverified assumptions.

## 5.0 DESIGN INPUTS

### 5.1 Original Compressive Strength Data

The original compressive strength data were used to determine the original elastic modulus using Equation 1. Seabrook Station provided MPR with Concrete Compressive Strength Test Reports from Pittsburgh Testing Laboratory (Reference 5). These lab reports contained the 28-day compressive strength data from cylinders that were representative of all but two locations of interest (E18 and E19). The cylinders used to determine the 28-day compressive strength were molded using concrete from the same concrete batch that was used to place the associated concrete structure at Seabrook Station.

Average compressive strength values for specific structures provided in Reference 4 were used when applicable Concrete Compressive Strength Test Reports from Pittsburgh Testing Laboratory were not available. Reference 4 evaluates available 28-day compressive strength values of concrete cylinders during the original construction of Seabrook Station. The calculation determines the average of all compressive strength values and calculates the range and standard deviation. Using the average compressive strength value for Seabrook Station for locations E18 and E19 is appropriate due to the fact that original compressive strength does not have a significant effect on the through-thickness expansion to-date.

Table 5-1 presents the average and standard deviation associated with the original compressive strength of each location. The average compressive strength is used to determine the nominal through-thickness expansion to-date. The range and standard deviation illustrate the variability among the original compressive strength data.

**Table 5-1.** Original Compressive Strength Data

| Location | Average (psi) | Range (psi) | Standard Deviation (psi) |
|---|---|---|---|
| E1 | 5197 | 1240 | 371 |
| E2 | 6163 | 2140 | 705 |
| E3 | 5666 | 1000 | 320 |
| E4 | 4429 | 1750 | 526 |
| E5 | 5266 | 880 | 363 |
| E6 | 5922 | 1200 | 401 |
| E7 | 6412 | 780 | 217 |
| E8 | 5426 | 980 | 315 |
| E9 | 4910 | 1510 | 400 |
| E10 | 5186 | 870 | 243 |
| E11 | 5774 | 1700 | 530 |
| E12 | 5666 | 1000 | 320 |
| E13 | 5710 | 180 | 104 |
| E14 | 5426 | 980 | 315 |

**Table 5-1.** Original Compressive Strength Data

| Location | Average (psi) | Range (psi) | Standard Deviation (psi) |
|---|---|---|---|
| E15 | 6037 | 170 | 93 |
| E16 | 5387 | 780 | 392 |
| E18 | 5456 | 3120 | 568 |
| E19 | 5456 | 3120 | 568 |

Note:
Compressive strength values for locations E1 through E16 were taken from Reference 5. Compressive strength values for locations E18 and E19 were taken from Reference 4.

## *5.2 Current Elastic Modulus Data*

Seabrook Station determined the current elastic modulus by testing cores removed from each location and provided the results to MPR (Reference 6 and Reference 7). Results from these tests are listed in Table 5-2.

Multiple elastic modulus values were obtained for each location of interest. The "-1," "-2," and "-3" after the location title designate between the specific core locations. Some locations have multiple modulus results because sufficient intact core length was available for two test specimens. The average and range values presented below consider all tests performed on cores from the same general location. The average current elastic modulus data is used to determine the nominal through-thickness expansion to-date. The range illustrates the variability associated with current modulus data.

**Table 5-2.** Current Elastic Modulus Data

| Location | Modulus 1 (psi) | Modulus 2 (psi) | Average (psi) | Range (psi) |
|---|---|---|---|---|
| E1-1 | 2.20E+06 | 2.10E+06 | 2.04E+06 | 8.50E+05 |
| E1-2 | 2.35E+06 | 1.50E+06 | | |
| E2-1 | 3.00E+06 | N/A | 2.70E+06 | 6.00E+05 |
| E2-2 | 2.40E+06 | N/A | | |

**Table 5-2.** Current Elastic Modulus Data

| Location | Modulus 1 (psi) | Modulus 2 (psi) | Average (psi) | Range (psi) |
|---|---|---|---|---|
| E3-1 | 2.35E+06 | 2.10E+06 | 2.49E+06 | 7.00E+05 |
| E3-2 | 2.80E+06 | 2.70E+06 | | |
| E4-1 | 2.80E+06 | N/A | 3.30E+06 | 1.00E+06 |
| E4-2 | 3.80E+06 | N/A | | |
| E5-1 | 4.45E+06 | N/A | 4.53E+06 | 1.50E+05 |
| E5-2 | 4.60E+06 | N/A | | |
| E6-1 | 2.95E+06 | 2.90E+06 | 2.91E+06 | 2.00E+05 |
| E6-2 | 3.00E+06 | 2.80E+06 | | |
| E7-1 | 3.15E+06 | 3.05E+06 | 2.97E+06 | 4.50E+05 |
| E7-2 | 2.70E+06 | N/A | | |
| E8-1 | 2.40E+06 | N/A | 2.55E+06 | 3.00E+05 |
| E8-2 | 2.70E+06 | N/A | | |
| E9-1 | 1.40E+06 | 1.80E+06 | 1.50E+06 | 5.00E+05 |
| E9-2 | 1.30E+06 | N/A | | |
| E10-1 | 2.20E+06 | 2.30E+06 | 2.41E+06 | 4.00E+05 |
| E10-2 | 2.50E+06 | 2.45E+06 | | |
| E10-2 | 2.60E+06 | N/A | | |
| E11-1 | 2.75E+06 | N/A | 2.83E+06 | 1.5E+05 |
| E11-3 | 2.90E+06 | N/A | | |
| E12-1 | 3.10E+06 | 3.05E+06 | 3.16E+06 | 4.00E+05 |
| E12-2 | 3.45E+06 | 3.05E+06 | | |
| E13-1 | N/A | N/A | 1.85E+06 | 0.00E+00 |
| E13-2 | 1.85E+06 | N/A | | |

**Table 5-2.** Current Elastic Modulus Data

| Location | Modulus 1 (psi) | Modulus 2 (psi) | Average (psi) | Range (psi) |
|---|---|---|---|---|
| E14-1 | 2.25E+06 | 1.90E+06 | 1.88E+06 | 6.00E+05 |
| E14-2 | 1.70E+06 | 1.65E+06 | | |
| E15-1 | 2.25E+06 | N/A | 2.38E+06 | 2.50E+05 |
| E15-2 | 2.50E+06 | N/A | | |
| E16-1 | N/A | N/A | 4.30E+06 | 0.00E+00 |
| E16-2 | 4.30E+06 | N/A | | |
| E18-1 | 2.85E+06 | N/A | 2.98E+06 | 2.50E+05 |
| E18-2 | 3.10E+06 | N/A | | |
| E19-1 | 3.10E+06 | N/A | 3.38E+06 | 5.50E+05 |
| E19-2 | 3.65E+06 | N/A | | |

# 6.0 Calculations and Results

## *6.1 Original Elastic Modulus*

The original elastic modulus was determined by using the average compressive strength data in Table 5-1 and Equation 1, where $f_c'$ is the 28-day compressive strength and $E_c$ is the original elastic modulus. Results are presented in Table 6-1.

**Table 6-1.** Nominal Original Elastic Modulus

| Location | Original Elastic Modulus (psi) |
|---|---|
| E1 | 4.11E+06 |
| E2 | 4.47E+06 |
| E3 | 4.29E+06 |
| E4 | 3.79E+06 |

**Table 6-1.** Nominal Original Elastic Modulus

| Location | Original Elastic Modulus (psi) |
|---|---|
| E5 | 4.14E+06 |
| E6 | 4.39E+06 |
| E7 | 4.56E+06 |
| E8 | 4.20E+06 |
| E9 | 3.99E+06 |
| E10 | 4.10E+06 |
| E11 | 4.33E+06 |
| E12 | 4.29E+06 |
| E13 | 4.31E+06 |
| E14 | 4.20E+06 |
| E15 | 4.43E+06 |
| E16 | 4.18E+06 |
| E18 | 4.21E+06 |
| E19 | 4.21E+06 |

### *6.2 Nominal Through-Thickness Expansion To-Date*

The average modulus values presented in Table 5-2 and the nominal original elastic modulus values listed in Table 6-1 were used to determine the normalized modulus (*modulus*). The nominal expansion to-date was calculated using the normalized modulus and Equation 3.

[redacted] (Equation 3)

The nominal through-thickness expansion values (i.e., unadjusted though-thickness expansion values) to-date for the eighteen locations of interest are presented in Table 6-2.

**Table 6-2.** Nominal Through-Thickness Expansion To-Date

[redacted]

### *6.3 Adjusted Through-Thickness Expansion To-Date*

Uncertainty in the original modulus (calculated from the original compressive strength) and the measurement variability in current modulus influence the calculated through-thickness expansion values.

To include an appropriate level of conservatism into the calculated through-thickness values, a normalized modulus reduction factor o[redacted] was applied, as shown in Equation 4 below.

[redacted] (Equation 4)

Equation 4 results in higher calculated through-thickness values. Results for the 18 locations of interest are shown in Table 6-3. The average original compressive strength, the calculated original elastic modulus, the average current elastic modulus, and the nominal through-thickness expansion values are included for reference.

**Table 6-3.** Through-Thickness Expansion To-Date

| Location ID | Average Original Compressive Strength (psi) | Original Elastic Modulus (psi) | Average Current Elastic Modulus (psi) | Nominal Through-Thickness Expansion | Through-Thickness Expansion ([redacted] factor) |
|---|---|---|---|---|---|
| E1 | 5197 | 4.11E+06 | 2.04E+06 | [redacted] | [redacted] |
| E2 | 6163 | 4.47E+06 | 2.70E+06 | [redacted] | [redacted] |
| E3 | 5666 | 4.29E+06 | 2.49E+06 | [redacted] | [redacted] |
| E4 | 4429 | 3.79E+06 | 3.30E+06 | [redacted] | [redacted] |
| E5 | 5266 | 4.14E+06 | 4.53E+06 | [redacted] | [redacted] |
| E6 | 5922 | 4.39E+06 | 2.91E+06 | [redacted] | [redacted] |
| E7 | 6412 | 4.56E+06 | 2.97E+06 | [redacted] | [redacted] |
| E8 | 5426 | 4.20E+06 | 2.55E+06 | [redacted] | [redacted] |
| E9 | 4910 | 3.99E+06 | 1.50E+06 | [redacted] | [redacted] |
| E10 | 5186 | 4.10E+06 | 2.41E+06 | [redacted] | [redacted] |
| E11 | 5774 | 4.33E+06 | 2.83E+06 | [redacted] | [redacted] |
| E12 | 5666 | 4.29E+06 | 3.16E+06 | [redacted] | [redacted] |
| E13 | 5710 | 4.31E+06 | 1.85E+06 | [redacted] | [redacted] |
| E14 | 5426 | 4.20E+06 | 1.88E+06 | [redacted] | [redacted] |
| E15 | 6037 | 4.43E+06 | 2.38E+06 | [redacted] | [redacted] |
| E16 | 5387 | 4.18E+06 | 4.30E+06 | [redacted] | [redacted] |
| E18 | 5456 | 4.21E+06 | 2.98E+06 | [redacted] | [redacted] |
| E19 | 5456 | 4.21E+06 | 3.38E+06 | [redacted] | [redacted] |

The results in Table 6-3 indicate that Equation 4 inherently provides significant conservatism. Key observations include the following:

- For the highest through-thickness expansion value of [redacted] (location E9), use of Equation 4 increased the expansion value to [redacted] (i.e., [redacted] expansion). The impact of the normalized modulus reduction factor (in absolute terms) increases with ASR progression (i.e., at higher levels of expansion).

- In relative terms, application of Equation 4 to the highest through-thickness expansion value (location E9) produced a conservatism of [redacted] (i.e., [redacted] expansion / [redacted] expansion).

- The relative conservatism of Equation 4 increases if ASR progression is less advanced. As an example, for location E1, where nominal expansion is [redacted] the relative conservatism of using Equation 4 is [redacted] (i.e., [redacted] expansion/ [redacted] expansion).

## 7.0 REFERENCES


1. MPR Calculation 0326-0062-CLC-01, *Evaluation of ACI Equation for Elastic Modulus*, Revision 0.

2. ACI 318-71, "Building Code Requirements for Structural Concrete and Commentary," American Concrete Institute, 1971.

3. MPR Calculation 0326-0062-CLC-03, *Correlation Between Through-Thickness Expansion and Elastic Modulus in Concrete Test Specimens Affected by Alkali-Silica Reaction (ASR)*, Revision 2.

4. MPR Calculation 0326-0062-CLC-02, *Compressive Strength Values for Concrete at Seabrook Station*, Revision 0.

5. Pittsburg Testing Laboratory Concrete Compressive Strength Test Report, transmitted to MPR from Seabrook Station via SBK-L-16086, "Documentation Transmittal to Support Determination of Through-Thickness Expansion to Date and Validate Expansion Behavior at Seabrook," June 9, 2016.

6. Simpson Gumpertz & Heger Report No. 160072-LR-01, Revision 0, "Laboratory Testing of Concrete Cores at SGH, NextEra Energy Seabrook Station, Waltham, MA," May 3, 2016.

7. Simpson Gumpertz & Heger Document No. 160072.02-L-001, "Onsite Support and Testing of Twenty-Eight Cores, NextEra Energy Seabrook Station, Waltham, MA," July 15, 2016.