Contents

36 Case Study: Seabrook Station Unit 1 ASR Problem 3
36.1 Reported Analyses/Investigation 5
36.1.1 Background 5
36.1.2 The Process 6
36.1.3 License Amendment Request 7
36.1.3.1 Ferguson Structural Engineering Laboratory 8
36.1.3.1.1 In/out-of-plane Shear Transfer 8
36.1.3.1.2 Concrete Mix 8
36.1.3.1.3 Beam Tests 8
36.1.3.1.3.1 Dimensions and Loading . 9
36.1.3.1.3.2 Structural Crack 9
36.1.3.1.3.3 Shear Failure 11
36.1.3.2 Building Deformation Aging Management 12
36.1.3.2.1 Crack Index 12
36.1.3.2.2 out-of-plane Expansion 15
36.1.3.2.3 Recorded Expansion 16
36.1.3.3 Building Deformation Assessment 18
36.1.3.3.1 Screening Evaluations 18
36.1.3.3.2 Factored Self-Straining Loads 19
36.1.3.3.3 Finite Element Analysis 19
36.2 Critical Review 22
36.2.1 The Process and Concepts for Development and Review of LAR 22
36.2.1.1 Role of NRC 23
36.2.1.2 Competence and Independence of LAR Preparation and Reviewers 24
36.2.1.3 Code approach 25
36.2.1.4 Tests Based on Tunnel not CEB 25
36.2.1.5 Scaling and Boundary Conditions 26
36.2.1.6 Box Limits not Applicable for Applications to Seabrook Site 27

36.2.2 License Amendment Request 28
36.2.2.1 Ferguson Structural Engineering Laboratory 28
36.2.2.1.1 In/out-of-plane Shear Transfer Mechanisms 28
36.2.2.1.2 Concrete representativeness 29
36.2.2.1.3 Beam Tests 30
36.2.2.1.3.1 Splitting crack 30
36.2.2.1.3.2 Chemical Prestressing Side Effects 32
36.2.2.1.3.3 Fracturing of stirrups 33
36.2.2.1.3.4 Size Effect 33
36.2.2.1.3.5 Creep 33
36.2.2.2 Building Deformation Aging Management 34
36.2.2.2.1 Crack Index 34
36.2.2.2.2 out-of-plane Expansion 37
36.2.2.2.3 Unaddressed Concerns 38
36.2.2.2.3.1 Internal Cracks 38
36.2.2.2.3.2 Potential Delamination 40
36.2.2.2.3.3 Uncertainty in Future Expansion; Threshold Factors 41
36.2.2.2.3.4 “Elastic” Margin for Future Expansion 41
36.2.2.3 Building Deformation Assessment 42
36.2.2.3.1 Screening Evaluation 42
36.2.2.3.2 Factored Self-Straining Loads 43
36.2.2.3.3 Finite Element modeling 44
36.2.2.3.3.1 Lack of Verification and Validation 44
36.2.2.3.3.2 Shell Elements 45
36.2.2.3.3.3 Nonlinear Analysis 46
36.2.2.3.3.4 Demand and Capacity 47
36.2.2.3.3.5 ASR Model 47
36.2.2.3.3.6 ASR Demand 48
36.2.2.3.3.7 Modeling chemical prestressing 48
36.2.2.3.3.8 Static Soil Structure Interaction 49
36.2.2.3.3.9 Dynamic Analysis Model . 49
36.2.2.3.3.10 Dynamic Analysis Time Integration 50
36.2.2.3.3.11 Nonlinear Analysis 51
36.2.2.3.3.12 Dynamic Uplift/Rocking . 51
36.3 Conclusion 51
36.4 Epilogue 53

36.4.1 Summary of the Board's Ruling . . . 54
36.4.1.1 Ruling Details . . . 54
36.4.1.2 Supplemental Testimony: Suggestions to Strengthen the Conditions . . . 57
36.4.2 Personal Final Assessment . . . 58
36.4.3 Chronology Key Phases . . . 60

Bibliography . . . 63

Index Subject . . . 68

Index Names . . . 70

List of Figures

36.1 Cracking at Seabrook 6
36.2 Integration of the three major components of the LAR, adapted from [81] 8
36.3 Concrete and specimens 9
36.4 Shear beam tests 10
36.5 Splitting structural crack, from Wald, Martinez, and Bayrak [88] 11
36.6 Shear test results from [15] 12
36.7 Crack index measurements 13
36.8 Relationship between normalized stiffness E_n and AAR expansion . . 15
36.9 Reported calibration for Seabrook based on NRC safety evaluation [61] 16
36.10 Snap ring borehole extensometer [45] 16
36.11 Directional expansion measurements from Wald, Martinez, and Bayrak [88] 17
36.12 Representative plots of the finite element analyses 21
36.13 in-plane and out-of-plane shear in a CEB [74] 29
36.14 Possible explanation for splitting cracks based on Wald, Martinez, and Bayrak [88] 31
36.15 Finite element simulation of specimen splitting 31
36.16 Issues about shear tests 34
36.17 Impacts of temperature, relative humidity, and reinforcement on limited surface CI measurements [75] 35
36.18 Concerns about out-of-plane expansion measurements 39
36.19 Crack patterns caused by reactive sand and aggregates 40
36.20 Causes and examples of delamination in walls without out-of-plane reinforcement 42
36.21 Example of overlayed four noded shell element 46
36.22 Stress induced anisotropy during volumetric ASR expansion [74] . . . 47
36.23 Problems arising from fitting $y = f(x)$ through interpolation [75] . . . 49

List of Tables

36.1 Severity zones [81] 12
36.2 Acceptance criteria for CI measurements [54] 14
36.3 Recommendations for confirming expansion behavior at Seabrook Station is similar to test programs [54] 17
36.4 ASR Expansion Limits For Structural Limit States 19
36.5 Load combinations [81] 20
36.6 Some commonly used scale factors [78]. 26
36.7 Comparison between FSEL test conditions and Seabrook Station 36

			I							II			III				IV												V				VI				VII	
			Mechanics	Plasticity	Fracture Mechanics	Creep	Seismology	Dynamic	Probability	Fracture Concrete	Chloride diffusion	AAR	FEA Intro	FEA Funadamentals	FEA Nonlinear	FEA Fracture Mechanics	Soil Structure Interaction	Fluid Structure Interacion	Thermal Load; Concrete	Uncertainty Quantification	Probabilistic FEA	Meta Models	PBEE	Ground Motion	Seismic Hazard	Capacity	Fragility	Damage Index	Potential Failure Mode	Dam Risk	Dam Deterministic	Dam Probabilistic	NPP Intro	NPP Aging Management	NPP FEA Others	NPP FEA Authors	AAR; Others	Case Study
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
I	Mechanics	1		3	3	2	0	2	0	3	2	1	0	1	3	3	2	2	3	0	0	0	0	0	0	1	0	1	1	1	2	2	1	2	2	2	2	3
	Plasticity	2			2	1	0	0	0	2	0	0	0	2	3	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1
	Fracture Mechanics	3				1	0	0	0	3	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	1	1	3
	Creep	4					0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1
	Seismology	5						2	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	3	3	0	1	0	0	0	1	1	0	0	1	1	1	0
	Dynamic	6							0	0	0	0	0	0	3	0	2	1	0	0	1	0	1	3	3	1	1	0	1	0	2	2	0	1	2	2	2	1
	Probability	7								0	0	0	0	0	0	0	0	0	0	3	3	2	2	2	2	1	3	1	1	0	0	3	0	2	1	3	2	2
II	Fracture Concrete	8									0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	2	2	1	1	2	3	2	3
	Chloride diffusion	9										1	1	2	0	0	0	0	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	2	0	0
	AAR	10											0	0	0	0	0	0	3	2	1	0	0	0	0	2	1	1	1	1	3	3	1	3	2	3	3	3
III	FEA Intro	11												3	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	3
	FEA Funadamentals	12													3	3	2	2	0	0	1	0	0	0	0	0	0	0	1	0	2	2	1	1	2	2	2	1
	FEA Nonlinear	13														3	1	1	0	0	1	0	1	0	0	3	2	2	2	0	3	2	1	2	3	3	3	3
	FEA Fracture Mechanics	14															0	0	0	0	0	0	0	0	0	1	0	2	2	0	3	2	1	2	3	3	3	3
IV	Soil Structure Interaction	15																1	0	0	0	0	1	1	1	2	1	0	0	0	2	2	1	2	1	3	1	1
	Fluid Structure Interacion	16																	0	0	0	0	0	0	0	0	1	0	1	0	2	2	0	0	0	0	0	0
	Thermal Load; Concrete	17																		0	0	0	0	0	0	0	0	0	1	2	2	3	0	3	1	1	1	0
	Uncertainty Quantification	18																			3	3	2	1	1	2	3	2	1	0	0	3	0	0	0	3	2	1
	Probabilistic FEA	19																				3	2	1	1	2	2	2	1	0	0	3	0	0	0	3	2	2
	Meta Models	20																					0	0	0	1	2	2	0	0	0	3	0	0	1	1	1	0
	PBEE	21																						3	3	3	3	3	2	1	0	3	1	1	0	3	2	0
	Ground Motion	22																							3	2	3	2	1	1	1	3	1	1	2	3	1	0
	Seismic Hazard	23																								1	3	2	1	0	1	3	0	0	1	3	1	0
	Capacity	24																									3	3	2	1	1	3	0	2	1	3	2	0
	Fragility	25																										3	2	2	0	3	0	2	1	3	2	0
	Damage Index	26																											2	1	0	3	0	0	0	3	1	0
V	Potential Failure Mode	27																												3	2	3	0	0	0	1	0	0
	Dam Risk	28																													1	2	0	0	0	0	0	0
	Dam Deterministic	29																														2	0	0	0	0	0	0
	Dam Probabilistic	30																															0	0	0	0	0	0
VI	NPP Intro	31																																3	3	3	3	3
	NPP Aging Management	32																																	2	3	3	3
	NPP FEA Others	33																																		3	1	3
	NPP FEA Authors	34																																			3	3
VII	AAR Others	35																																				1
	Case Study	36																																				

Connection between chapters
0 None
1 Weak
2 Moderate
3 Strong

Chapter 36
Case Study: Seabrook Station Unit 1 ASR Problem

Abstract
In this chapter, we examine a particularly complex case-study, one that brings together multiple issues separately addressed in this book and is thus a fitting last chapter.
More specifically. we examine the response by a single nuclear reactor's private owner and the governmental regulator to aging and cracking issues due to ASR. The reactor, Seabrook Station Unit 1 in New Hampshire, owned and operated by NextEra Energy Seabrook LLC, is the first and only United States reactor where ASR has been discovered. ASR affects significant safety structures at Seabrook, including the containment enclosure building (CEB) which surrounds the reactor containment and protects against radiation releases from the reactor core. Because the adequacy of NextEra's program for detection and monitoring of ASR at Seabrook was subject to an investigation and licensing process by the regulator, the U.S. Nuclear Regulatory Commission (NRC), the response to ASR at Seabrook is relatively well-documented.
As previously discussed, ASR is a highly complex problem that poses significant challenges in any attempt to assess it. In the case of a nuclear reactor, the stakes are particularly high, given the increase in seismic vulnerability that may be induced by ASR. In the case of Seabrook, both the private licensee and the government regulator pursued a code-based engineering heuristic approach. While that approach is standard and often acceptable for addressing nuclear reactor engineering problems, it is not sufficiently sophisticated to account for the complexities of ASR. From the authors'[1] *point of view, the most critical concerns are the licensee's inability to detect internal potential delamination, and the reduced shear capacity of the CEB in resisting seismic excitation. This is a serious deficiency, given the importance of the CEB in protecting public health and safety against the inadvertent release of radioactivity during an earthquake.*

This chapter will provide detailed information on Seabrook Station Unit 1, the first reported nuclear power plant in the U.S. known to suffer from ASR. This detailed information was yielded by private and government investigations into ASR since its discovery in 2009, as well as a license amendment request (LAR) submitted by NextEra to the NRC in 2016. The LAR, which was approved by the NRC technical

[1] Though this chapter will make multiple references to the "authors", it was entirely written by the first author of the book: VES

staff in 2019, sought approval of NextEra's ASR assessment and its proposed ASR monitoring program, and has been used to justify extended operation of Seabrook beyond its current 2030 operating deadline until 2050[2].

Whereas the previous chapter addressed some aging or cracking issues at four nuclear reactors, this chapter will be dedicated exclusively to a single reactor which suffers from ASR. Seabrook is appropriate for separate coverage within this book, for three reasons. First, ASR at Seabrook has been studied for ten years, and thus it provides a good test-case for how aging/shaking and cracking issues, the subject of this book, are addressed in practical terms. Second, the investigations of ASR at Seabrook are relatively well-documented and publicly available in the NRC's Agency wide Documents Access and Management System (ADAMS) the official record-keeping system through which the NRC provides access to publicly available documents [50]. In this context, the NRC should be complimented for the high level of transparency to the public as practically all (non-confidential) information are available for examination. Third, useful comparisons and insights can be gleaned from [88] and [89], reports of contemporaneous research into the same ASR-related issues as were investigated at Seabrook. This research was conducted at the same laboratory that conducted key Seabrook-related testing, used similar if not identical test specimens and protocols, and was supervised by an individual who also had a key role in the Seabrook investigation. In addition, both documents explicitly acknowledged the financial support of a principal Seabrook contractor (MPR).

Naturally, ASR is a very complex issue that has been scrutinized at Seabrook for over 10 years, and relevant information is disseminated in multiple reports. Hence, to increase comprehension/readability, the authors have not hesitated to logically subdivide this chapter in up to five levels of sub sectioning. In addition, the reader will find multiple cross-referencing to topics covered in the first part of the book (Theory).

The authors wish to point out that not all factual information relevant to the Seabrook investigation is publicly available, for two reasons. First, some information has been redacted, i.e., withheld from public disclosure, by NextEra Energy, on the ground that it is proprietary. Second, some information inevitably is unavailable because it simply has not been developed.

To the extent that information has been redacted from publicly available documents and is not available from any other source, it is not discussed in this chapter. The authors apologize for any possible misrepresentations resulting from lack of documentation. On the other hand, the authors make no apologies for reviewing the publicly available documents with the same, if not more (given what is potentially at stake) zeal and scrutiny they would have exercised in reviewing a manuscript submitted for journal publications.

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[2] Disclaimer: In 2014, the first author received a grant from NRC to evaluate ASR, and prepared three detailed reports for the agency that were submitted in 2017. After finishing that work, he served as an expert witness for a small "citizens" group (C-10 Research and Education Foundation) that has challenged the reliability of the LAR in the NRC's license amendment proceeding. A summary of C-10's concerns and the author's testimony can be found in [19], the Proposed Findings of Fact and Conclusions of Law submitted by C-10 to the NRC

Regarding organization: this chapter will be broken into two parts. First the underpinnings of the LAR will be described, primarily based on public information available through ADAMS,. Then, the authors will provide their own assessment (or critical review of the process). Again, it should be noted that all reported details of Seabrook are taken from publicly available documents.

36.1 Reported Analyses/Investigation

36.1.1 Background

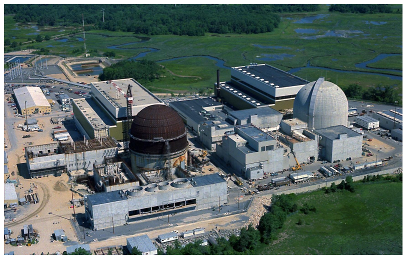
First, it should be noted that the design of Seabrook unit 1 is somewhat unusual, Figure 36.1(b). Unlike many other pressurized water reactors, it has a 30 inch thick CEB "wrapped around" a containment structure (48 inches). The CEB serves to collect any fission products that may leak from the primary containment structure following a loss of coolant accident (LOCA). The area between the two containment structures is maintained at a negative pressure ($\sim$ 0.25" water gauge) to ensure that any leakage into the area is 1) collected; 2) filtered; and 3) released from an elevated location in a controlled and monitored fashion [57].

In 2010, NextEra [48] submitted an application for renewal of the Seabrook Station NPP Unit 1 operating license for another 20 years beyond the current licensing date of May 15, 2030. This renewal process consisted of two concurrent reviews: a technical review of safety issues and an environmental review. For the safety review, the NRC's license renewal rule process and application requirements for commercial power reactors are based on two key principles: a) that the current regulatory process, continued into the extended period of operation, is adequate to ensure that the continuing license basis of all currently operating plants provides an acceptable level of safety, with the possible exception of the detrimental effects of aging on certain passive systems, structures, and components (SSCs), and possibly a few other issues related to safety only during the period of extended operation; and b) each plant's continuing license basis is required to be maintained [59]. Hence, as part of the license renewal process, an aging management program (AMP) is to be identified that is determined to be acceptable to manage potential problems such as ASR on passive safety components such as the CEB.

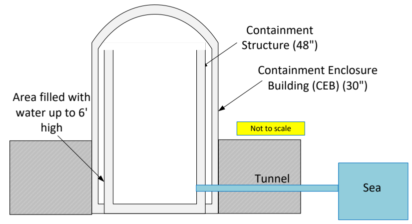
ASR was first discovered in 2010 in a tunnel (Bravo-1) that is supposed to provide intake and discharge cooling water to the ocean (ultimate heat sink). Later on, it was determined that ASR was much more pervasive and affected numerous structures including the concrete CEB. This was clearly highlighted by the NRC's safety evaluation report (SER) [59], Figure 36.1(c).

Consequentially, the NRC informed NextEra that in order to gain approval of its license extension application, it must provide a reasonably accurate assessment of ASR at Seabrook, as well as a monitoring program for the 20-year license extension period.

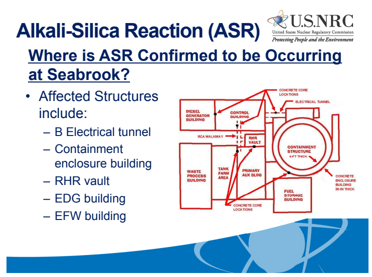
Moreover, the NRC made it clear that a final decision on the license renewal application would not be announced until concrete degradation issues identified at the plant had been satisfactorily addressed, [31].

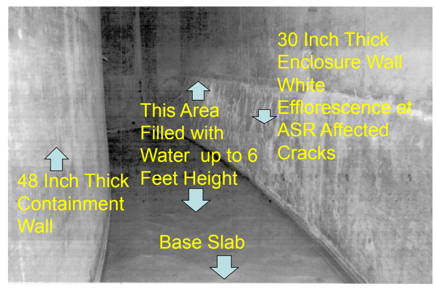


(a) Seabrook. Unit 1 (right) and “moth-balled” Unit 2 (left) in the background https://www.telegram.com/news/20180706/criticism-of-seabrook-nuclear-power-plant-finds-new-momentum



(b) Schematic of the reactor (based on [58]





(c) Identification of damage [58] [60]

Fig. 36.1: Cracking at Seabrook

In 2013, a root cause investigation [51] determined that ASR developed because the concrete mix designs unknowingly utilized a coarse aggregate that, in the long term, would contribute to the Alkali Silica Reaction. Although testing at the time of construction was conducted in accordance with ASTM standards, these standards were subsequently found to be limited in their ability to predict the presence of slow reactive aggregates that produce ASR in the long term. Furthermore, based on the long-standing belief that ASR is not a credible failure mode due to the concrete mix design, the original operating license did not require any consideration of conditions related to ASR in the licensee’s reports involving groundwater intrusion or concrete degradation, or in the structural health monitoring program. Hence, NextEra’s LAR was the first licensing document to address ASR.

36.1.2 The Process

The discovery of ASR at Seabrook constituted the first time that the NRC was confronted with a nuclear reactor infected by ASR. Unfortunately, rather than issuing regulations for NextEra to utilize in assessing the safety of Seabrook, the Agency for all practical purposes delegated this task to NextEra. This was an iterative process, during which the NRC initially asked NextEra to provide the necessary information and analyses, then requested additional details or explanation.

In turn, NextEra contracted with a major reputable consulting company Simpson Gumpertz & Heger (SGH) to lead the task. SGH oversaw the overall project and took the lead in the finite element analysis and monitoring program. It also solicited the assistance of MPR Associates (MPR) a company with extensive expertise in the nuclear engineering field. MPR in turn oversaw Seabrook-related laboratory testing, known as the Large-Scale Testing Program (LSTP), at the Ferguson Structural Engineering Laboratory (FESL) at the University of Texas in Austin. MPR reported the LSTP's results in MPR-ML16216A242 [45] and MPR-ML19170A332 [46]. In addition, the LSTP was described in [15], a report by Dr. Ogyzhan Bayrak, FSEL's director and supervisor of the LSTP.

As will be discussed below, the authors do not question the qualifications of SGH or MPR to address well-understood nuclear engineering problems. However, they showed a lack of understanding of the complex challenges posed by ASR, or even an appreciation of the skill level that would be needed to address it adequately.

In preparing this chapter, the authors also consulted two contemporaneous academic documents regarding ASR testing at the FSEL: [88] a journal article by Wald, Martinez, and Bayrak; and [89], a Ph.D thesis. Both discuss ASR testing using similar if not identical testing materials and protocols as the LSTP. Both papers give credit to MPR as a sponsor, and both also credit Dr. Bayrak as an author [88] or thesis advisor Wald [89]. While neither [88] nor [89] mentions Seabrook, their relevance is established by the close similarity of their concerns, their methods, their timing, and their provenance.

36.1.3 License Amendment Request

In 2016, NextEra submitter the LAR [52]. The major technical arguments of this document will first be reported, and in a subsequent section they will be commented on by the authors. The LAR was essentially based on three major and inter-related components, Figure 36.2:

Large-Scale Testing Program (LSTP): at the Ferguson Structural Engineering Laboratory (FSEL) in which large beams were tested for shear strength, flexural stiffness, and anchor capacity (Only the first will be reviewed). In addition, there was an instrumentation testing component to this task.

Building Deformation Aging Management (BDAM): to monitor and measure the *in-situ* total volumetric ASR expansion since construction.

Building Deformation Assessment (BDA): to assess numerically the integrity of the structures (primarily through the finite element analysis).

To the extent possible, this section will describe each of those components. The authors note that much of the key information described in this section can be found in publicly available redacted versions of the LAR and/or reports by NextEra's consultants that are available on ADAMS. For instance, Dr. Bayrak's report [15] contains information on the dimensions of testing specimens that has been redacted

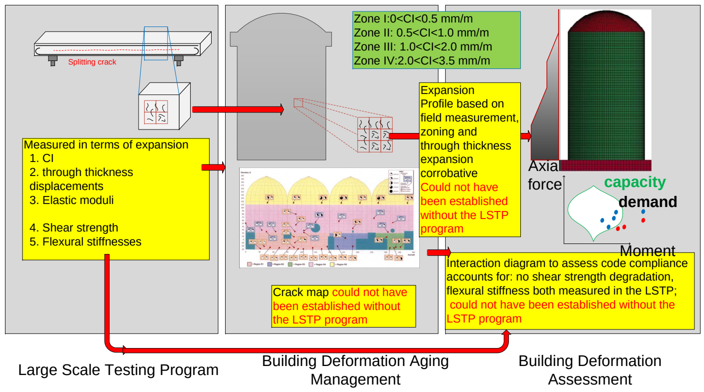


Fig. 36.2: Integration of the three major components of the LAR, adapted from [81]

from public reports by NextEra's consultants. Information that has been redacted from the publicly available reports, and that is not available in any other publicly available document, is not discussed.

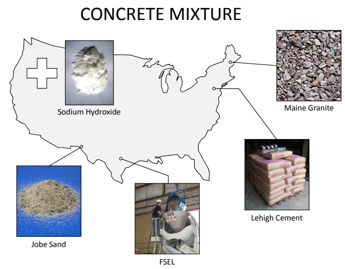
36.1.3.1 Ferguson Structural Engineering Laboratory

36.1.3.1.1 In/out-of-plane Shear Transfer The LSTP did not test for the in-plane shear mode. As the NRC stated

> the LSTP did not test for the in-plane shear mode. This was because the out-of-plane shear failure mode was judged to be more critical than in-plane shear mode (note: nominal permissible out-of-plane shear stress in concrete per the ACI 318-71 code is $2\sqrt{f'_c}$ versus allowable total shear stress of $10\sqrt{f'_c}$ for in-plane shear.
>
> NRC-ML19261A762 [62]

36.1.3.1.2 Concrete Mix One of the first tasks of the LSTP was the design of the concrete mix for the test beam and expansion measurement block. The LSTP concrete mix included high reactive fine aggregate as well as reactive coarse aggregates and cement with high alkali content to accelerate the reaction [54]. Furthermore, MPR claimed that "to the extent practical, concrete constituents were obtained from sources that were consistent with concrete at Seabrook Station" [45]. The mix was used for anchor block, anchorage, the 24-inch shear and instrument specimens, Figure 36.3(b). However, as noted in the figure, all details are regretfully redacted.

36.1.3.1.3 Beam Tests This review will limit itself to the shear tests of the FSEL beam (and will not include anchorage).



(a) Concrete mix design [15]

Parameter	Anchor Block Specimens	Reinforcement Anchorage Specimens	24-inch Shear Specimens	Instrument Specimen
Height	[redacted]	[redacted]	[redacted]	[redacted]
Width	[redacted]	[redacted]	[redacted]	[redacted]
Length	[redacted]	[redacted]	[redacted]	[redacted]
Presence of Lap Splice	No	Yes	No	No
Vertical Rebar Size & Spacing	[redacted]	[redacted]	[redacted]	[redacted]
Horizontal Rebar Size & Spacing	[redacted]	[redacted]	[redacted]	[redacted]
Stirrups Size & Spacing	[redacted]	[redacted]	[redacted]	[redacted]

*Two half-length specimens were fabricated in a single placement

(b) Specimens tested [45]

Fig. 36.3: Concrete and specimens

36.1.3.1.3.1 Dimensions and Loading For shear loading, we relied on MPR-ML16216A242 [45], Figure 36.4(a). However, beam dimensions and loading are not reported by MPR in [45] or [46]. Thus for these parameters we made assumptions based on other relevant sources.

For LSTP test beam dimensions, we assumed the values reported by Bayrak [15], Figure 36.4(b).

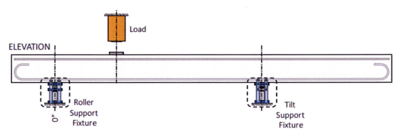
For reinforcement of the LSTP test specimens, we also assumed the same values reported by Wald, Martinez, and Bayrak [88] and Wald [89], Figure 36.4(c). The authors note that the test beam dimensions presented in Bayrak [15] and Wald, Martinez, and Bayrak [88] are similar, Figure 36.4(b) and 36.4(c).

For conditioning of test specimens, we assumed per Wald, Martinez, and Bayrak [88] and Wald [89] that the beams are to be partitioned into three wetting zones: A (away from stirrups and with periodic moist conditions), B (close to stirrups and periodic moist conditioning) and C (close to stirrups) with constant wet conditioning), Figure 36.4(d) and 36.4(e), to assess impact of relative humidity (RH). Finally, we assumed that all specimens were cured inside an environmental conditioning facility as reported by Bayrak [15], Figure 36.4(f), where specimens were:

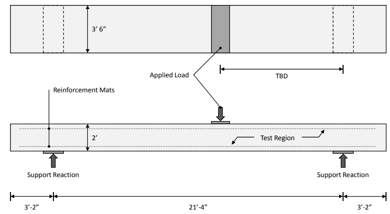
> exposed to temperatures on the order of 5–10°C greater than seasonal ambient outdoor temperatures. In central Texas, ambient temperatures typically ranged between 5 and 40°C from winter to summer. The entire specimen was subjected to alternating, week-long wet and dry conditioning cycles using mist foggers to produce a periodic state of 90–100% relative humidity within the storage space.
>
> Wald, Martinez, and Bayrak [88].

36.1.3.1.3.2 Structural Crack MPR reported the presence of a large crack on the LSTP test beam, which it asserted was confined to the specimen edges and penetrated only a few inches into the specimen height [45]. According to NextEra:

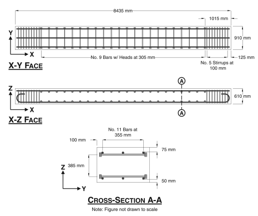
> This large crack is not representative of expansion behavior of structures at Seabrook Station, which have a network of members that are either cast together or integrally cast with special joint reinforcing details. In an actual structure, a vertical wall with two-dimensional



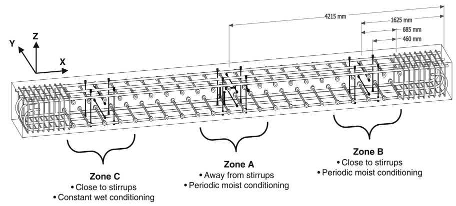
(a) Shear loading MPR-ML16216A242 [45]



(b) Dimensions Bayrak [15]



(c) Reinforcement Wald, Martinez, and Bayrak [88]



(d) Wetting zones Wald, Martinez, and Bayrak [88]

(e) Conditioning Bayrak [15]

(f) Environmental conditioning facility Wald, Martinez, and Bayrak [88]

Fig. 36.4: Shear beam tests

reinforcement will be confined in the through-thickness direction at its intersection with neighboring members (i.e., at the top and bottom with floor and ceiling slabs, at the sides with perpendicular walls, and uniformly along the wall face by the subgrade for below grade external walls). The confinement provided by the network of members in a structure is likely sufficient to preclude large cracks like those seen in the FSEL test specimens.

MPR-ML16216A242 [45]

Wald, Martinez, and Bayrak [88] also described a structural crack in their test specimen:

the formation and subsequent growth of large cracks on the side (x-z) surfaces of the specimen perpendicular to the mats of reinforcement, [Figure 36.5]. The cracks were located midway between the mats of reinforcement and oriented parallel to the x direction reinforcement. The cracks were located only in the biaxially reinforced part of the beam; they did not extend into the beam ends where stirrups were present.

> The cracks on the x-z faces of the specimens were identified to be caused largely by a mechanical boundary effect rather than purely due to ASR expansion perpendicular to the cracks (i.e., in the z direction). It was suggested that the cracks formed due to tension induced in the outer fibers of the specimen from nonuniform restraint to expansion provided locally by the two discretely placed mats of reinforcement. The concrete between these reinforcing layers, separated by more than 350 mm, was freer to expand. The net effect was a concentrated deformation of concrete near the reinforced surfaces with the interior concrete outwardly "bending" between reinforcement locations, which acted as supports.
>
> Wald, Martinez, and Bayrak [88]

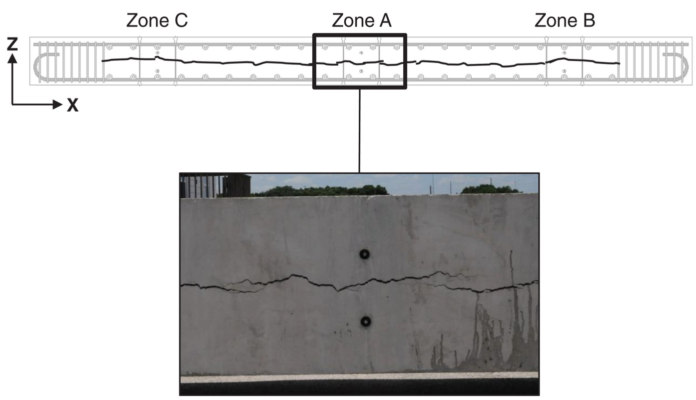
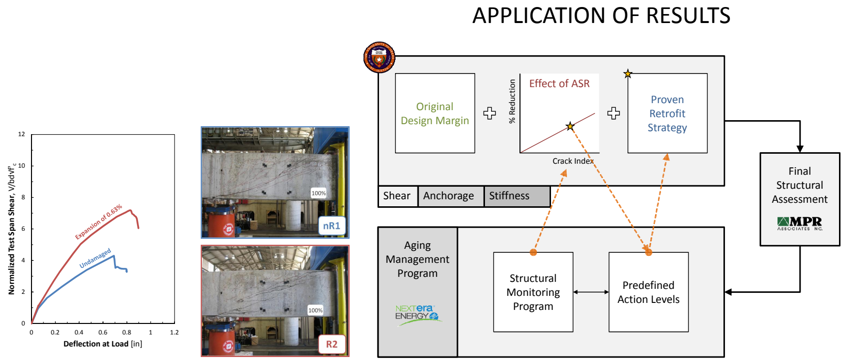


Fig. 36.5: Splitting structural crack, from Wald, Martinez, and Bayrak [88]

36.1.3.1.3.3 Shear Failure Per [45], shear capacity was based on the ACI 318 definition: onset of diagonal cracking which was identified visually. In addition there was a slight reduction in load carrying capacity shown on the load-deflection curve. Yet, per [15] testing continued until failure of the specimen, as identified by a rapid loss in load carrying capacity, Figures 36.6(a) and 36.6(b).

As expected and widely reported in the literature [21] [5] [23] [90], an increase in shear capacity was reported in conjunction with the ASR expansion. All shear test results exceed the theoretical shear capacity calculated per ACI 318-71, which is a normalized shear capacity of 2.0. The large number of tests and the repeatability of the data provide strong confidence in the conclusion that there was no adverse effect on shear capacity at the expansion levels tested. Likewise, the stiffness in ASR-affected test specimens is reported to be clearly greater than the control test specimen and that there was an increasing trend with respect to through-thickness expansion [45].



(a) Representative results (b) Application of results

Fig. 36.6: Shear test results from [15]

36.1.3.2 Building Deformation Aging Management

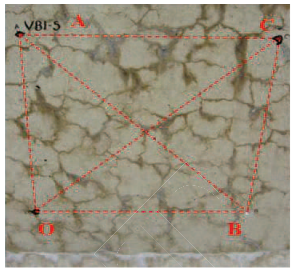
The Building Deformation Aging Management Program (BDAM) uses visual inspections of cracking associated with the Structures Monitoring Program and out-of-plane expansion measurements associated with the ASR to identify buildings that are experiencing deformation. Cracks are measured by the classical crack index (CI) approach to measure in-plane expansion. The second method is an innovative one (never noted by the authors in the context of ASR measurements) that measures the through thickness expansion. Through thickness expansion measurements are expected to be much higher than the former [88] as evidenced in Figure 36.11.

36.1.3.2.1 Crack Index Crack indices, Figure 36.7, will be correlated to measured expansions as well as structural tests results for use in Seabrook Station [15]. The CEB was subdivided into four regions selected to contain CI values that are generally within the limits of an ASR Severity Zone defined as [81], Table 36.1.

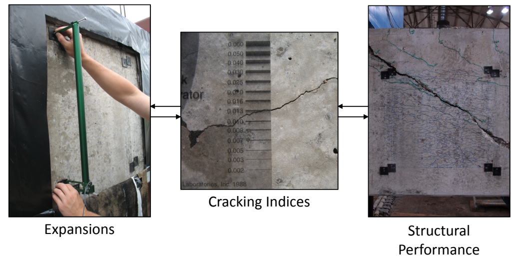
Table 36.1: Severity zones [81]

Zone	CI [mm/m] Min	CI [mm/m] Max
I	0	0.5
II	0.5	1.0
III	1.0	2.0
IV	2.0	3.5

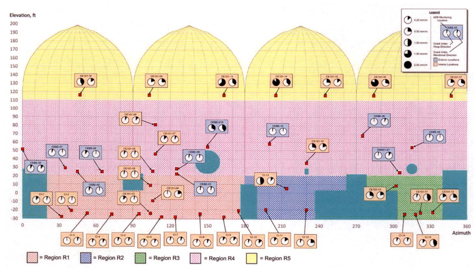
CI readings in turns are subdivided in three tiers, as shown in Table 36.2.



(a) Crack Index grid [30]



(b) Expansion monitoring by the FSEL [15]



(c) ASR regions and crack index measurement locations [81]

Fig. 36.7: Crack index measurements

Table 36.2: Acceptance criteria for CI measurements [54]

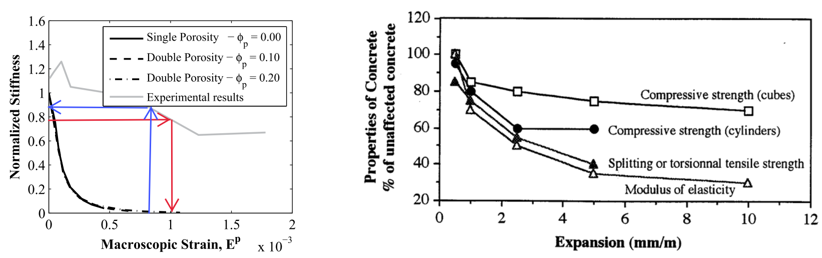
Tier	Structures Monitoring Program	Recommendation for Individual Concrete Components	Criteria
3	Unacceptable (requires further evaluation)	• Structural Evaluation • Implement enhanced ASR monitoring such as through-wall expansion monitoring using Extensometers	1.0 mm/m (0.1%) or greater strain measurement (CCI or pin-pin)
2	Acceptable with deficiencies	Quantitative Monitoring and Trending	• 0.5 mm/m (0.05%) or greater strain measurement (CCI or pin-pin) • CI or pin-pin measurement of greater than 0.5mm/m (0.05%) in the vertical and horizontal direction
		Qualitative Monitoring	Any area with visual presence of ASR (as defined in [87] accompanied by a CI of less than 0.5 mm/m (0.05%) in the vertical and horizontal directions.
1	Acceptable	Routine inspection as prescribed by the Structural Monitoring Program	Area has no indication of pattern cracking or water ingress; No visual symptoms of ASR

36.1.3.2.2 out-of-plane Expansion The out of plane expansion is composed of two stages: the first is the past expansion since construction until coring of the wall, and the later starting from coring and installation of a recording device.

1. Past Expansion can be readily determined if we can quantify the normalized elastic modulus E_n

$$E_n = \frac{E_{present}}{E_{28\text{ days}}} \qquad < 1 \tag{36.1}$$

versus AAR expansion.
Indeed, it should be recalled that the Elastic modulus decreases with increase of AAR expansion (Equation **??**), Institution of Structural Engineers [38] and Thomas, Fournier, and Folliard [86]. The change can be expressed as a normalized quantity as shown by [27], Figure 36.8(a) or 36.8(b). One can first experimentally determine the



(a) Esposito and Hendriks [27]

(b) Institution of Structural Engineers [38]

Fig. 36.8: Relationship between normalized stiffness E_n and AAR expansion

curves following the blue arrow in Figure 36.8(a) using naturally the *same* concrete under accelerated conditions. However, one can also use the curve in reverse: given a separately obtained E_n, seek the corresponding expansion of a *different* concrete that has expanded for many years.
Following the red path above, the initial (28 day) elastic modulus itself can be determined from the ACI approximation

$$E_{28\text{ days}} = 57,000\sqrt{f'_{c,\,28\text{ days}}} \tag{36.2}$$

And where f'_c is the recorded 28 days strength (in psi units). Present elastic modulus $E_{present}$ can be measured from a core based using ASTM C469 [10].
Such a so-called "corroborative modulus expansion" is reported by NRC's safety evaluation [61] to measure the through thickness expansion.

2. Future Expansion through the wall is recorded by a commercial device: snap ring borehole extensometer (SRBE), Figure 36.10 [45].

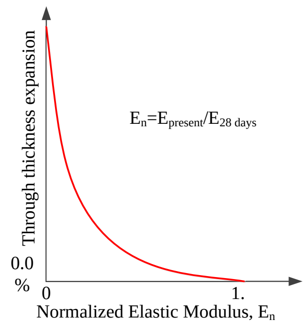


Fig. 36.9: Reported calibration for Seabrook based on NRC safety evaluation [61]

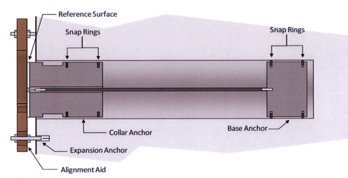


Fig. 36.10: Snap ring borehole extensometer [45]

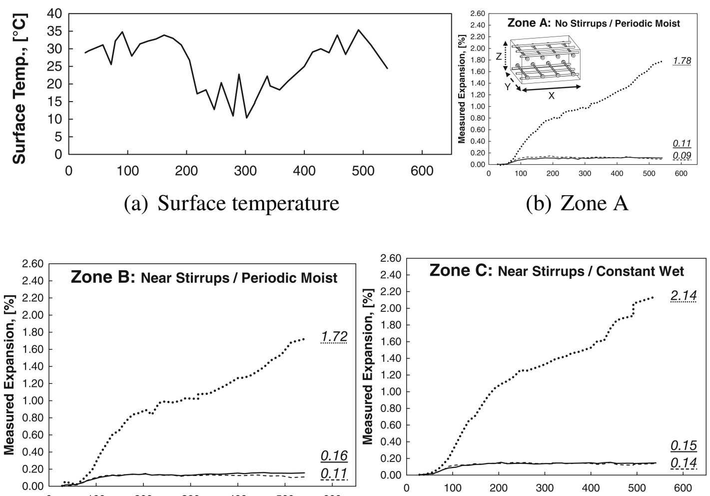
Finally, the volumetric total ASR strain is the sum of the through thickness (by far the largest) and the two in-plane expansions measured by CI.
To confirm that expansion behavior at Seabrook Station is similar to the FSEL test specimens, NextEra-ML18141A785 [54] recommends that checks identified in table 36.3 be conducted.

36.1.3.2.3 Recorded Expansion Finally, with regard to the directional expansions for the three zones, we credit the conclusions by Wald, Martinez, and Bayrak [88] that:

> each biaxially restrained portion of the beam exhibited a similar expansion response. At all times, expansions in the unreinforced direction (z) were greater than those in the reinforced directions (x and y). Despite differences in gross reinforcing ratios for the x and y directions, the beam expanded nearly identically in the two directions. At approximately 90-100 days after casting, there was a relatively abrupt shift in expansion behavior. The data, [Figure 36.11] indicate that the expansions in the reinforced directions effectively stopped while the beam continued to expand in the unreinforced direction. The expansions in the X and Y directions reached maxima of approximately 0.1-0.15%. These expansions were less than an approximate yielding strain of 0.2% for the reinforcement. Continued expansion of the beam in the z direction was sensitive to thermal fluctuations with less additional expansion occurring during colder months. The rate of this expansion in the z direction was increased in Zone C, which was under constant wet conditioning.
>
> Wald, Martinez, and Bayrak [88]

Table 36.3: Recommendations for confirming expansion behavior at Seabrook Station is similar to test programs [54]

Objective	Recommended Approach	When
Ongoing Monitoring		
Expansion within limits from test programs	Compare measured in-plane expansion (ε_{xy}), through-thickness expansion (ε_z), and volumetric expansion (ε_v) at the plant to limits from test programs ($\varepsilon_{xy} \leq$ [redacted]%, $\varepsilon_z \leq$ [redacted]%, and $\varepsilon_v <$ [redacted]%)	Intervals as specified in Structures Monitoring Program (SMP) or Aging Management Program (AMP)
Lack of mid-plane crack	Inspect cores removed from ASR-affected structures (and boreholes) for evidence of mid-plane cracks	When cores are removed to install extensometers or for other reasons.
Periodic Confirmation of Expansion Behavior		
Lack of mid-plane crack	Review of records for cores removed to date or since last assessment	Periodic assessments • At least 5 years prior to the Period of Extended Operations (PEO) • Every 10 years thereafter
Expansion initially similar in all directions but becomes preferential in z-direction	Compare ε_{xy} to ε_z using a plot of ε_z versus in-plane expansion	
Expansions within range observed in test programs	Compare measured ε_{xy}, ε_z, and ε_v at the plant to limits from test programs ($\varepsilon_{xy} \leq$ [redacted]%, $\varepsilon_z \leq$ [redacted]%, and $\varepsilon_v <$ [redacted]%) to check margin for future expansion	
Corroborate modulus-expansion correlation with plant data	For 20% of the extensometer locations: • Remove cores for modulus testing. • Compare ε_z determined from the modulus-expansion correlation with ε_z determined from the extensometer and the original modulus result. A detailed explanation of this approach is provided in Appendix C.	At least 5 years prior to PEO (initial study) and 10 years thereafter (follow-up study).



(a) Surface temperature (b) Zone A

(c) Zone B (d) Zone C

Fig. 36.11: Directional expansion measurements from Wald, Martinez, and Bayrak [88]

36.1.3.3 Building Deformation Assessment

36.1.3.3.1 Screening Evaluations The LAR [53] defines self-straining loads as a term that encompasses ASR expansion (largest contributor), creep, and shrinkage as those contribute to the observed deformations and were not included in the original analysis.

A three-stage screening analysis is applied to Seismic category I structure [3], Figure 36.1(c) although the inner containment is assessed separately. All three stages of the evaluation process use the original design acceptance criteria given in Seabrook's Updated Final Safety Analysis Report (UFSAR) [49]. In applying the three-stage process to each structure, the original design loads are combined with the self-straining.

> Each stage of the analysis applies more sophisticated methods and uses additional field data to improve the accuracy of the results.
>
> Stage One, Screening Evaluation: Each of the seismic Category I structures is screened for susceptibility to structural deformation caused by ASR using existing field data and conservative calculations.
>
> Stage Two, Analytical Evaluation: An analytical evaluation is performed for each structure that the Stage One Screening Evaluation identifies as susceptible to deformation but does not satisfy ACI 318-71 acceptance criteria. A finite element model of the structure is used to estimate structural demands due to self-straining loads, while all other demands are taken from existing design calculations. Additional field data are obtained to use in the analysis. The evaluation verifies compliance with ACI 318-71 using the same criteria as the original design.
>
> Stage Three, Detailed Evaluation: A detailed design confirmation calculation is performed when the Stage Two Analytical Evaluation concludes that some area of a structure does not satisfy ACI 318-71 acceptance criteria or when the structure has sufficient deformation that may impact demands computed in the original design. The detailed evaluation uses the Stage Two finite element model to compute demands due to self-straining loads as well as all other design loads. In the Stage Three evaluation, consideration is given to cracked section properties, self-limiting secondary stresses, and the redistribution of structural demands when sufficient ductility is available.
>
> NextEra-ML16216A240 [53]

As shown in Figure 36.1(c), the inner containment structure is protected from the outside elements by the CEB. Thus, NextEra considers it to be less susceptible to deleterious effects of ASR. While NextEra states on the one hand that assessment will be performed using the three stage process discussed above, on the other it states that it is expected that the Containment will be screened as only Stage 1 evaluation. Each analysis stage will determine threshold monitoring limits to define the criteria for re-evaluating structures with deformation. The threshold monitoring limits are specific to each structure and will be included in the Structural Monitoring Program. Monitoring and acceptance criteria for ASR cracking and deformation of structures are shown in Table 36.4.

[3] Defined by the NRC as "Structures, systems, and components that are designed and built to withstand the maximum potential earthquake stresses for the particular region where a nuclear plant is sited (https://www.nrc.gov/reading-rm/basic-ref/glossary/seismic-category-i.html)."

Table 36.4: ASR Expansion Limits For Structural Limit States

Structural Limit State	ASR Expansion Limit
Shear	[redacted]% through-thickness
Flexure	[redacted]% through-thickness
Reinforcement Anchorage	[redacted]% through-thickness
Anchors	[redacted]% in-plane

36.1.3.3.2 Factored Self-Straining Loads In accordance with the load and resistance factor design (LRFD) method of [2], factored load combinations are used, Table 36.5. The factored self-straining loads are combined with the original design load combination for the screening and analytical evaluations discussed above. The load factors for dead load are used for the shrinkage, creep, and swelling loads in accordance with ACI 318-71. However, since the code does not have load factors applied to ASR, those were developed to yield reliability index values (§**??**) similar to load factors specified in ACI 318-71 [80]. The ASR load factors account for the uncertainty in ASR expansion by considering the variability in crack index measurements from all ASR monitoring grids in Seabrook Station structures. For unusual load combinations, such as SSE and tornado wind combinations, all load factors are taken as 1.0 [81].

36.1.3.3.3 Finite Element Analysis The reported finite element analysis [81] is composed of the following:

Static Analysis: All analyses are linear elastic and use shell elements. ASR expansion is simulated by applying an isotropic thermal expansion to the elements representing the CEB concrete. Steel reinforcement membrane elements are included in the model and are given thicknesses based on the total area of reinforcement provided. The expansion of the concrete creates tension in the steel membrane elements, which also causes a corresponding compression force in the concrete elements.

Applied ASR expansion magnitude and distribution are adjusted to match field measurements in two ways: First, strain in the finite element model caused by unfactored ASR expansion of the CEB wall is compared with field measurements of CI. In general there is a match. Second, deformations due to unfactored sustained loads plus unfactored self-straining loads are compared to field measurements of seismic gap (the structural gap between the CEB and adjoining concrete structures). There is recognition that abrupt transitions in ASR expansion can cause stress concentration, hence an artificial taper (about 60 ft long) is used between regions.

For the CEB analysis, factored (to account for uncertainty) ASR loads are amplified by an additional threshold factor (1.2) to account for additional ASR expansion that may occur in the future. This factor applies only to the CEB.

Table 36.5: Load combinations [81]

Label[1]	Combination
N0 1	(2.0× k_{th})S_a + 1.4S_w + 1.40 + 1. 7L + 1. 7H
N0 2	(1.5× k_{th})S_a + 1.4S_w + 1.050 + 1.28L + 1.28H
N0 3	(1.0× k_{th})S_a + 1.4S_w + 1.00 + 1.0L + 1.0H + 1.5P_a
OBE 1	(1.3× k_{th})S_a + 1.4S_w + 1.40 + 1.7L + 1.9Eo + 1.7H + 1.9H_e
OBE 2	(1.0× k_{th})S_a + 1.4S_w + 1.050 + 1.28L + 1.43Eo + 1.28H + 1.43H_e
OBE 3	(1.3× k_{th})S_a + 1.4S_w + 1.20 + 1.9Eo + 1. 7H + 1.9H_e
OBE 4	(1.0× k_{th})S_a + 1.4S_w + 1.00 + 1.0L + 1.25Eo + 1.0H + 1.25H_e + 1.25P_a
SSE	(1.0× k_{th})S_a + 1.4S_w + 1.00 + 1.0L + 1.0Ess + 1.0H + 1.0H_s
SSE	(1.0× k_{th})S_a + 1.4S_w + 1.00 + 1.0L + 1.0Ess + 1.0H + 1.0H_s + 1.0P_a
W 1	(1.× k_{th})S_a + 1.4S_w + 1.40 + 1.7L + 1.7W + 1.7H
W 2	(1.28× k_{th})S_a + 1.4S_w + 1.050 + 1.28L + 1.3W + 1.28H
W 3	(1.?× k_{th})S_a + 1.4S_w+ 1.20+1.7W+ 1.7H
W 4	(1.0× k_{th})S_a + 1.4S_w + 1.00 + 1.0L + 1.0Wt + 1.0H
W 5	(1.0× k_{th})S_a + 1.4S_w + 1.00 + 1.0L + 1.0W + 1.0ls
W 6	(1.0× k_{th})S_a + 1.4S_w + 1.00 + 1.0L + 1.0W + 1.0ls + 1.0F

1 NO: Normal load comb1nations (non-se1sm1c and non-wind)
QBE Load combinations including operating basis earthquake E_a
SSE Load combinations including safe shutdown earthquake E_{ss}
W Load combinations including wind, W, and tornado wind, W_t
2 OBE and SSE combinations are performed for each of the directional combinations

D	Dead load (includes hydrostatic pressure)	L	Live load
H	Lateral static soil pressure	w	Wind load
E_a	Operating basis earthquake (OBE)	E_{ss}	Safe shutdown earthquake (SSE)
H_e	Dynamic earth pressure due to OBE	$H-s$	Dynamic earth pressure due to SSE
W_t	Tornado wind load	P_a	Accidental Pressure load
L_s	Unusual snow load	F	Design basis flood load
S_a	ASR expansion of wall and backfill concrete	S_c	Creep (self-straining force)
S_h	Shrinkage (self-straining force)	S_w	Concrete swelling (self-straining force)

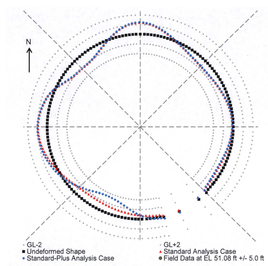
Dynamic Analysis: A finite element model of the most limiting area was developed to address the potential of an adverse dynamic response associated with the apparent modulus of elasticity tests conducted on the extracted core samples. According to this model, a differential analysis of the structure with various modulus changes could be performed [51]. This analysis concluded that

> Finite Element Model Results:
>
> - Maximum acceleration profiles and In Structure Response Spectrum not significantly impacted by ASR affected properties
> - Distribution of forces and moments are not significantly impacted by ASR affected properties.
>
> NextEra-ML121160422 [50]

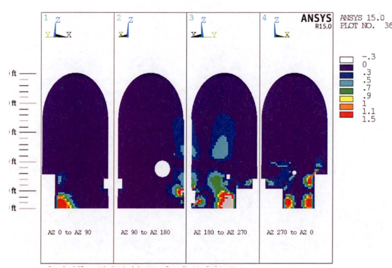
Structural Evaluation: Analyses are conducted for multiple load cases using an element by element approach as well as section cut approach. Evaluation criteria

are based on strength according to [2]. Maximum displacements are are compared against clearances with adjacent structures.
Finally, it is argued that

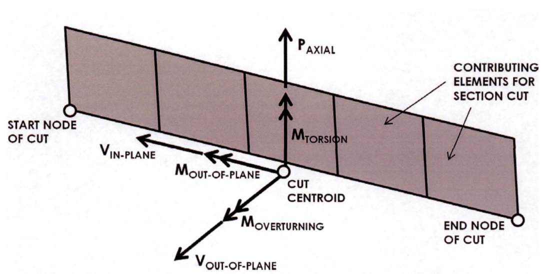
> Evaluating a structure on an element-by-element basis is considered a conservative approach because it does not allow for concentrations of high demands to be distributed locally within the structure. Factored demand exceeding capacity in the element-by-element evaluation does not necessarily indicate a structural deficiency. Since a relatively small finite element size is used in the analyses, stress concentrations can cause localized capacity exceedances in the element by element evaluation which may not have any real structural impact. If an element's capacity is exceeded in the element-by-element evaluation, the area is evaluated again using a section cut approach. If the element-by-element capacity exceedance is identified as insignificant (i.e., a stress concentration that will not impact structural performance), then further analysis/evaluation is not performed.
>
> Simpson Gumpertz & Heger-ML16279A049 [81]



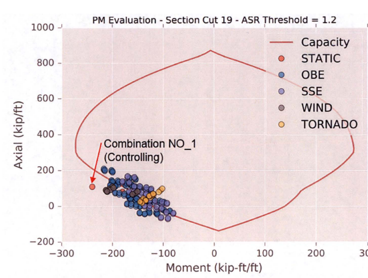
(a) Comparison between as-deformed condition simulations and field measurements [81]



(b) Representative finite element analysis model using shell elements [81]



(c) Section cut resultant forces and moments at cut centroid [81]



(d) Interaction diagram check [81]

Fig. 36.12: Representative plots of the finite element analyses

36.2 Critical Review

At issue here is how to make a prediction of remaining service life. And of course, service life must be reasonably safe as required by federal law (the Atomic Energy Act). In pursuing this important (if not vital) task, NextEra was confronted with a common problem plaguing engineers who pursue similar objectives. First, there is a glaring absence of codes for the assessment of existing structures[4]. This is particularly troublesome when the aging of our infrastructure is widely recognized. The second is the danger of entrusting engineers, reared in the design of new structures, with the safety assessment of older ones. Those two tasks require two very different skill sets; simply put, the former may be performed by an engineer with minimum training (as one would "simply" have to follow the myriad of code provisions), but the latter would require one to have had some graduate education. And this was blatantly clear throughout our review. As stated by the drafters of ASCE 4-16 [6]

> Regulatory government agencies are frequently faced with decisions related to the seismic design of operating nuclear facilities... As new information becomes available, the design basis may be challenged. ... Because of its pervasive nature, an earthquake will"seek out" facility vulnerabilities... At issue is whether the changes can be accommodated within the inherent capacity of the original design or whether facility modifications are required.... current design practice does not provide a picture of the actual margin to failure, nor does it provide enough information to make realistic estimates of seismic risk.
>
> ASCE 4-16 [6]

Unfortunately, however such recommendations[5] were mostly ignored.
Hence, guided by this spirit, and ultimately concerned by the lack of a rigor scientific study, this section will now "dissect" the LAR using basic principles of scientific/engineering examination. While the authors acknowledge that the NRC technical staff has approved the LAR, they have applied their own independent analysis.

36.2.1 The Process and Concepts for Development and Review of LAR

Having reported to the best of our ability the complex technical underpinning of the LAR, this section will review it. By now it is quite evident that a code-based engineering heuristic approach was followed by NextEra and approved by the NRC. Under normal circumstances, this would be perfectly acceptable. However, in this case of ASR we are dealing with an exceedingly complex and challenging problem, one with which the the industry annd the NRC have been confronted for the first time, and one where an erroneous safety assessment could lead to a nonconservative response and perhaps devastating consequences. The authors see a disturbing

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[4] The ACI 365 code "Service-Life-Prediction; State-of-the-Art Report" [3] has 10 lines under §4.3 focusing on *Prediction of remaining service life*.

[5] Though written for challenges caused by seismic considerations, one could easily substitute "seismic" with "ASR" without loss of relevance

dichotomy between the relatively simplistic engineering approach taken by NextEra and the NRC, and the much more rigorous "first principle" based analytical approach used in the numerous analyses reported throughout this book.
In-fine it is hoped that this section will be ultimately perceived by all as constructive criticisms driven by a thirst for scientific rigor.

36.2.1.1 Role of NRC

It is evident that rather than *regulating* ASR, the NRC instead subcontracted the work of determining how to assess the extent and gravity f ASR at Seabrook to the very same corporation it is supposed to oversee. While the NRC posed a number of questions to NextEra during its technical review, the agency did not exercise due diligence in scrutinizing the scientific validity of NextEra's response. Unfortunately, this is reminiscent of the problem that came to plague the Boeing 737 MAX. As stated by the Boeing 737 MAX flight Control System Joint Authorities Technical Review (JATR)

> 1. A complicated system is characterized by a linear relationship between cause and effect, whereas a complex system is characterized by a non-linear relationship between cause and effect, such that small causes could lead to very large effects.
> 2. The Federal Aviation Administration (FAA) failed to provide an independent assessment of the adequacy of the Boeing proposed certification activities...
> 3. The BASOO [FAA's Boeing Aviation Safety Oversight Office] delegated a high percentage of approvals and findings of compliance to the Boeing ODA for the B737 MAX program.
> 4. [FAA should] conduct a workforce review of the BASOO engineer staffing level to ensure there is a sufficient number of experienced specialists to adequately perform certification and oversight duties, commensurate with the extent of work being performed by Boeing. The workforce levels should be such that decisions to retain responsibility for finding compliance are not constrained by a lack of experienced engineers.
> 5. [FAA should encourage applicants to] have a system safety function that is independent from the design organization, with the authority to impartially assess aircraft safety and influence the aircraft/system design details.
> 6. The FAA and applicants should develop, validate, and implement analytical tools appropriate for the analysis of complex systems.
>
> JATR [39]

Each one of those quotes would be applicable to the approach taken by NextEra and the NRC:

1. As Boeing, NextEra erroneously assumed that it was dealing with merely a complicated system, whereas it is actually dealing with a complex one.
2. There was no *independent assessment of the adequacy* of the LAR.
3. The NRC *delegated a high percentage of approvals and findings of* the LAR to NextEra.
4. The NRC should have had *a workforce review* and *engineer staffing level to ensure there is a sufficient number of experienced specialists to adequately perform*

certification and oversight duties, commensurate with the extent of work being performed by NextEra.

5. The NRC should *have a system safety function that is independent from the design organization, with the authority to impartially assess* nuclear power plant safety.
6. The NRC and NextEra *should develop, validate, and implement analytical tools appropriate for the analysis of complex systems*.

36.2.1.2 Competence and Independence of LAR Preparation and Reviewers

Regretfully, the LAR was not prepared by persons who were competent in the complexity of ASR, nor was it peer-reviewed by an independent panel of experts. In addition, while the LAR was reviewed by two layers of government reviewers, none of them had the requisite competence to evaluate the LAR. More specifically:

- Neither NextEra nor the SGH and MPR consulting firms used engineers with significant and broad experience in ASR.
- While NextEra claimed to have support from the Brookhaven National Laboratory, the focus of the Brookhaven support was mainly on the [linear elastic!] analysis methodology, and the Brookhaven scientists did not have any ASR expertise [63, pg. 269, l. 9].
- The only external academic expert consulted by NextEra was Prof. Ellingwood, an eminent researcher. However, Dr. Ellingwood reviewed only the load amplification factor for ASR, Table [63, pg. 799, l. 14]. He was not retained to review the entire LAR or NextEra's overall solution strategy.
- The head internal reviewer at the NRC is a senior geotechnical engineer, with no expertise whatsoever in ASR. The closest link he has to expertise in concrete is that "he looks at the performance of concrete structures and vaults for housing low-level waste" [63, pg. 799, l. 14].
- Neither NextEra nor the NRC staff sought to apply the current state of knowledge regarding ASR to obtain independent review of their work [63, pg. 285, l. 18]
- The NRC staff did not even consult research that it had contracted for. When the NRC staff was asked if they have seen the report written by the first author under the NRC's grant [56][6], the NRC's reply was "No. We, we have only seen the, the summary report that's part of the exhibit here" [63, pg. 875, l. 1].
- The NRC stated that their regional office did get an independent review of the ASR, the ASR issue at Seabrook by a faculty at the University of Pittsburgh.

> [H]e helped the NRC staff to, to do our initial assessments of the safety of the ASR issue and its effect on structures. He accompanied us on, on a couple of inspections and also assisted the NRC in forming its confirmatory action letter which was an enforcement interaction where, where the licensee was required To do corrective actions. And, that was, that was with the help of, of Prof. [xxx] who is a professor of structural engineering and mechanics from the University of Pittsburgh, and also had expertise in, in ASR.
>
> NRC-ML19312B609 [63, p. 801, l. 19]

[6] Grant No. NRC-HQ-60-14-G-0010, [70] [69] [72] [73].

To the best of the authors' knowledge, the faculty mentioned has never undertaken any research on ASR, nor had he published any peer reviewed journal article on said topic at the time he was retained.

- While NextEra claimed to have support from the Brookhaven National Laboratory, the focus of the Brookhaven support was mainly on the [linear elastic!] analysis methodology, and the Brookhaven scientists did not have any ASR expertise [63, pg. 269, l. 9].
- As required by the Atomic Energy Act, NRC's independent watchdog, the Advisory Committee on Reactor Safeguard (ACRS) reviewed the LAR and also the NRC's review process. The ACRS found both were satisfactory. But none of the ACRS officials involved in these reviews was specifically familiar with ASR. Nor was any of these individuals a structural engineer [63, pg. 267, l. 21].
- A number of former NRC/DOE employees would have been eminently qualified to perform a peer review. Inexplicably, their technical advise was not solicited.

36.2.1.3 Code approach

As discussed above, NextEra took a strictly code-based approach to evaluating ASR at Seabrook. In this context, the licensee carries a burden to demonstrate that the structures will remain safe and operable. The structures must also continue to stay within their design and licensing bases. Despite the complexity and potential gravity of the problem at hand, NextEra (with the consent of the NRC) opted to simply demonstrate that the "design codes and original licensing basis remains intact" [63, pg 574 l. 17]. In fact, however, applying the code was not a simple matter, given that ASR was not (for obvious reasons) addressed by ACI 318-71 [2]. Thus, NextEra followed a very convoluted approach to propose modifications to the code that would –according to NextEra– address ASR. Hence, for NextEra looking beyond the codes was outside of the scope of the requirement for the structures to remain operable and to stay within the bounds of their licensing basis [63, pg. 574, l. 12].
It is most regretful that the NRC has endorsed this simplistic approach, because it lacks the level of sophistication needed to address the extremely complex problem of ASR in a CEB. It is the authors' understanding that the Atomic Energy Act gives the NRC full statutory authority to take all measures needed to protect public health and safety, including requiring a stricter and more sophisticated science-based approach to ASR (as opposed to the inadequately sophisticated engineering code). It is however unacceptable to wait for accidents to happen for a forensic investigation to finally perform proper nonlinear analyses.

36.2.1.4 Tests Based on Tunnel not CEB

All the tests at the FSEL were driven by considerations of the Bravo electrical tunnel, which was deemed to be the most critical component. Indeed, SGH states that: "The hydrostatic load is significantly larger ... than seismic load. It varies with structure" [63, pg. 1048, l. 25]. And the NRC stated that

> So, well, when we looked at the – when we were reviewing the LAR, we looked at what the licensee proposed and that was to use the same geometric configurations and dimensions and reinforcement of the worst area that we were aware of, which was the bravo electrical tunnel. So there was we agreed that that – that it would be reasonable to use that area to model considering that that was the worst ASR area.
>
> NRC-ML19312B609 [63, pg. 1047, l. 14]

For this reason, no scaling was performed.

36.2.1.5 Scaling and Boundary Conditions

Ultimately, a test (FSEL) is a model of a prototype (Seabrook), and Buckingham's law [17] of similitude must be respected to the extent possible. In other words, all prototypes' dimensions must be scaled by the same factor λ in order to correctly model the prototype, Table 36.6

Quantity	Prototype	Model at λ–g
Length	1	$1/\lambda$
Time	1	$1/\lambda$
Mass	1	$1/\lambda^3$
Force	1	$1/\lambda^2$
Energy	1	$1/\lambda^3$
Fracture Energy	1	$1/\lambda$
Pressure	1	1
Stress	1	1
Strain	1	1
Density	1	1

Table 36.6: Some commonly used scale factors [78].

So, when asked whether models have been the results of a proper scaling analysis, NextEra's reply was

> In terms of a specific scaling analysis, we didn't perform one, but we did note that the containment enclosure building was different in that up to a certain height it's got triaxial reinforcement. The amount of ASR was much – was different and less severe than the bravo electrical tunnel. And so we didn't – we weren't presented with a large-scale test that was specific to the containment enclosure building, but we found it acceptable, what the licensee proposed because it modeled the worst location for ASR.
>
> NRC-ML19312B609 [63, pg. 1047, l. 19]

Hence, the representativeness of the tests in properly modeling the CEB is open to legitimate question.
Another critical requirement for a model test, is that it be subjected to representative boundary conditions. Should the beam model the tunnel, then conceivably the beam was sufficiently long to assume that the simply supported boundary conditions were adequate.

However, should the beam pretend to be representative of the CEB, the boundary conditions are not correct. The CEB walls are subjected an axial compressive force resulting from weight of the container itself. This compressive force, is ignored in the tests. Likewise, shear would be caused by inertial forces distributed equally all along the model and point loads may not necessarily capture this effect.
At the very minimum, this should have been addressed, and convincing arguments made to ignore the misrepresentation of the boundary conditions.

36.2.1.6 Box Limits not Applicable for Applications to Seabrook Site

NextEra's establishment of and reliance on conceptual "box" limits to assess the gravity of ASR at the Seabrook site is one of the authors' most serious concern about the LAR.
The box concept is described at length, and with approval, in the NRC staff's hearing testimony on the ASR. The Staff's testimony established that staying with the "box" established by NextEra is the key measure agreed on by NextEra and the Staff for ensuring that ASR remains at safe levels. For instance, the NRC staff stated

> At a very high level, the staff determined that, one, since the test specimens were representative of structures at Seabrook, and two, since they showed no adverse structural impacts from ASR expansion and cracking in the concrete, there is reasonable assurance that the existing Seabrook structures can continue to carry the loads imposed upon them as provided by their licensing basis building codes, as long as the level of expansion in those structures is less than the level of expansion in the test specimens. In order to provide additional assurance for this finding, the staff conditioned it in part on NextEra performing assessments of expansion behavior at Seabrook to confirm that future in situ expansion is comparable to what was observed in the test specimens.
>
> Moreover, because of the uniqueness of the issue, the staff office with the responsibility for the review of the license amendment request, the Office of Nuclear Reactor Regulation, or NRR, had a separate staff office, the Office of Nuclear Regulatory Research, or Research, provide its opinion of NextEra's method. Research agreed with NRR that NextEra's method was reasonable.
>
> The staff also presented NextEra's method to the Advisory Committee on Reactor Safeguards, or ACRS, which is a body separate from the staff that is composed of highly qualified professionals. The ACRS found that NextEra's method was acceptable because, in part, it used highly representative test specimens and used a similar approach and produced similar results as a large body of ongoing ASR research. Based in part on these findings, the staff granted the license amendment request in March 2019.
>
> NRC-ML19312B609 [63, pg 253]

Similarly, the staff stated

> Right, the whole point, remember, of this entire project, is to know where we are, and stay inside that box that's defined by the testing program that shows that we're still inside that design basis.
>
> NRC-ML19312B609 [63, pg. 331]

> But what we're kind of seeing here, the reason we didn't, gets to the crux of what we've been talking about for the last probably hour is the fundamental approach. We're not trying to

> understand where we may go in the future and what the effects might be. The fundamental piece of trying to stay within the design basis and the law that governs it is to see where we are now and within a reasonable amount of growth – that's exactly what the LSTP was designed to do – to define that box where we understand the properties of the concrete, we understand what's happening, and then we make sure that we stay within that box.
>
> NRC-ML19312B609 [63, pg. 376]

In other words, as long as expansions measured at Seabrook are within the values measured in the FSEL (the "box"), then both NextEra and the NRC assume that everything is fine. This assumption is wrong on multiple levels.

First and foremost, one can not assume that a highly complex three dimensional 30+ years old structure (Seabrook), will responds structurally the same way as one-dimensional beam tested in ideal conditions: a) on-site, there is a complex stress redistribution mechanism which is not necessarily conservative; b) ASR is not uniformly occurring; c) there are gradients of ASR that can cause localized failures; and d) often failure occurs when and where least expected due to an oversight of secondary stresses. For reference, the authors' study of a CEB affected by ASR expansion of only 0.3% resulted in substantial cracking and damage (Figure **??**). Although the reported values of ASR in the LSTP are not publicly available, measurements as high as 1.72-2.14% were recorded in the similar tests reported by Wald, Martinez, and Bayrak [88] in Figure 36.11. If the box limits of the LSTP are anything close to (or even half of) those values they are dangerously high.

In our professional/scientific opinion, should the NRC allow for an ASR expansion to get anywhere close to this limit, there would be major structural damage (and not all of it visible on the surface) such as delamination. Again, to assume that a CEB will respond to ASR the same way as a beam in a laboratory is a very gross, simplistic, and hugely unconservative assumption. At the very least, NextEra should have performed proper finite element studies to support the validity (or limitations) of such an assumption.

Last, but not least, the authors find numerous reasons of concern regarding the beam tests relied upon to define the "box". Those are described below in §36.2.2.1.

36.2.2 License Amendment Request

36.2.2.1 Ferguson Structural Engineering Laboratory

36.2.2.1.1 In/out-of-plane Shear Transfer Mechanisms The FSEL beam tests modeled only the out-of-plane shear and not the in-plane shear(§36.1.3.1.1). This concern can be visualized by holding a can in one's hand and pushing in one direction. Along that direction the can must provide an out-of-plane shear resistance, but at 90 degrees, the can will be in in-plane shear mode. The latter mode was neither tested, Figure 36.13 nor was its role numerically investigated.

The fact that the ACI 318-71 code allows 10 times the square root of the compressive strength for in-plane shear, as opposed to only two times for out-of-plane, is irrelevant. In both cases, the relative loss in strength will be equal to the square root of the fraction of the loss (because the 2 and the 10 cancel out). For instance, if the original compressive strength is 100 (never mind the units), and due to ASR the compressive drops to 70, the loss in shear strength for both in-plane and out-of-plane will be equal to the square root of 70 divided by 100 (0.83).

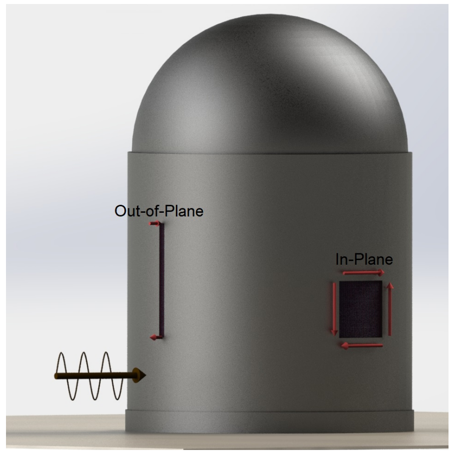


Fig. 36.13: in-plane and out-of-plane shear in a CEB [74]

Furthermore, NextEra assumes that

> Cracked section properties do not affect the global seismic response of the CEB. This assumption is justified because the global response of the CEB to seismic motion primarily causes in-plane shear and overturning stresses; both are resisted by the membrane stiffnesses of the CEB wall that are not impacted by cracking.
>
> Simpson Gumpertz & Heger-ML16279A049 [81, pg 215]

This is clearly wrong, because the lateral load is equally resisted by in-plane and out-of-plane shear, Figure 36.13.

36.2.2.1.2 Concrete representativeness Ideally, the FSEL test beam concrete would be (nearly) identical to the concrete used at Seabrook (§36.1.3.1.2), i.e. the same aggregates, sand and cement. The FSEL used aggregates with physical properties (shape, hardness, strength, and size distribution) that were similar to the physical properties of Seabrook concrete (but not with the same mineralogical composition). However, the FSEL did not use identical sand. Instead it used a highly reactive sand in order to accelerate the development of ASR for purposes of conducting the test. It should be noted that usage of the so-called "jobe" sand to accelerate laboratory expansion is not uncommon if one is simply trying to induce expansion.
However, the problem is that the same laboratory mix design was used to establish the correlations for the CI and out-of-plane expansion, Figure 36.9. In this instance, having reactive concrete is not sufficient; there has to be a mineralogical similarity. Indeed:

- It is well established [65] that fine aggregates (sand) will yield a faster reaction (by virtue of their high volume to-surface ratio which facilitates diffusion) than coarse ones. However, the coarse aggregates will ultimately yield larger total expansion than the expansion yielded by the sand. Hence, expansion testing on fine aggregates will under-estimate total expansion in the long run.
- Expansion is highly dependent on mineralogical types of aggregates. Some are so called early-expansion, others are late-expansion. Overlooking the geological nature of the aggregate and sand will fatally compromise the outcome of any investigation [68].

Additional related concerns are addressed in §36.2.2.2.3.1.
As a result, the key feature of ASR internal micro-cracking and surface manifestations of cracking may greatly differ depending on the mineralogy of the aggregates/sand/ used.

36.2.2.1.3 Beam Tests Tests were conducted on flexural beams designed to fail in shear (§36.1.3.1.3.1); yet the actual failure mode of the CEB due to ASR and seismic load is not determined. It is assumed to be in shear, but could also very well be in flexure for certain load combinations (Table 36.5). Indeed, Wang and Morikawa [90] performed tests on beams subjected to AAR for up to three years. Specifically designed to assess the impact of AAR on shear strength, a relatively low span to depth ratio of 5 was selected. As expected, failure load increased due to ASR, due to the well known prestressing effect of the reinforcement on the concrete swelling. However, what is noteworthy is that only the control specimen had the intended shear failure, and "all others failed through flexure".
Nevertheless, there are five major concerns in regard to the tests. Each will be addressed separately.

36.2.2.1.3.1 Splitting crack As noted above (§36.1.3.1.3.2), a splitting crack occurred in all specimens prior to testing. The cause of the crack is pretty straightforward. ASR being opportunistic will redirect the expansion along the two restrained directions to the one which is un-reinforced, Figure 36.14.
This was too rapidly dismissed by NextEra as an "edge effect" (not a technical term), because there were no visible cracks when the specimen was cored. Visual examination does not provide a sufficient basis to dismiss the splitting crack, however, FSEL should have performed petrographic studies to determine whether there were microcracks (see below). Indeed as noted in §**??** when inspecting for cracks, it is customary to assume the presence of a crack equal to the smallest detectable size.
The explanation is quite elementary, Figure 36.14. AAR being "opportunistic" will expand in the unconstrained direction. Hence, since there was no shear reinforcement in the center, Figure 36.4(c), expansion took place in that zone. At some point, the AAR induced stress exceeded the tensile strength and a splitting crack snapped. Concrete being a brittle material, one would suspect that this was accompanied by a loud noise. Indeed it is a common practice to have acoustic emission sensors on the surface of specimens when internal cracking may occur, [83]).

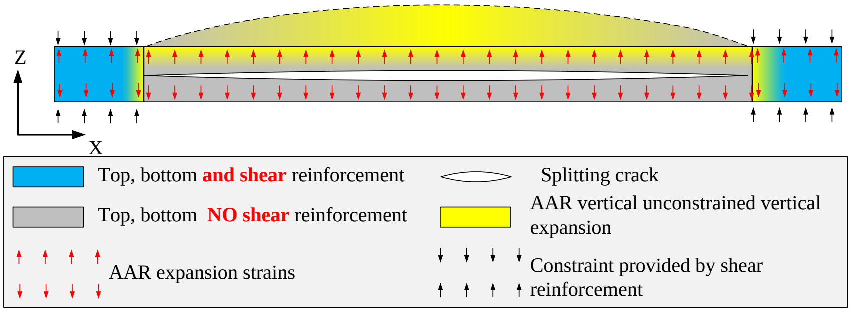
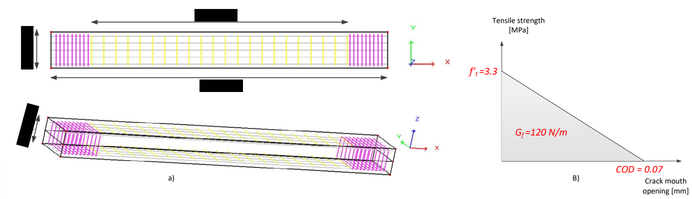
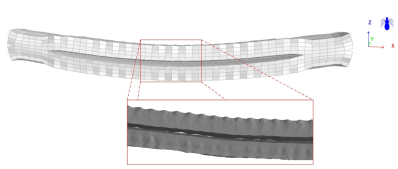


Fig. 36.14: Possible explanation for splitting cracks based on Wald, Martinez, and Bayrak [88]

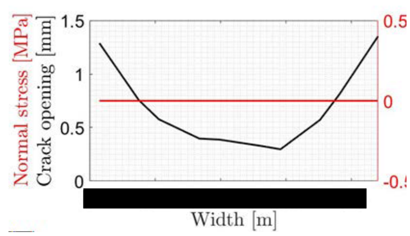
To confirm our interpretation, a nonlinear 3D fracture mechanics based finite element analysis [**chap:fracfembook**] of the tested beam was conducted (Figure 36.15(a)) by the authors. As the location of the splitting crack was sharply defined, the discrete joint element discussed in §**??** was used.



(a) Nonlinear fracture mechanics based finite element model adapted from Wald, Martinez, and Bayrak [88]



(b) Highly amplified deformation showing crack opening in between the stirrups [75]



(c) Crack opening profile across the beam (along y axis) [75]

Fig. 36.15: Finite element simulation of specimen splitting

Results are summarized below :

1. Because of unconstrained vertical expansion, indeed a crack formed in the portion of the beam that is not resisted by shear reinforcement (stirrups) as shown in Figure 36.15(b). The authors conclude that this crack is comparable to the crack observed in the LSTP, Figure 36.5.
2. At midspan, the computed crack profile is shown in Figure 36.15(c). It matches what has been reported by NextEra, that is the crack opening is largest on the edge. We estimated it to be 1.4 mm (this may be less than what was determined, but again in the absence of tests we had to estimate the fracture energy G_F).
3. The close-up showing an "oscillation" in the vertical displacements is due to the confinement provided by the transverse rebars (along the Y-axis). In other words, displacements are constrained by the bars, but in between, we have small spikes.
4. We also have the crack profile showing a minimum in the center (about 0.3 mm crack width). Again, this (to some extent) matches what NextEra has characterized as "inconsequential edge crack" (a non technical term which does not mean much).
5. Note that whereas a 0.3 mm may not necessarily be visible by the naked eye, it is enough to inhibit transfer of tensile stresses per the model (§**??**).

It is not surprising that NextEra did not detect a crack when they examined the specimen visually, because the crack was too small for the naked eye.
Again, it should be emphasized that this analysis does not pretend to be quantitatively exact; however, it is most certainly qualitatively correct and based on sound, established, fracture mechanics models. Hence, we can safely assert that the observed splitting crack is far more serious than asserted by NextEra.
NextEra also asserts that delamination will not occur in the CEB. This statement is unfounded. Given the lack of reinforcement across the thickness of the CEB, a delamination crack (similar to Crystal River) is in the realm of possibilities.
The relevance of such an (unanticipated) crack, one which inhibits tensile stress transfer, can not be discarded. They simply were not anticipated during planning purposes, caught NextEra by surprise (though any basic understanding of ASR expansion would have anticipated them) and should disqualify test results. An biological analogy would be if a Petri dish had been contaminated by an external agent, thus rendering results questionable. Similarly, a basic tenant of experimental mechanics is to avoid any secondary source of uncertainty. Indeed, one can not discard the likelihood that the presence of the splitting crack has not affected the trajectory of the shear-flexural crack in Figure 36.5.
Most importantly, and contraily to NextEra's assessment, such a crack (delamination) may form inside the walls of Seabrook. Currently, it may not be detected with the naked eye, but with microscopic (i.e., petrographic) examination.

36.2.2.1.3.2 Chemical Prestressing Side Effects Chemical prestressing is not a panacea to solve ASR problems. While MPR states that "the beneficial effects of confinement are recognized in the structural engineering community" [55], the potentially adverse effects of chemical prestressing are also recognized in [23] (summarizing work conducted for the Texas Department of Transportation at the FSEL and which indicated that thirty cases of "fractured reinforcements" have been found in bridges and other structures).

The phenomenon is simply illustrated in Figure 36.16(a) based on the classical free body diagram of flexurally-cracked reinforced concrete beams [22].

Unfortunately, no strain gauges were installed to quantify the additional steel and compressive strains (and thus stresses). Hence, the effects of prestressing had to be numerically estimated by NextEra.

36.2.2.1.3.3 Fracturing of stirrups Another possible "side effect" of restrained expansion is that it may either yield or fracture the stirrups that provide both shear reinforcement as well as confinement for the concrete (thus increasing its strength) [40]. Such a failure did occur [44], Figure 36.16(b).

The reported rupture has triggered much research in Japan[7].

36.2.2.1.3.4 Size Effect Simply put, size effect is the reduction in strength with increase in size (§**??**). This has an impact in the reported study because the beam itself was about [[redacted value]] scale [[redacted value]] depth whereas the wall of a CEB and the containment structure are 30 and 48 inches respectively. This is not unusual in component testing. However, given the brittle nature of shear failure and associated size effect, the shear strength in the CEB will be lower than the one from the LSTP. This very well-known phenomenon of size effect, first highlighted by Bažant [13] [14] (and later generalized by the author [71]) was experimentally validated for large size shear unreinforced beams by Bentz [16], Figure 36.16(c).

Size effect is relevant to NextEra's reliance on the B tunnel (allegedly prototype) to *model* the ASR in the CEB. Indeed, the beam may have been a proper model for the tunnel, however, it was not an appropriate model for the more critical CEB prototype.

Hence, failure to account for the size effect may lead to an overestimation of the shear carrying capacity.

36.2.2.1.3.5 Creep was addressed in Chapter **??**, or more precisely its corollary relaxation will reduce in time the beneficial effect of chemical prestressing (§**??**). Indeed estimating prestress loss due to creep is the dedicated subject of an ACI publication [4] and it is unequivocally clear that prestressing will diminish with time. Likewise chemical prestressing will decrease with time.

The phenomenon of creep or relaxation was completely ignored by NextEra. As a result, the LAR fails to account for the fact that the full beneficial effect of chemical prestressing is only temporary, and will be reduced with time.

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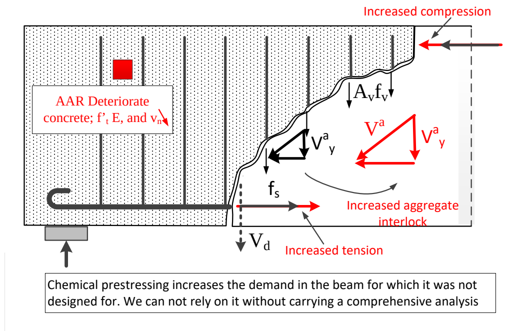
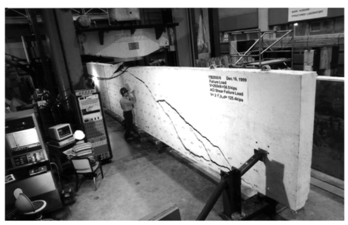
[7] Inoue et al. [37] states: "In recent years, it is reported in Japan that stirrups, as well as longitudinal steels, in T-shaped beams of bridge piers were ruptured at the bent corner or butt joints. In order to make clear the causes of this rupture, vigorous research works has been done after the finding of the rupture in existing reinforced concrete structures. Up to the present, it is recognized that this phenomenon occurred not only due to excessive ASR expansion but also under complex combinations of several factors, such as mechanical properties and surface shape of reinforcing bars, bending or welding methods of reinforcing bars, corrosive atmospheres and so on."

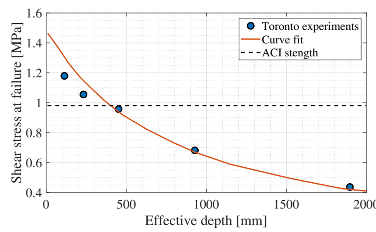


(a) Side effects to "chemical prestressing" [75]

(b) Fractured reinforcement due to ASR [44]



(c) Picture of tests performed by Bentz [16]



(d) Experimentally recorded size effect in shear for reinforced concrete members without stirrups; $f_{;c}$=35 MPa, agg=10mm, (adapted from Bentz [16])

Fig. 36.16: Issues about shear tests

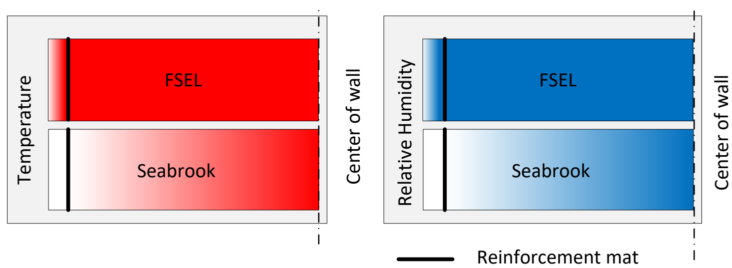
Had the tests at the FSEL lasted longer (which could have been prohibitively expensive), the full impact of creep would have been assessed. But NextEra had other feasible means for assessing creep. A simple numerical calculation could have provided a reasonable estimate for that nefarious effect.

36.2.2.2 Building Deformation Aging Management

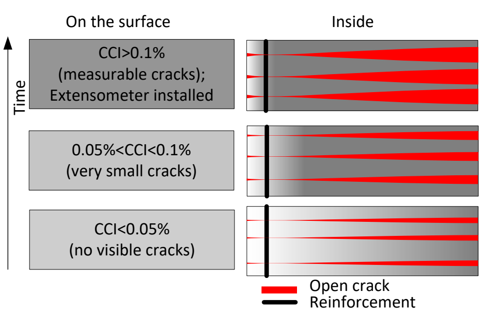
36.2.2.2.1 Crack Index Determination of the CI (§36.1.3.2.1) is NextEra's "first line of defense" in detecting ASR induced expansion. But *in-fine*, CI readings are only a small fraction of the total volumetric expansion, Figure 36.11. Thus they are extremely misleading.

NextEra's reliance on CI also fails to account for the critical role played by relative humidity (RH) in the expansion of concrete. As mentioned previously, a RH less than 80% will not result in any expansion [20] [84]. This has very strong implication for the reliability of surface measurements of cracks to ascertain the presence/extension of ASR. In other words, due to shrinkage and external exposure, the surface of the wall most certainly has a relative humidity less than 80% . As such, one would only

capture severe cracks emanating from the center and reaching the surface. Those are what we will refer to as ASR cracks, not to be confused with internal structural cracks that we will address separately. The result is (and this will be again discussed in the next question) that the CI will not be reliable.
However, it is important to observe that, unlike the consistent temperature and humidity conditions created for the beams in the LSTP, neither the relative humidity nor the temperature is constant across the 30-48” containment structure walls. This is schematically illustrated by Figure 36.17(a).



(a) Temperature and elative humidity distributions across the wall



(b) Impact of reinforcement mat on the “pinching” of ASR cracks

Fig. 36.17: Impacts of temperature, relative humidity, and reinforcement on limited surface CI measurements [75]

Table 36.7 highlights the different environmental conditions:

Table 36.7: Comparison between FSEL test conditions and Seabrook Station

FSEL	Seabrook
Temperature kept high to simulate ASR expansion. Given the dimensions of the beam, and the internal heat of hydration, one can reasonably state that the temperature was uniform (no gradient) across the beam.	There is always a temperature gradient across the 30-48" CEB, the containment structure will have a constant (higher) temperature. wall.
The relative humidity was kept high in the FSEL (by covering the specimen with burlap, Figure 36.4(e). Because of the continuously wetted burlap and the high water to cement ratio, it is safe to state that in the FSEL the relative humidity was constant across the specimen. ∗	The surface of the CEB wall has dried, and is not prone to expansion whereas the expansion will take place inside the wall where the relative humidity is much higher. The expansion of the containment structure is the one likely to be uniform.
The FHWA report stipulates that for CI measurements, the "most severely cracked" components "generally correspond to those exposed to moisture and severe environmental conditions, as well as those where ASR should normally have developed to the largest extent." [30, pg 12].	The surface of the CEB is certainly no longer moist, it has dried. The surface of the containment structures is likely to be within a higher relative humidity

"The internal humidity of the concrete and the atmospheric conditions in the ECF were sufficient to drive progression of ASR uniformly throughout the test specimens"[46].

Hence, the ideal conditions in the LSTP which were intended to validate the CI measurements' reliability for Seabrook are not representative of *in-situ* conditions at Seabrook.

This has strong negative implications for NextEra's ability to capture internal cracks by surface measurements.

The low RH on the surface of the wall, compounded with the proximity of the large mat reinforcement clearly inhibit the formation of surface material ASR cracks. While the reinforcement sizes in the surface mat are not provided by the MPR report, the authors have used the assumption by Wald, Martinez, and Bayrak [88] of # 11. It should be noted that such a size is also commonly used (along with # 18) in containers, and was used more recently in the laboratory tests of Hayes et al. [32]. In other words the reinforcement will "pinch" the crack and the opening on the surface will be much smaller than on the inside. This is further illustrated in Figure 36.17(b) (where the crack opening is in red).

Finally, it should be noted that the applicability of the crack index method has been the subject of internal discussion at the NRC. In one NRC document, it is indeed stated 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. 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.
>
> Buford [18]

Those were very correct statements, however they were subsequently deemed

> not to be an official NRC position on the topic, but rather was prepared by an individual staff member to facilitate internal technical discussion and inform staff review of an issue. The NRC's current position on the role of visual inspections in identifying ASR is set forth in this document. The referenced position paper does not state that visual examination is insufficient to identify indications of ASR. However, it does note that surface cracking or crack mapping, alone, may not indicate the severity of ASR degradation and is not adequate to determine structural effects of ASR. The NRC agrees that surface crack mapping alone is not adequate to monitor ASR progression and to address its structural effects. In addition, petrographic examination provides very limited information to evaluate the structural effects of ASR.
>
> Federal Register [29]

In light of the above, we continue to insist that the expansion inside Seabrook CEB is almost certain to be much higher than what can be recorded by CI.

36.2.2.2.2 out-of-plane Expansion As shown in Figure 36.11 the bulk of the volumetric strain is along the unreinforced out-of-plane expansion. This value is to be measured when CI exceed certain threshold values (Table 36.2).
The method has been calibrated with measurements from the FSEL (Figure 36.9). Yet this method is most unreliable for the following reasons:

- As described above, the difference in mineralogy will result in different expansion characteristics (due to the microcracking).
- Values of the compressive strength measured in mid 1970's are likely to be: relatively few, not accurate enough to be applied with Equation 36.2, Figure 36.18(c) (20% strength increase will result in $\sim$ 14% increase in E) .
- A most critical component of the process is the determination of the ASR induced deterioration. This hinges first on Equation 36.2, but also on data collected at the FSEL, resulting in a highly approximate phenomenological model[8] that estimates expansion in terms of normalized elastic modulus, Figure 36.9. As shown in Figure 36.18(a) two experimental errors are compounded:

[8] A phenomenological model is one "that describes the empirical relationship of phenomena to each other, in a way which is consistent with fundamental theory, but is not directly derived from theory. In other words, a phenomenological model is not derived from first principles. A phenomenological model foregoes any attempt to explain why the variables interact the way they do, and simply attempts to describe the relationship, with the assumption that the relationship extends past the measured values." (Wikipedia).

- Horizontal axis: the normalized elastic modulus is most approximate. Let us not forget that it hinges on determining the elastic modulus *during construction* based on cylinder tests collected for quality assurance. Again two sources of errors here:
  - The volume of concrete in a CEB is very large, and though hundreds of cores may have been tested *in-situ*, the concerns are that the testing method (back then) were neither reliable, nor sufficient. Indeed, it is very likely that the measurement density (number of tests per cubic yard) will be too low to accommodate the one needed to capture the elastic modulus at various locations 30+ years later. As such, it is very possible that ASR will be taking place in a location not tested for compressive strength.
  -
  - Equation 36.2 is known to be very approximate by itself, and is only a substitute for the direct measurement of the concrete elastic modulus per ASTM C469 [10].
- Vertical axis: expansion is determined in the laboratory under ideal conditions, with concrete whose representativeness *vis à a vis* of the one at Seabrook given that "mineralogically" speaking they are different (§36.2.2.1.2). Even if the mineralogy was indeed correct, any time precise and critical measurements are to be taken, margin of errors must be reported.

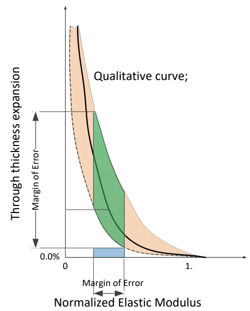
- Concrete gains in strength the first two years (about 20%) [22], Figure 36.18(b). Ignoring this will result in an underestimate of the ASR.

With so many potential errors, ultimately errors bars are not provided[9] [63, pg 473, line 18]. This is particularly problematic, as one can not develop a heuristic model, based on laboratory testing without also providing an indication of the experimental errors. [35].
The authors would argue that a far more reliable approach to the determination of the past expansion is the one presented in §**??** (Figure **??**).

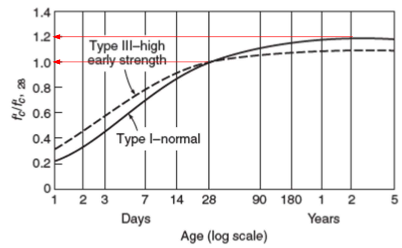
36.2.2.2.3 Unaddressed Concerns

36.2.2.2.3.1 Internal Cracks There is ample evidence that ASR will cause internal micro-cracking (Figure **??**) [38]. Furthermore, sand and gravel will cause drastically different internal crack patterns, Figures 36.19(a) and 36.19(b) [30]. This is further evidenced by Figures 36.19(c) and 36.19(d) which show images of concrete with reactive sand (cracks run thorough the paste, impregnated and polished sample in UV light) and an image of reactive gravel (diameter 5 cm, impregnated and polished sample for SEM) courtesy of Leemann [41].
NextEra has repeatedly indicated that no cracks were observed when cores were extracted

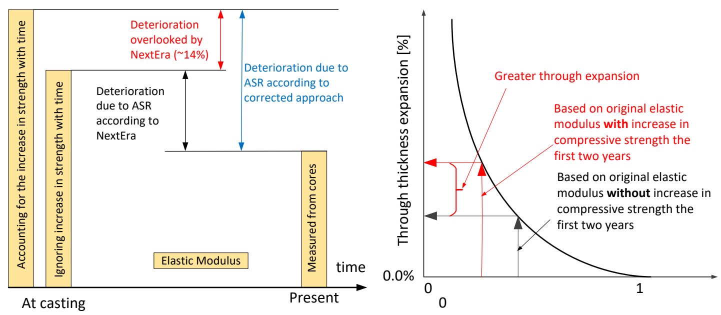
[9] Such omission, would only be permitted when the equation has been vetted/verified/validated by multiple researchers before they are typically enshrined in a code (such as Equation 36.2).



(a) Procedural margins of error [75]



(b) Early age compressive strength increase in concrete [22]



(c) Impact of early strength gain on out-of-plane expansion determination [76]

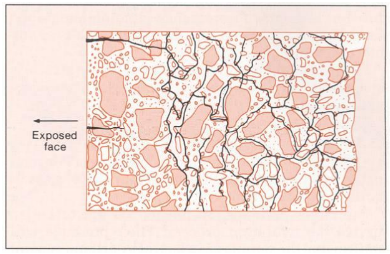
Fig. 36.18: Concerns about out-of-plane expansion measurements

> [i]n the prior session regarding the taking of the core. Not only do we take the cores and do the compression and modulus testing. We actually do, a visual examination of those cores as they're taken. We validate that there's no – that the core is coming out solid. That it's not crumbling within its – when it's removed from its confinement. We're validating there's no midline cracks. We actually inspect the bore hole and verify there's no voids. No cracking. No deterioration of the aggregate.
>
> NRC-ML19312B609 [63, pg 532]

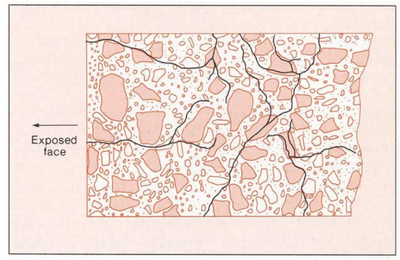
Yet, throughout the documents, indications are micro-cracks are present,

> Micro-cracking due to ASR is generated through forces applied by the expanding aggregate particles and/or swelling of the alkali silica gel within and around the boundaries of reacting aggregate particles.
>
> NextEra-ML16216A240 [52]

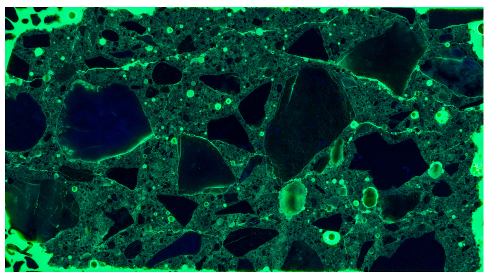
> It was determined that ASR caused this additional aging effect through cumulative micro-cracking in ASR-affected structures. In addition, there was discrete large cracks and the effects were not anticipated. They were identified by the NRC as a different consequence of ASR.
>
> NRC-ML19312B609 [63, pg 204]



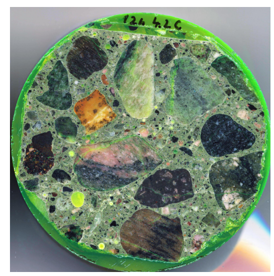
(a) Internal crack pattern which can be caused by ASR: reactive silica in the sand fraction [30]



(b) Internal crack pattern which can be caused by ASR: reactive silica in the coarse aggregate [30]



(c) Reactive Sand [41]



(d) Reactive Aggregate [41]

Fig. 36.19: Crack patterns caused by reactive sand and aggregates

The key takeaway is that NextEra has conducted *visual examination* to detect cracking, with the expectation that cracking may mean crumbling. This will be a false-negative reading of the situation because NextEra is looking for macro-cracks (visible with the naked eye), when it should be scrutinizing all the cores through petrographic analysis for unusual micro-cracking, and understanding that those micro-cracks are ominous and are likely to grow, coalesce and ultimately delaminate the CEB.

36.2.2.2.3.2 Potential Delamination The internal cracks, previously addressed, will

Propagate as a result of increased ASR with time, and as a result of creep fracture discussed in §**??**.

Coalesce as the crack density is at first high, and some of those micro-cracks will eventually coalesce (as discussed in §**??**).

Again, ASR induced delamination will occur when swelling is constrained in two directions (in-plane) and unconstrained in the third (out-of-plane). Indeed, given all the swelling potential being now channeled along the weak direction, this could be problematic.

With reference to Figure 36.20(a) a segment of the wall is subjected to compressive stresses, and is reinforced only in the periphery vertically and radially. Micro-cracks are likely to coalesce in the center where the temperature and the relative humidity are highest, and this would be an in-plane crack. Due to ASR, expansion will be as indicated.

When the whole wall is considered, Figure 36.20(b), we consider four stages corresponding to different times. At first, expansion affects the center zone, and ASR would be localized in the middle where temperature and relative humidity are high. With time, the zone affected by ASR will expand but cracks are unlikely to "daylight" in significant way as a) the surface is likely to have dried over time; and b) and the reinforcement will pinch the crack. As such, the cracks will remain confined to the center, and will eventually fully coalesce into a major internal in-plane crack.

One cannot rely on visual inspection to determine whether there is internal cracking. Such a crude approach could be valid only once there has been a major crack, and this may be too late.

Such a delamination did occur in the FSEL, Figure 36.5 (§36.2.2.1.3.1), and at Seabrook, there is a very strong likelihood that micro-cracks already exist.

Indeed, such cracks have been reported in topologically similar structures (retaining walls with no shear reinforcement) in Switzerland 36.20.

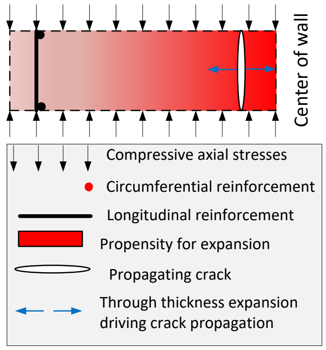
36.2.2.2.3.3 Uncertainty in Future Expansion; Threshold Factors As mentioned in §36.1.3.3.3, Simpson Gumpertz & Heger-ML16279A049 [81] defined a threshold factor K_{th} of 20% (to the CEB only) to account for "additional ASR load that may occur in the future".

This is symptomatic of many aspects of the LAR: when confronted with what could be determined (experimentally or numerically), NextEra simply considers it an unknown and defines (yet another) "safety factor". The problem is that we do not know how reliable is that safety factor, i.e. could it be too low?

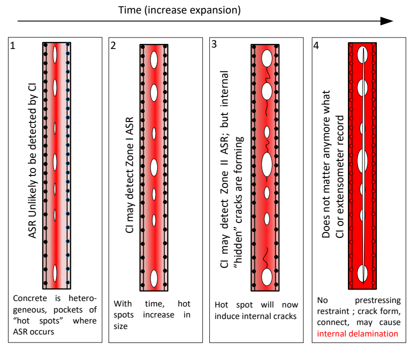
In this particular instance, it is reasonable to ask on which basis was the 20% value selected? And why not 10% or 40%? Short of a study similar to that described in §**??**, one can not assume that 20% would be appropriate.

36.2.2.2.3.4 "Elastic" Margin for Future Expansion NextEra also made allowances for "margin for future expansion" [46]. More specifically, based on "expansion rate", NextEra acknowledged the potential for future expansion to exceed the anticipated limits. In that event, NextEra plans to consider relaxation of the limits

> NextEra's review should include consideration of the uncertainty associated with extensometer readings and with in-plane expansion measurements. Assessments of "expansion rate" for the purpose of projecting future expansion should rely on trends comprised of multiple data points. If such projections indicate that the limits may be exceeded prior to the next periodic check, NextEra should include consideration of the uncertainty associated with extensometer readings and with in-plane expansion measurements. if such projections indicate that the limits may be exceeded prior to the next periodic check, then NextEra should further investigate the location(s) in question or develop contingency plans for extending the expansion limit (e.g., supplemental testing).

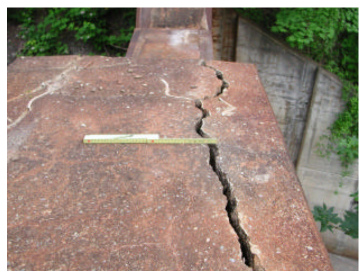


(a) Delamination mechanism [75]



(b) Delamination process [75]

(c) [41]



(d) [36]

Fig. 36.20: Causes and examples of delamination in walls without out-of-plane reinforcement

MPR-ML19170A332 [46]

By setting such an elastic “margin for future expansion” raises a significant concern about the scientific credibility of its approach. In addition, the “moving target” paradigm for establishing regulatory compliance raises questions about the rigor of NextEra’s program for protecting public health and safety. It is hard to understand the rationale (if not the ethics) of NextEra’s approach to regulatory compliance, i.e. to first establish allowable limits for code compliance, to then assessing the code compliance of a structure, and finally – should the expansion rate be found to exceed allowable limits–, to then *extend those limits*. The authors are not aware of any organization that would allow for such an elastic interpretation of a safety code.

36.2.2.3 Building Deformation Assessment

36.2.2.3.1 Screening Evaluation was addressed in §36.1.3.3.3. A finite element analysis would result in Gauss point stresses at the Gauss points (§**??**), and indeed the most natural approach would be to perform a stress-based failure assessment based on failure criterion (§**??**). However, the approach taken by NextEra is to determine

equivalent forces (axial and moments) from nodal values (themselves not ideal for evaluation), and then perform a force-based failure assessment based on ACI code interaction diagrams.
The authors recognize that this is not an uncommon approach for some structural components, such as beams and columns subjected to loads covered by the ACI code. However, in the case of ASR we are dealing with an exceedingly complex and challenging problem, one with which the NRC has been confronted for the first time, and one where an erroneous safety assessment could lead to a nonconservative response and perhaps devastating consequences. The authors see adisturbing dichotomy between the relatively simplistic engineering approach taken by NextEra and the much more rigorous "standards" with which the authors are accustomed by virtue of their (academic/researcher) background.
NextEra's approach reduces the CEB to a series of parallel columns with no interaction among them. Furthermore, the model relies heavily on the conclusion of the FSEL beam tests (showing an increase in shear strength and flexural stiffness). But the limitation of these tests have been previously highlighted §36.2.2.1.3.5. Furthermore, NextEra's approach allows the analysis to ignore any material deterioration in the CEB [81, pg 18].
NextEra claims that

> Evaluating a structure on an element-by-element basis is considered a conservative approach because it does not allow for concentrations of high demands to be distributed locally within the structure. Factored demand exceeding capacity in the element-by-element evaluation does not necessarily indicate a structural deficiency.
>
> [81, pg 53]

This assertion is purely speculative however, and no supporting argument is made.

36.2.2.3.2 Factored Self-Straining Loads The so-called Load Resistance Factor Design (LRFD), used in [2] hinges on the concept of Reliability Index (§**??** Figure **??**) and was addressed in the seminal paper of [25]. Simply put, load will be multiplied by a factor λ [7] and we reduce the ultimate capacity by Φ.

$$\Phi C_n \geq \Sigma \lambda_i D_i \tag{36.3}$$

where C_n and D are the nominal capacity and demands (or nominal resistance and load), and limit states are generally determined from the plastic capacity *without* a nonlinear analysis. LRFD will assign α and Φ such that the probability of failure does not exceed a certain value. In practical terms this implies seeking to have a Reliability Index β (Equation **??**) such that $\beta >\sim 3.5$. The Reliability Index is a "universal" indicator on the adequacy of a structure, and can be used as a metric to 1) assess the health of a structure, and 2) compare different structures targeted for possible remediation. For instance in [1] Φ is 0.9 in flexure and 0.7 in shear; likewise α for dead load and live loads are 1.4 and 1.7 respectively. The difference in the numerical value of the factors reflects different consequences of failure (shear failure being sudden and brittle, while flexural failure is ductile), as well as the uncertainly

associated with the load (larger uncertainties are associated with the live load than with the dead load).
Irrespective of the code, load factors are developed following statistical analysis of numerous sources, .e. as many sources as possible

> The sources for statistics and distributions for individual loads are primarily the load subcommittees within ANSI Committee A58 that have expertise in and responsibility for the loads in the current version and projected revisions of the A58 Standard. Similarly, data on resistance of structural members and components is obtained from the numerous research reports and papers published by individual researchers, industrial groups and trade associations.
>
> Ellingwood et al. [25]

Now, for the LAR, the challenge was to develop load factors for ASR (Sa or λ_{AAR}), from a very limited data set (i.e. sufficient reliable, trustworthy experiments). This was for all practical purposes an impossible task, and thus

> The load factors applied to ASR loads (Sa) are developed to yield reliability index values similar to load factors specified in ACI 318-71 (Reference 17). The ASR load factors account for the uncertainty in ASR expansion by considering the variability in crack index measurements from all ASR monitoring grids in Seabrook Station structures.
>
> NextEra-ML16216A240 [53]

Thus, the load amplification factors are based on the crack index measurements at Seabrook. But those are very poor indicators of the ASR expansion (§36.2.2.2.1). Thus, while NextEra's procedure is most certainly correct, given that it was reviewed by a highly respected researcher (indeed, the only external faculty/expert consulted) the reliability of the raw data used to develop the load amplification factors is very questionable.
Furthermore, as shown in Figure 36.11 the in-plane strain measurements, upon which the load factors are built, are negligibly small compared to the out-of-plane strain. Hence those amplifications factors can-not be representative.
Yet, despite the large margins of errors associated with λ_{AAR}, this factor is 1.45. In comparison, the very well-known factor for dead load is 1.4 and the highly uncertain factor for live load is 1.7, Table 36.5.
Hence, whereas we do not dispute the procedure to determine the (relatively low) amplification factors associated with ASR, we believe that they are based on incomplete, and erroneous data, and are consequently both unrepresentative and unconservative.

36.2.2.3.3 Finite Element modeling

36.2.2.3.3.1 Lack of Verification and Validation The very first concern is: How reliable is the finite element code used by NextEra in capturing ASR? And the corollary concern: Have those capabilities been verified and validated? The importance of these preliminary tasks was addressed in §**??**. Indeed, verification is needed to [85]

- Reduce risk of high-consequence code errors;
- Reduce development and maintenance costs by finding code implementation errors sooner;
- Quantify numerical errors as part of validation and predictions;
- Reduce numerical errors through mesh adaptivity; and
- Assist the NRC licensing process by providing application-driven evidence of code and solution quality.

Regulations [67, Appendix K Part 50] explicitly defines acceptable and required features of the Emergency Core Cooling Systems evaluation models as described in §50.46, including:

- Code documentation;
- Spatial and temporal convergence studies;
- Code validation;
- Sensitivity Studies; and
- Uncertainty Quantification.

One could argue that the same requirements should be applicable to ASR (especially when it is the very first time that it is addressed by the NRC).
Some software quality assurances procedures for the NRC are already in place and available to licensees like NextEra

> Software quality assurance (SQA) is the planned and systematic actions to provide confidence that the software product meets established technical requirements. Quality assurance procedures ensure that software correctly performs all intended functions and does not perform any unintended function. SQA activities can be categorized as follows:
>
> 1. documentation of the software or software modules as they are developed,
> 2. verification and validation activities and their documentation,
> 3. nonconformance (error) reporting and corrective actions and their documentation,
> 4. acceptance testing and installation of the software and upgrading of code manuals,
> 5. configuration management, and
> 6. quality assessment and improvement.
>
> NUREG-1737 [64]

It is thus puzzling that the software used for the ASR analysis was not subjected to any scrutiny. Guidelines for ASR finite element code validation are given in [68, chapter 21].

36.2.2.3.3.2 Shell Elements "The CEB walls and dome concrete consist of four-node shell elements ... modeled using centerline geometry" [81, pg 32]. The shell elements used in the finite element study (`SHELL181` in ANSYS Release 15) would have been a reasonable *approximation* had there not been a need to capture the through-the-thickness impact of factors affecting ASR expansion. Each shell element is a four-noded element with six degrees of freedom at each node: translations/rotations in the x, y, and z directions. However, a shell element can not capture the through thickness expansion which is lower on the surfaces and higher in the center (different RH). Given the nature of the problem, one would have thought that solid 3D elements would be used for a more accurate modeling. On the other hand, if NextEra insisted on using shell elements, then a minimum of 2-4 elements would have to be used as *overlayed* elements, Figure 36.21. Yet a thorough search in all available documents failed to show that any overlayed elements were used [63, pg 953]. .

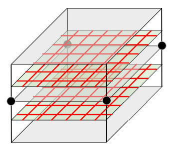


Fig. 36.21: Example of overlayed four noded shell element

36.2.2.3.3.3 Nonlinear Analysis About twenty years ago, the drafters of the ASME code for concrete reactor vessels and containments wrote

> In recent years, detailed two- and three-dimensional finite element modeling of these discontinuity regions to include the effects of cracking and nonlinear concrete behavior have significantly reduced the uncertainty of structural response in these regions.
>
> It has been said that in the late 1960s it took two days to design a containment and two weeks to analyze it before the release of the design for construction. Today it would still take about two days to design a containment but about two years to analyze it. This is particularly interesting, for the actual amounts of concrete and deformed-bar or prestressing reinforcing steel have changed little in location and quantity over the past 35 years.
>
> Ashar et al. [8]

The need for nonlinear analysis is even more acute for Seabrook where *additional* nonlinearity is caused by the time dependent (thus incremental) swelling with accompanying cracking, degradation of the concrete mechanical properties (tensile, shear and compressive strength along with elastic modulus), possible yielding of the steel, stress redistribution. This non linearity has been recognized in the analysis of Gentilly (§**??**) and all ASR analyses reported in this book.

Another concern is the idiosyncrasy embedded in ACI codes: determine capacity from a plastic analysis, and demand from *amplified* loads (Equation 36.3) with a linear elastic analysis. Whereas this may be acceptable for well understood structures (such as buildings) with adequate reliability indexes (β Equation **??**), it is not necessarily correct for a CEB.

Finally, ACI-318 does not concern itself solely with strength (factored load), but also serviceability (service load). This results in code requirements for minimum crack width. In the context of the CEB analysis, capturing the impact of cracks on possible gas leakage (in the absence of liners and notwithstanding the presence of

the two containment walls, Figure 36.1(b)) is critical. A linear elastic analysis will underestimate cracking, Figure **??**.
Guidelines have indeed been written for the nonlinear analysis of nuclear structures (reviewed in Chapter **??**), Hessheimer, M.F. and Dameron, R.A. [34][26] and most recently [70].

36.2.2.3.3.4 Demand and Capacity NextEra's safety assessment determines demand from a linear elastic analysis, but capacity is determined at either the element or section level. This is much different from the common finite element procedure of first determining the computed stresses at the Gauss Points (§**??**), and then applying a failure criterion to assess localized failure (§**??**).
NextEra's approach may very well be a commonly-followed procedure for the linear elastic analysis of nuclear structures, but can not be defended when the ASR itself is inherently so nonlinear, and most importantly when miscalculations may be as consequential as they would be for a nuclear structure compromised by ASR..

36.2.2.3.3.5 ASR Model None of the minimum requirements for ASR modeling addressed in **??** have been considered. In addition the reported finite element modeling of ASR suffers from many flaws.
Most glaring, is the modeling of ASR as an isotropic thermal load. Indeed, a compressive stress greater than about 8 MPa will either limit or entirely prevent expansion in the corresponding direction [33]. Thus, under complex triaxial state of stress, expansion will redirect in the other directions (thus inducing an anisotropic expansion) [47] [42], Figure 36.22. NextEra's isotropic model of ASR at Seabrook would assign only one-third of that expansion to the out-of-plane direction [77]. This is clearly

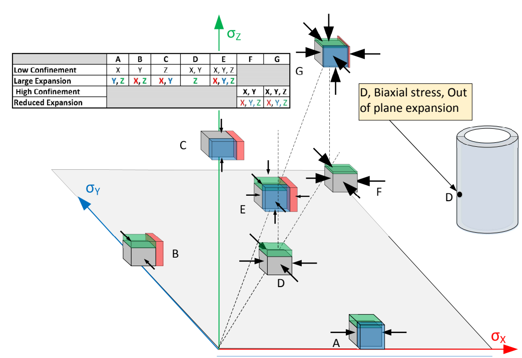


Fig. 36.22: Stress induced anisotropy during volumetric ASR expansion [74]

unconservative, because it is anticipated (lack of radial confinement) and verified (Figure 36.11) that by far, most of the expansion occurs radially, i.e. out-of-plane.

In addition, such a thermal equivalent load does not account for the relative humidity or temperature gradients across the CEB wall. These gradients may be sharp, i.e. far more critical than the absolute ones.

NextEra has attempted to avoid sharp gradients in the ASR expansion by “smoothing” its distribution across zones of different measured expansion. But that is not a realistic or conservative approach. In reality, there is potentially a significant gradient of expansion across the thickness that should be modeled (Figure 36.17(a)).

Finally, it is well established that ASR will reduce the tensile strength and the elastic modulus of concrete [30] by as much as 60%. In addition, there is a recent evidence [28] that compressive strength is reduced also by ASR, thus contradicting the long-held assumption that compressive strength is not affected by ASR. None of these types of degradation was modeled by NextEra, based on the justification that ASR was found in the FSEL to increase the shear strength and flexural stiffness as a result of “chemical prestressing”. This argumentation was partially refuted in §36.2.2.1.3.

36.2.2.3.3.6 ASR Demand NextEra determined the ASR load as follows

> Alkali-silica reaction (ASR) demands are selected based on extensive field measurements of strain on the CEB and are increased by a load factor to account for uncertainty in the demands and a threshold factor to account for limited future ASR expansion.
>
> The strains due to ASR expansion simulated by the finite element model (FEM) reasonably approximate crack index measurements.
>
> [81, pg 14-15]

Field measurement of both the CI and the out-of-plane ASR strains are prone to much criticism (§36.2.2.2.3.1 and 36.2.2.2.3.4). (The authors note, however, that consideration of out-of-plane ASR strains is unlikely to be captured by the use of a single shell element). Hence, they may not provide an accurate picture for purposes of assessing the structural safety of the CEB.

Furthermore, this procedure is akin to a glorified “curve fitting”. And these field measurement are not necessary, given that it is indeed expected that the finite element analysis would be able to capture the *essential* boundary conditions (§**??**), otherwise a wrong FEA program is used. What is lost on NextEra, is that “capturing” the response of few selected points (where the ASR expansion is imposed) does not make the analysis correct. This is illustrated by Figure 36.23 where one is able to fit a curve through a few data points. While this is an easy task, there is a near certainty that the model (curve in this case) will give erroneous values for the intermediary points.

36.2.2.3.3.7 Modeling chemical prestressing is addressed by NextEra as follows

> ASR expansion is simulated by applying a thermal expansion to the elements representing the CEB concrete. Steel reinforcement membrane elements are included in the model and are given thickness based on the total area of reinforcement provided. The expansion of the concrete creates tension in the steel membrane elements, which also causes a corresponding compression force in the concrete elements.

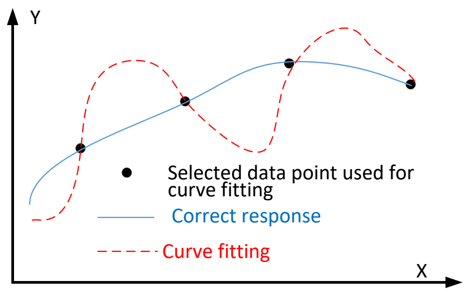


Fig. 36.23: Problems arising from fitting $y = f(x)$ through interpolation [75]

> - In the absence of external restraint, the steel tensile force due to ASR and the concrete compressive force due to ASR will sum to zero. However, external boundary conditions, applied loading, and restraint from other portions of the structure can restrict the concrete from expansion and cause a net force or moment to be developed.
> - The steel membrane elements are only included in the model when applying ASR expansion of the CEB wall and concrete swelling.
>
> [81, pg 41]

Thus, steel is modeled only to capture the negative impact of the chemical prestressing (Figure 36.16(a)). However, this approach is not only convoluted, but also unconservative and erroneous. Chemical prestressing is a deleterious additional parasitic stress added to the pre-existing stress due to other loads. The combined stresses (reportedly not computed) could possibly result in the yielding (if not fracturing) of the reinforcement.

36.2.2.3.3.8 Static Soil Structure Interaction Generally, in non-ASR related engineering analyses, one would not have to worry about the static soil structure interaction. In the presence of a swelling concrete, however, there may be unanticipated and large deformation that could cause separation of the structure from the surrounding soil. This may occur both laterally and along the foundation, figure **??** and **??**.
Yet, allowance for such detachment was not made for Seabrook: "The base of the CEB foundation is restrained vertically... Since ASR expansion of the wall is largest below-grade" [81]. This omission could result in an erroneous stress field.

36.2.2.3.3.9 Dynamic Analysis Model As discussed above, about twenty years ago, the authors of the ASME code for concrete reactor vessels and containments wrote

> The dynamic analysis of containment structures for earthquake loads have progressed from a few two-dimensional lumped three or four mass stick models employing response spectrum modal analysis (in the late 1960s) to complex three-dimensional hundreds to thousands of degrees of freedom finite element models (in the 1970s and 1980s).
>
> Ashar et al. [8]

Hence, we were surprised that for such an important structure as Seabrook+ASR, it is reported that [81, pg 45] “Response spectra analysis was performed using a simplified “stick” model. For lateral analyses, the model was fully fixed below EI. 0 ft. For vertical analyses, the model was fixed at the base at El. (-)30 ft.”
The stick model is a model of the past when computers did not have sufficient capability to handle the time history analysis of a 3D model. The model cannot capture the seismic contact between the (ASR induced wall expanded wall) with the adjacent soil unless joint elements are inserted, Figure **??**.

> The dynamic analysis of containment structures for earthquake loads have progressed from a few two-dimensional lumped three or four mass stick models employing response spectrum modal analysis (in the late 1960s) to complex three-dimensional hundreds to thousands of degrees of freedom finite element models(in the 1970s and 1980s). The dynamic modeling of containment has generally included Soil-Structure Interaction (SSI) effects.
>
> Ashar et al. [8].

36.2.2.3.3.10 Dynamic Analysis Time Integration Historically, engineers have favored modal analysis in conjunction with the response spectrum method (RSM) as it was not computationally expensive. However, one must recognize that the RSM is a very approximate method which only produces positive values of displacements and member forces which are not in equilibrium; thus demand/capacity ratios have very large errors.

> Seismic loads are applied using a static equivalent method utilizing the design-basis maximum acceleration profiles, which were computed during original design from response spectra analysis. Amplify ASR loads by a threshold factor to account for potential future ASR expansion. Evaluate capacity based on ACI 318-71 criteria with combined demands from all design loads, including the self-straining loads associated with the as deformed condition.
>
> [81, pg 2]

This oversimplified method brings to mind what Prof. Wilson is reported to have said

> Ray Clough and I regret we created the approximate response spectrum!method for seismic analysis of structures in 1962.... At that time many members of the profession were using the sum of the absolute values of the modal values to estimate the maximum member forces. Ray suggested we use the SRSS method to combine the modal values. However, I am the one who put the approximate method in many dynamic analysis programs which allowed engineers to produce meaningless positive numbers of little or no value... After working with the RSM for over 50 years, I recommend it not be used for seismic analysis.
>
> Wilson [92]

We conclude that using the combination of RSM and static equivalent load is an oversimplification for such a critical analysis.

36.2.2.3.3.11 Nonlinear Analysis

> The seismic analysis of safety-related structures is typically performed by analysis of linearly elastic mathematical models. Nonlinear analysis may be performed in some cases, especially for beyond design basis calculations or evaluation of existing facilities.
>
> ASCE 4-16 [6]

In this case, a linear analysis was conducted to assess the effects of ASR at an existing facility (Seabrook). While the analysis addressed compliance with the design basis (not beyond design basis accidents), ASR has not previously been included in the design basis for NPPs. Thus, in some respects, the analysis went beyond the design basis. Under the circumstances, a linear analysis was not appropriate.
A reasonably accurate determination of the appropriate margin of safety is critical where a potential leak may occur as a result of concrete degradation. The authors submit that in these circumstanaces, it can only be achieved through a nonlinear analysis.

36.2.2.3.3.12 Dynamic Uplift/Rocking Fixing the mat to the foundation is not good as it restricts ASR expansion of the mat, and most importantly, it can not capture rocking (or uplift) as suggested by [6, chap 11] and discussed in chapter **??**. Hence, the dynamic analysis in or opinion was flawed.

36.3 Conclusion

The authors examined the response by a private industry licensee (NextEra) and the responsible federal regulatory agency (NRC) to the presence of ASR in the CEB, a major safety structure at the Seabrook nuclear power plant. ASR was not discovered in a U.S. nuclear plant until 2009, when it was found at Seabrook. Thus, ASR is not addressed in the original licensing regulations or building codes for Seabrook, nor is it addressed in current operating regulations or codes. Nevertheless, the NRC had full statutory authority to develop all requirements needed to protect public health and safety, including requiring an adequately strict and sophisticated science-based approach to ASR.
The authors found that:

- The Seabrook case illustrates the importance of a rigorously scientific and sophisticated approach to ASR in a regulatory setting. ASR is a dangerous phenomenon because it compromises the integrity of concrete during seismic events, and thus challenges the design basis by which the NRC assures the protection of public health and safety. An erroneous safety assessment could lead to a nonconservative response and perhaps devastating consequences.

- The LAR was not prepared, nor was it internally or externally reviewed, by competent persons with a solid understanding of ASR and its nefarious impact on a structure as complex as a CEB.
- While NextEra relied on reputable engineering firms to assess ASR at Seabrook, they nevertheless lacked sufficient expertise in the complexities and challenges that ASR poses in a structure as complex as a CEB. As a result, rather than applying modern understanding of ASR, they adopted a simplistic and heuristic approach rooted in a 1971 design code. The authors see a disturbing dichotomy between the relatively simplistic engineering approach taken by NextEra and the much more rigorous approach with which the authors are accustomed by virtue of their (academic/researcher) backgrounds.
- NextEra did not avail itself of widely available modern computational tools that have been used internationally with success. Nor did NextEra consult experts with broad ASR experience.
- NextEra's consultants relied heavily on laboratory beam tests and calibration methodologies that were deficient in multiple respects. They also made the grossly simplistic and hugely consequential assumption that a CEB will respond to ASR the same way as a simply supported beam with in a laboratory.
- The authors are particularly concerned about NextEra's effective dismissal of the potential for the formation, propagation, and coalescence of microcracks inside the CEB that could result in a delamination of the walls; or the likelihood that this delamination would be undetectable in a timely fashion by the proposed monitoring program.
- NextEra also devised a "box" concept based on the beam tests to establish acceptable limits for ASR expansion in the CEB. However, the parameters of the box were set arbitrarily, and were not scientifically established. NextEra further undermined the scientific credibility of its approach by setting an elastic "margin for future expansion", allowing relaxation of the box limits if they were exceeded or even approached. This raises questions about the rigor of NextEra's program for protecting public health and safety. The authors are not aware of any organization that would allow for such an elastic interpretation of a safety code.
- Whereas one may reasonably use a code-based approach for the design of new structures, the safety assessment of a swelling and cracking structure, that is required to resist seismic load, can only be assessed by a proper nonlinear analysis. Such a nonlinear analysis was not performed.
- The NRC, as regulator, had a significant responsibility for assuring that its own review was competent and independent. Yet, none of the NRC reviewers had any ASR expertise.
- Nor did the NRC's watchdog agency, the Advisory Committee on Reactor Safeguards – which conducted an additional review and gave approval to the LAR – have any ASR expertise.

The authors find it particularly disturbing that the NRC, as the regulator with ultimate responsibility for ensuring the protection of public health and safety, lacked sufficient expertise or independence to make an objective and scientifically accurate assessment. Most troublesome was the glaring absence of an independent review panel. As a result, a private industry licensee with no experience in addressing ASR and was essentially left to regulate itself. The seriously inadequate LAR now stands as the NRC's model for an adequate program for addressing ASR at nuclear facilities. The Seabrook case constitutes a warning sign that the U.S. government's systems for regulating facilities may lack sufficient systems and controls to ensure the application of sound scientific methods to address emerging risks. While sophisticated methods for addressing ASR were most certainly available in the scientific literature, the NRC seemed unaware of them. Instead, the NRC stuck to the well-trodden path of standard engineering expertise, which was grossly insufficient. The lack of awareness of attention to modern methods for addressing emerging problems is a matter of particular concern for the NRC, given that it is now in the process of renewing nuclear reactor licenses to operate for as long as 80 years – twice the term originally anticipated when the reactors were first licensed. ASR is one of numerous phenomena emerging in aging reactors for which the construction codes used in original licensing are far from adequate to address. The authors recommend that the NRC undertake a rigorous scientific evaluation of ASR and establish a rigorous regulatory system in consultation with knowledgeable scientists. The NRC should also take measures to ensure that programs for addressing ASR at U.S. nuclear facilities receive thorough reviews by independent expert panels. If the ACRS performs that function, it should obtain the necessary expertise from consulting experts.

In summary, NextEra thought ASR was a complicated problem that could be handled with the engineering skills it already knew well; however, it was a complex one requiring a complementary skill set that it lacked. Thus the solution was bungled and the regulatory system failed to correct the mistakes.
Seabrook could and should provide a test case for improving NRC's regulatory program for emerging safety and service problems.

36.4 Epilogue

Just before the manuscript for this book went to press, the ASLB issued its Initial Decision concerning the case brought by C-10 against the license renewal of Seabrook. While the ASLB did not deny NextEra's license amendment request, as C-10 had requested, it did impose several significant new license conditions on the operation of Seabrook over the next 30 years. In §36.4.1, the first author (VES) will provide a summary of the ASLB decision. §36.4.1.1 contains his evaluation of the ASLB decision, and reasons for recommending the addition of language to strengthen the license conditions. §36.4.2, will provide VES overall assessment of the Seabrook case, including his opinion regarding the current and future safety of Seabrook's operation in the presence of ASR. Finally, §36.4.3 provides a chronology of the case and links to key documents, including VES testimony.

36.4.1 Summary of the Board's Ruling

On August 21, 2020, the ASLB issued its Initial Decision in the Seabrook case. A redacted non-proprietary version was later made available, on September 10, 2020. Preparation of the decision had taken almost a year, and the decision ran to nearly 200 pages.

The Board did a very thorough job of reviewing all the facts and expert opinions presented in this case, weighing them and explaining the basis for its decision. Ultimately, the ASLB agreed with C-10 that NextEra's program for assessing and monitoring ASR was inadequate; but concluded that the program could be made acceptable by adding a set of four new license conditions. These license conditions direct NextEra Seabrook to conduct much more frequent and stringent monitoring and engineering evaluations in a number of situations. They are:

Monitoring concrete expansion: NextEra will have to increase the frequency of instrumentation monitoring by twenty-fold, moving from proposed intervals as long as ever ten years, up to monitoring every six months.

Monitoring reinforced steel: Under certain conditions, NextEra must develop a monitoring program to either anticipate or monitor rebar failures.

Knowing when to monitor more aggressively: If the degradation-related expansion rate in any area of a "seismic Category I" structure significantly exceeds 0.2mm/m per year, NextEra must evaluate whether to implement more frequent monitoring.

Looking deep inside the concrete: Each concrete core extracted from Seabrook must undergo a detailed microscopic petrographic evaluation to detect microcracks.

These conditions must be complied with throughout Seabrook's operating license term, including the remainder of the current term and the renewal term, i.e., until 2050.

By imposing the four license conditions, the ASLB gave C-10 much of the relief it sought. However, several of the license conditions were written in a way that allowed for too great a range of interpretations. Therefore, with the support of supplemental testimony by VES, C-10 has sought to clarify and thereby strengthen them. At this writing, C-10 is awaiting a ruling from the ASLB regarding whether it will impose the refinements to the license conditions. In §36.4.1.1 below, VES will quote some of the ASLB's key rulings, as well as the text of the license condition related to each ruling (in italics). And in §36.4.1.2, he will explain in more detail why C-10 proposed changes to the new license conditions imposed by the Board.

36.4.1.1 Ruling Details

Representativeness of Concrete

C-10's Case: C-10 has challenged the representativeness of the concrete used in the Texas test, and as such questioned whether some of the findings can be applied to Seabrook.

ASLB Concerns: "Because the Board questions whether the LSTP specimens were sufficiently representative to Seabrook concrete, we also question NextEra's reliance on the LSTP data to justify the [REDACTED] extensometer threshold. [An extensometer is a device that is used to measure changes in the length of an object]." (pg 92)
"Nevertheless, we have identified a significant problem with the schedule for monitoring the control extensometers. . . This schedule fails to provide adequate protection of public health and safety...That premise is fundamental to NextEra's monitoring program, and if it is incorrect, potentially damaging ASR expansion could go undetected for years. There is no apparent reason why NextEra should not monitor these control extensometers every six months. The burden of doing so is not significant. . . (pg 96)
New License Condition:

> *The Board therefore modifies Check 3 as follows: NextEra shall undertake the monitoring required by MPR-4273, Appendix B, Check 3, for control extensometers every six months, rather than in 2025 and every ten years thereafter.*
>
> (pg 97)

Monitoring Rebars

C-10's Case: Dr.Saouma has raised "the potential for ASR to cause or contribute to the fracture or yielding of reinforcing steel bars and a resulting loss of structural capacity. While The first author has not established that this will occur at Seabrook, he has raised a substantial question as to the likelihood that it may eventually happen." (pg 126)
ASLB Concerns: "Dr. Saouma has identified a plausible risk that rebar fracture or yielding may occur in the highly stressed areas of seismic Category I structures from the negative impacts of the chemical prestressing effect. As ASR expansion increases, it is reasonable to expect that the negative impacts of chemical prestressing will also increase".(pg 127)
New License Condition:

> *The Board therefore concludes that, in order to provide reasonable assurance of adequate protection of public health and safety, it is necessary to add a license condition requiring the development of such a monitoring program contingent on the results of future stress analyses, as follows: If stress analyses conducted pursuant to the SEM [Structural Evaluation Methodology] show that the stress in the rebar from ASR-induced expansion and other loads will exceed the yield strength of the rebar, NextEra must develop a monitoring program sufficient to ensure that rebar failure or yielding does not occur, or is detected if it has already occurred, in the areas at-risk of rebar failure or yielding.*
>
> (pg 128)

Monitoring Frequency

C-10's Case: "Dr. Saouma testified that 'Seabrook is most likely in the very early slower phase, but the rate of expansion will accelerate at some point. Through-thickness expansion monitoring only began in 2016, and the Board lacks data sufficient to demonstrate that NextEra knows where it is on the sigmoid curve [s-shaped curve on a graph]." (pg 135)

ASLB Concerns: " Based on the preponderance of the evidence in the record before us regarding the ASR monitoring interval for Tier 3 areas [tier pertains to level of ASR severity], the Board finds that the ASR monitoring intervals under the SMP [Structures Monitoring Program] fail to provide reasonable assurance in accordance with 10 C.F.R. §§50.40(a) and 50.57(a) that operation of Seabrook Unit 1 will not endanger the health and safety of the public.(pg 134)

"Specifically, NextEra has not shown by a preponderance of the evidence that the current SMP can effectively account for an increase in the rate of ASR expansion, especially when NextEra's own data indicates the SMP through-thickness expansion limit may be reached in [REDACTED]" (pg 134)

"We find action must be taken by NextEra well before the through-thickness expansion limit is reached. Since the license renewal authorizes operation until March 15, 2050, the Board finds that NextEra must establish a tangible mechanism that will detect an increased expansion rate and timely implement more frequent monitoring intervals, if necessary, because of an increased expansion rate. By NextEra's own admission, the through-thickness expansion acceptance limit will be exceeded in [REDACTED], with [REDACTED] additional years of licensed operation."(pg 134-35)

"However, even without considering that the expansion rate may increase, a steady expansion rate will put NextEra beyond the acceptance limit within its licensed operating timeframe. (pg 135)

"Thus, the Board finds the SMP and the Staff's license condition inadequate to fulfill the maintenance rule's directive that a licensee monitor the condition of its structures 'in a manner sufficient to provide reasonable assurance that these structures . . . are capable of fulfilling their intended functions."(pg 140)

New License Condition:

> *To remedy this deficiency, the Board imposes the following license condition: If the ASR expansion rate in any area of a Seabrook seismic Category I structure significantly exceeds 0.2 mm/m (0.02%) through-thickness expansion per year, NextEra's Management will perform an engineering evaluation focused on the continued suitability of the six-month monitoring interval for Tier 3 areas. If the engineering evaluation concludes that more frequent monitoring is necessary, it shall be implemented under the SMP.*
>
> (pg 140)

Potential Delamination of Concrete

C-10's Case: "Dr. Saouma stated that changes in humidity and temperature may produce gradients within the Seabrook walls, and when coupled with Seabrook's rebar being located close to the surface, cracking on the surface of its walls will not be representative of cracking in the interior." (pg 174)

"Dr. Saouma testified that NextEra should perform petrographic analysis of concrete cores from Seabrook structures to detect microcracks, which eventually coalesce into larger cracks that may lead to delamination [when layers 'flake off']".(pg 173)
"We need to define failure, because failure does not mean the collapse of the whole structure. We have localized failure. This is what is of concern. It's the localized failure which is going to lead to an unacceptable leakage". (pg 177)
ASLB Concerns:"Given the uncertainties in NextEra's approach and the potential severity—catastrophic failure—of a delamination event, NextEra has not persuaded us that it is properly accounting for the possibility of delamination. Indeed, given the example of the unforeseen delamination and subsequent significant structural damage at the Crystal River nuclear plant, albeit for non-ASR reasons, delamination is an issue that cannot be ignored.(pg 183)
"Indeed, microcracking cannot be seen with the naked eye, but must be observed by another method, such as petrography, and NextEra testified that it did not perform petrographic examinations on all the cores that it extracted from Seabrook...The Board finds that NextEra does not have an adequate screening procedure to detect internal cracking and delamination in Seabrook's concrete."(pg 184)
"The further complicating issue of localized excursions of Seabrook structures outside the linear elastic regime is a serious concern. Since the failure mode associated with combined ASR degradation and an earthquake is a brittle, shear failure without ample warning of its occurrence, the Board is concerned about the potential for sudden significant, localized damage due to shear failure, given that all parties agreed that there may be localized excursions of Seabrook Unit 1 into the nonlinear structure plastification regime."(pg 184)
"The Board notes the lack of experience in the other reactors around the country in addressing the possibility of ASR-induced localized excursions outside the linear elastic regime. The Board also is not persuaded that NextEra and the Staff have a sound plan in place to detect and address internal microcracking and the potential for an unforeseen delamination. Thus, the Board finds that NextEra has not shown, by a preponderance of the evidence, that there is reasonable assurance that the continued operation of Seabrook Unit 1 will not endanger the health and safety of the public with regard to this particular issue of delamination." (pg 185)
"the Board finds that the petrographic analysis of each extracted core would gauge the degree of internal microcracking (possibly resulting in macrocracking) that could lead to catastrophic delamination."(pg 185)
New License Condition:

> *Therefore, the Board imposes the following license condition: Each core extracted from Seabrook Unit 1 will be subjected to a petrographic analysis to detect internal microcracking and delamination.*
>
> (pg 185)

36.4.1.2 Supplemental Testimony: Suggestions to Strengthen the Conditions

Concerned that the four license conditions imposed by the ASLB were not clear enough to guard against misinterpretation, C-10 proposed more specific language for making them stronger and unambiguously enforceable. VES also provided supporting testimony. These suggestions include:

1. Quantifying reliability of concrete expansion monitoring by inserting error bars to connote the uncertainties in the calibration curve used by NextEra, as it relies on many field data obtained during construction, approximate equations, and assumptions which collectively are not properly safeguarded against NextEra's arbitrarily defined safety factor.
2. Installing acoustic emission sensors to detect possible reinforcement failure, using ultrasonic waves to detect and measure when a material deforms under stress.
3. Eliminating ambiguous terms such as "significantly exceed" (this suggestion has been supported by the NRC staff).
4. Specifying that petrographic studies of recovered cores be made in accordance with the international standard ASTM C856 to ensure that microcracks will be properly detected via microscopic analysis.

It is VES opinion that the first recommendation is by far the most critical. The importance of error bars has been addressed in §36.18(a).

If the ASLB ultimately admits VES testimony and revises its final order to incorporate his suggestions, this will give C-10 and the public a much higher level of confidence that Seabrook Station is following best practices to monitor and manage ASR, thus truly enhancing public safety.

As of writing, both NextEra and the NRC's staff have strenuously opposed the consideration of C-10's further recommendations by the Board. C-10 expects that the Board's order will be finalized by mid-December of 2020, given the current timeline.

36.4.2 Personal Final Assessment

Key Observations

First, it is most regretful that NextEra has opted to redact the documents to the extent it did under the pretext that it is safeguarding trade secrets that could jeopardize its ability to market the acquired know-how. To the best of VES's observation, not a single methodology has been redacted, on the other hand what was redacted were countless data (such as dimensions of test specimens, measured expansions and others). Such an effort cannot reassure the public about the extent of the ASR induced damage, and the quality of the related studies.

Second, the U.S. is fortunate to have a very transparent, well codified, and regulated process for public participation in regulatory decisions., whereby even a tiny NGO can challenge a large corporation as well as a major regulating federal agency. Many other OECD countries do not have that luxury. There is no indication that the public had a formal say in soliciting the closure of Fessenheim reactor in France. In that case, the "battle" was fought nearly exclusively in the media.

Third, and related to my second point, the power of an educated and concerned public in advocating for strong, science-based regulation cannot be underestimated. In this case, C-10 a small but determined NGO, relying heavily on volunteer efforts, has monitored the operation of the Seabrook nuclear plant since it began operating. After ASR was discov ered at Seabrook in 2009, C-10 quickly perceived that ASR was not only a major safety challenge to Seabrook, but also a potential problem at other nuclear plants. C-10 then used the NRC's legal process to force a desperately-needed scientific review on Seabrook's concrete aging man- agement plan. And C-10 brought about the imposition of license conditions which are essential to any future confidence in the safety of Seabrook. This is a remarkable achievement for a single nuclear plant, and it seems reasonable to hope that the science based approach advocated here will influence how future ASR policy is made for a range of circumstances.

Finally, it is the first-author's opinion that whereas "good" engineering was applied by NextEra, that was far from sufficient. Given the complexity of the problem, the current State of the Art in ASR, was ignored.

Luckily for NextEra, it only had to show continuous compliance with the 1971 ACI-318 design code, and most importantly it took advantage of what one can only qualify as a complacent regulating agency. There as not a single expert in ASR throughout the process, no peer-review, and no in-depth follow up to the proposed LAR. Of course, there is a major cultural (and motivational) difference between the licensee and a peer reviewer such as this first author. The former would find safeguard within the confine of the law where:

> "The burden on the licensee is that the structures are required to remain operable. And they are required to continue to stay within their design and licensing bases. And so what the licensee opted to do to demonstrate that the design codes and licensing basis remains intact was the charge of the staff to review. So looking beyond the codes is outside of the scope of the requirement for the structures to remain operable and to stay within the bounds of their licensing basis".
>
> NRC-ML19312B609 [63, p. 574, l. 12].

The Academic (University Professor) on the other hand sets aside the shackles of the laws, dissects the problem, break it down and scrutinize every statement/assumption to determine if it passes the muster test of scientific rigor.

Last, but not least, and on a personal note, VES would like to acknowledge the essential role played by C-10's attorney, Diane Curran Esq. in absorbing very technical details and recasting them in the proper legal terms. This perfect symbiosis between a scholar and a lawyer was critical to the success in securing additional safety measures by NextEra.

Safety of Seabrook

Ultimately, the most critical question is whether Seabrook is safe. Mere compliance with the 1971 ACI code provisions *does not ensure* safety in the spirit of [25]. Those provision are written with the assumption of sound concrete, with known mechanical properties (assessed by multiple field core tests) and unencumbered by random unquantified degradation caused by ASR (Fig. 36.7(c) provides a glimpse of the very extensive cracking of the CEB). They are primarily used for design of new structures (though they can be used for the assessment of existing structure when applicable).

For critical structures (such as CEB), safety can be assessed either through their Reliability Index (RI) β (Eq. **??**) or their fragility curves. The former is discussed in §**??**, and major design codes specify β to be around 3.5 (which translates in a risk of approximately one failure per 100,000 during 50 years). The RI concepts has indeed been used for nuclear sensitive components [11, 12, 79].

As to fragility curves, it is explicitly a probabilistic approach which quantify the probability of exceedance of a certain limit state for a level of ground motion intensity (§**??**). The concept originated with the NRC through the classical WASH-1400 report [91] and [43] and has been used to the aging of nuclear structures [24].

In both cases, safety is an abstract (yet most existential) concept that would require far more advanced nonlinear (deterministic or probabilistic) analyses than performed for Seabrook.

Finally, for Seabrook, given the simplicity of the analyses, the assumptions made, and despite the revised inspection put in place, and in light of how structural safety is assessed, VES would argue that Seabrook is not safe.

Of course, this does not imply that the reactor has to be shut-off, it simply means that the structure is at a societal unacceptable risk and the regulating agency owes a credible safety assessment to the public living within the 10 miles radius.

36.4.3 Chronology Key Phases

2010	ASR causes Seabrook to be placed under special NRC oversight.
Aug 1, 2016	NextEra files a License Amendment Request (LAR)16-03 relative to the concrete
April 10, 2017	C-10 petitions to intervene in the LAR, NRC Docket 50-443
Oct 6, 2017	NRC's Atomic Safety and Licensing Board Grants Intervenor Status to C-10
Oct 24, 2018	Addition of expert Professor Victor Saouma to C-10's case
Jan 2019	Attorney Diane Curran begins representing C-10 in the case
Feb 13, 2019	**C-10 Files Emergency Enforcement Petition with NRC** • ML19044A767 - Cover letter to NRC Secretary re Emergency Petition to NRC Commissioners in Seabrook License Amendment Proceeding. • ML19044A768 - C-10 Emergency Petition to Reverse No Significant Hazards Determination and Immediately Suspend License Amendment And License Renewal Decisions. • ML19044A769 - Declaration of Victor E. Saouma, Ph.D. • ML19044A770 - Exhibit 1 to Saouma Declaration: Curriculum Vitae for Dr. Victor E. Saouma. • ML19044A771 - Exhibit 2 to Saouma Declaration: NRC grant award letter. • ML19044A772 - Exhibit 3 Experimental and Numerical Investigation of Alkali Silica Reaction in Nuclear Reactors, Final Summary Report to the NRC by Saouma. • ML19044A773 - Exhibit 4a Saouma Declaration: Introduction and Executive Summary.
Feb. 25, 2019	NRC Staff's Answer To C-10's Emergency Petition
Mar 12, 2019	NRC Grants license extension to Seabrook Station
Apr 10, 2019	NRC sets September hearing date for C-10 filing

Apr 11, 2019	C-10 Motion Regarding Seabrook Station Site Tour
Jun 10, 2019	C-10 Initial Statement Of Position On C-10's Contentions Regarding Nextera's Program For Managing ASR At Seabrook and written Testimony of Professor Saouma
Jun 24, 2019	Colo. Professor Saouma to visit Mass. for concrete degradation discussion
Jun 27, 2019	Presentation by Professor Saouma and Attorney Diane Curran at C-10 Annual Public Meeting: slides, full video , 15-min video
Sep 24-27 2019	Hearing before NRC's ASLB in Newburyport, Mass.
Sep 24, 2019	Consolidated documents filed by Dr. Victor Saouma
Nov. 2019	Proposed Findings of Fact and Conclusions of Law: C-10, NRC, and NextEra.
Aug 21, 2020	ASLB Ruling
Aug 31, 2020	C-10 petitions to reopen the record to submit supplemental testimony. Diane: can I put a link to INT052 (in my personal web site)?
Sep 10, 2020	NextEra and NRC staff file objections to C-10's motion and supplemental testimony. Diane I guess we are waiting for their approval of our proposed redaction before we can upload and then link here, correct?
Jan 23, 2020	Diane Curran files a Freedom of Information Act (FOIA) request with the NRC for key documents.
Winter 2020	Final ruling anticipated by the ASLB

References

[1] ACI 318. "Building code requirements for structural concrete (ACI 318-19) and commentary". In: American Concrete Institute. 2019.

[2] ACI 318-71. "Building code requirements for structural concrete (ACI 318-71) and commentary". In: American Concrete Institute. 1971.

[3] ACI 365. *Service Life Prediction; State of the Art Report*. Tech. rep. American Concrete Institute, 2010.

[4] ACI-ASCE 423.10R-16. "Guide to Estimating Prestress Loss". In: American Concrete Institute. 2016.

[5] T. Ahmed, E. Burley, and S. Rigden. "The state and fatigue strength of reinforced concrete beams affected by alkali-silica reaction". In: *Materials Journal* 95.4 (1998), pp. 376–388.

[6] ASCE 4-16. *Seismic Analysis of Safety-Related Nuclear Structures*. Tech. rep. American Society of Civil Engineers, 2016.

[7] ASCE/SEI 7. *Minimum Design Loads For Buildings and Other Structures*. Tech. rep. American Society of Civil Engineers, 2010.

[8] H. Ashar et al. "Code for concrete reactor Vessels and containments". In: *ASME Boiler & Pressure Vessel Code, Sec. III* 504.2 (2001).

[9] ASLB-ML20254A339. *In the Matter of NEXTERA ENERGY SEABROOK, LLC (Seabrook Station, Unit 1); Initial Decision*. Docket No. 50-443-LA-2, ASLB No 17-953-02-LA-BD01. 2016.

[10] ASTM C469. "469, Standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression". In: *Annual book of ASTM standards* 04.02 (2016).

[11] K. Avrithi and B. M. Ayyub. "A reliability-based approach for the design of nuclear piping for internal pressure". In: *Journal of pressure vessel technology* 131.4 (2009).

[12] K. Avrithi and B. M. Ayyub. "A reliability-based approach for low-cycle fatigue design of class 2 and 3 nuclear piping". In: *Journal of pressure vessel technology* 132.5 (2010).

[13] P. Bažant Ž. "Instability, Ductility and Size Effect in Strain Softening Concrete". In: *Journal of Engng. Mech., ASCE* 102.2 (1976), pp. 331–344.

[14] Z. Bažant and J. Planas. *Fracture and Size Effect in Concrete and Other Quasibrittle Materials*. CRC Press, 1998.

[15] O. Bayrak. *Structural Assessment of Seabrook Station; Findings and Structural Testing Plan*. Tech. rep. Online; accessed 2018-07-11. University of Texas, Austin, 2012.

[16] E. Bentz. "Empirical modeling of reinforced concrete shear strength size effect for members without stirrups". In: *ACI structural journal* 102.2 (2005), p. 232.

[17] Buckingham, E. "The principle of similitude". In: *Nature* 96 (1915), pp. 396–397.

[18] A. Buford. *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*. 2013.

[19] C-10-ML20043E252. *C-10 Research and Education Foundation's Proposed Findings Of Fact And Conclusions Of Law)*. Submitted in NRC Docket No. 50-443). 2019.

[20] B. Capra and J. Bournazel. "Modeling of induced mechanical effects of alkali-aggregate reactions". In: *Cement and Concrete Research* 28.2 (1998), pp. 251–260.

[21] P. Chana and G. Korobokis. *The structural performance of reinforced concrete affected by alkali silica reaction: Phase I*. Tech. rep. British and Cement Association, 1992.

[22] D. Darwin, C. Dolan, and A. Nilson. *Design of Concrete Structures*. 15th Ed. McGraw-Hill, 2014.

[23] D. J. Deschenes, O. Bayrak, K. J. Folliard, et al. *ASR/DEF-damaged bent caps: shear tests and field implications*. Tech. rep. Austin, TX: Ferguson Structural Engineering Laboratory, The University of Texas, 2009.

[24] B. Ellingwood. "Issues related to structural aging in probabilistic risk assessment of nuclear power plants". In: *Reliability Engineering & System Safety* 62.3 (1998), pp. 171–183.

[25] B. Ellingwood et al. *Development of a probability based load criterion for American National Standard A58: Building code requirements for minimum design loads in buildings and other structures*. Vol. 13. US Department of Commerce, National Bureau of Standards, 1980.

[26] EPRI. *Modeling Existing Concrete Containment Structures: Lessons Learned*. Tech. rep. 58 pages. Electric Power Research Company, 2017.

[27] R. Esposito and M. A. Hendriks. "A multiscale micromechanical approach to model the deteriorating impact of alkali-silica reaction on concrete". In: *Cement and Concrete Composites* 70 (2016), pp. 139–152.

[28] R. Esposito et al. "Influence of the alkali-silica reaction on the mechanical degradation of concrete". In: *Journal of Materials in Civil Engineering* 28.6 (2016), p. 04016007.

[29] Federal Register. "Improved Identification Techniques Against Alkali-Silica Reaction (ASR) Concrete Degradation at Nuclear Power Plants". In: *Federal Register* 84.228 (2019), pp. 65024–65032.

[30] FHWA. *Report on the Diagnostis, Prognosis, and Mitigation of Alkali-Silica Reaction (ASR) in Transportation Structures*. Tech. rep. FHWA-HIF-09-004. Federal Highway Administration, 2010.

[31] S. Haberman. "Seabrook Station nuclear plant license advancing". In: *Seacoast On-Line* (2013).

[32] N. Hayes et al. "Monitoring Alkali-Silica Reaction Significance in Nuclear Concrete Structural Members". In: *Journal of Advanced Concrete Technology* 16.4 (2018), pp. 179–190.

[33] D. Hayward et al. “Engineering and Construction Options for the Management of Slow/Late Alkali-Aggregate Reactive Concrete”. In: *16th International Congress of Large Dams, Q62?C R33?* San Francisco, 1988.

[34] Hessheimer, M.F. and Dameron, R.A. *NUREG/CR-6906 SAND2006-2274P: Containment Integrity Research at Sandia National Laboratories; An Overview*. 2006.

[35] I. Hughes and T. Hase. *Measurements and their uncertainties: a practical guide to modern error analysis*. Oxford University Press, 2010.

[36] F. Hunkeler, C. Merz, and A. Griesser. “Langzeiterfahrung in der Schweiz”. In: *Conference on Alkali Silica Reaction*. 2005.

[37] S. Inoue et al. “Effect Of Rupture Of Shear Reinforcement On Shear Capacity Of ASR Damaged Reinforced Concrete Beams”. In: *Proceedings of the 13th International Conference on Alkali-Aggregate Reaction in Concrete*. Ed. by Broekmans, MA and Wigum, BJ. 2008.

[38] Institution of Structural Engineers. *Structural effects of alkali-silica reaction. Technical guidance on the appraisal of existing structures*. Tech. rep. Report of an ISE task group, 1992.

[39] JATR. *Boeing 737 MAX Flight Control System; Observations, Findings, and Recommendations*. 2019.

[40] D. Kent and R. Park. “Flexural Members with Confined Concrete”. In: *Journal of the Structural Division, ASCE* 97.ST7 (1971).

[41] A. Leemann. *Personal Communication*. EMPA/Switzerland, 2019.

[42] J. Liaudat et al. “ASR expansions in concrete under triaxial confinement”. In: *Cement and Concrete Composites* 86 (2018), pp. 160–170.

[43] LLNL-ML090500182. *An Approach to the Quantification of Seismic Margins in Nuclear Power Plants*. 1985.

[44] T. Miyagawa et al. “Fracture of reinforcing steels in concrete structures damaged by alkali-silica reaction-field survey, mechanism and maintenance”. In: *Journal of Advanced Concrete Technology* 4.3 (2006), pp. 339–355.

[45] MPR-ML16216A242. *MPR-4273, Revision 0, Seabrook Station - Implications of Large-Scale Test Program Results on Reinforced Concrete Affected by Alkali-Silica Reaction. July 2016 (ML16216A242))*. Online; accessed 2018-10-15. 2016.

[46] MPR-ML19170A332. *MPR-4273, Rev. 1, Seabrook Station - Implications of Large-Scale Test Program Results on Reinforced Concrete Affected by Alkali-Silica Reaction*. 2016.

[47] S. Multon and F. Toutlemonde. “Effect of Applied Stresses on Alkali-Silica Reaction Induced Expansions”. In: *Cement and Concrete Research* 36.5 (2006), pp. 912–920.

[48] NextEra. *License Renewal Application*. 2010.

[49] NextEra-ML12087A194. *Seabrook Station Updated Final Safety Analysis Report*. Revision 12; Report does not have a date! 2018?

[50] NextEra-ML121160422. *Impact of Alkali Silica Reaction on Seabrook Concrete Structure*. 2012.

[51] NextEra-ML13151A328. *Response to Confirmatory Action Letter*. 2013.

[52] NextEra-ML16216A240. *Seabrook, License Amendment Request 16-03 - Revise Current Licensing Basis to Adopt a Methodology for the Analysis of Seismic Category I Structures with Concrete Affected by Alkali-Silica Reaction. Attachment 1 Markup of UFSAR Pages Enclosed. (73 page(s), 8/1/2016)*. 2016.

[53] NextEra-ML16216A240. *Seabrook, License Amendment Request 16-03 - Revise Current Licensing Basis to Adopt a Methodology for the Analysis of Seismic Category I Structures with Concrete Affected by Alkali-Silica Reaction.* ADMAS access number ML16216A250. 2016.

[54] NextEra-ML18141A785. *Seabrook Station - Approach for Determining Through-Thickness Expansion from Alkali-Silica Reaction*. Redacted Document. 2016.

[55] NextEra-ML19205A489. *Testimony of NextEra Witnesses Michael Collins, John Simons, Christopher Bagley, Oguzhan Bayrak, and Edward Carley ("MPR Testimony")*. 2019.

[56] NRC-CU Grant. *Experimental and Numerical Investigation of Alkali Silica Reaction in Nuclear Reactors*. Tech. rep. Grant and Cooperative Agreement NRC-HQ-60-14-G-0010, 2014.

[57] NRC-ML 12054A735. *FOIA/PA No. 2013-0332; Partial. Group E (Records Being Released in Their Entirety).*

[58] NRC-ML12131A431. *Seabrook Station Safety Performance in 2011 & Seabrook Station Safety in light of the Alkali-Silica Reaction Occurring in-Plant Structures* . 2011.

[59] NRC-ML12160A374. *Safety Evaluation Report With Open Items Related to the License Renewal of Seabrook Station*. Tech. rep. United States Nuclear Regulatory Commission, 2012.

[60] NRC-ML12199A300. *Seabrook Advisory Committee on Reactor Safeguards presentation slides*. 2012.

[61] NRC-ML18226A205. *Non-Proprietary Draft Safety Evaluation Nextera Energy Seabrook, LLC Seabrook Station, Unit No. 1;Docket No. 50-443; (ML 18226A205, 2018*. 2018.

[62] NRC-ML19261A762. *NRC Staff Testimony of Angela Buford, Bryce Lehmanm and George Thomas*. 2019.

[63] NRC-ML19312B609. *Official Transcript of Proceedings; NextEra Energy Seabrook, LLC Seabrook Station, Unit 1; Docket Number: 50-443-LA-2;ASLBP Number:17-953-02-LA-BD01*. Newburyport, Massachusetts, 2019.

[64] NUREG-1737. *Software Quality Assurance Procedures for NRC Thermal Hydraulic Codes*. Tech. rep. NUREG-1737. U.S. Nuclear Regulatory Commission, 2000.

[65] S. Poyet et al. "Chemical modelling of Alkali Silica reaction: Influence of the reactive aggregate size distribution". In: *Materials and Structures* 40 (2007), pp. 229–239.

[66] Y. Rashid. "Analysis of Prestressed Concrete Pressure Vessels". In: *Nuclear Engineering and Design* 7.4 (1968).

[67] N. Regulations. *NRC Title 10, Code of Federal Regulations; Part 50*. Vol. 2. 50-199. Nuclear Regulatory Commission, Office of Administration, Division of Rules, 1987.

[68] V. Saouma, ed. *Diagnosis & Prognosis of AAR Affected Structures; State-of-the-Art Report of the RILEM Technical Committee 259-ISR*. *in-print*. Springer Nature, 2020.

[69] V. Saouma. *Effect of AAR on Shear Strength Panels*. Tech. rep. Final Report to NRC, Grant No. NRC-HQ-60-14-G-0010, Task 1-C. University of Colorado, Boulder, 2017.

[70] V. Saouma. *Probabilistic Based Nonlinear Seismic Analysis of Nuclear Containment Vessel Structures with AAR*. Tech. rep. Final Report to NRC, Grant No. NRC-HQ-60-14-G-0010, Task 3-B. University of Colorado, Boulder, 2017.

[71] V. Saouma and G. Fava. "On Fractals and Size Effects". In: *International Journal of Fracture* 137 (2006), pp. 231–249.

[72] V. Saouma, R. Sparks, and D. Graff. *Development Of ASR Concrete Mix for Large Scale Testing*. Tech. rep. Report to the Nuclear Regulatory Commission, Grant No. NRC-HQ-60-14-G-0010. University of Colorado, Boulder, 2016.

[73] V. Saouma et al. *AAR Expansion; Effect of Reinforcement, Specimen Type, and Temperature*. Tech. rep. Report to the Nuclear Regulatory Commission, Grant No. NRC-HQ-60-14-G-0010. University of Colorado, Boulder, 2016.

[74] Saouma-C-10-ML19254F151. *Saouma, Review of Selected Documents Pertaining to the Structural Evaluation of Seabrook Nuclear Power Plant (Feb. 12, 2019) (Non-Proprietary Version)*. Submitted in NRC Docket No. 50-443). 2019.

[75] Saouma-C-10-ML19254F154. *Pre-Filed Rebuttal Testimony of Victor E. Saouma, Ph.D Regarding Scientific Evaluation of Nextera's Aging Management Program for ASR at the Seabrook Nuclear Power Plant Submitted on Behalf of C-10 Research)*. Submitted in NRC Docket No. 50-443). 2019.

[76] Saouma-C-10-ML19265A019. *Supplemental Rebuttal Testimony Of Victor E. Saouma, Ph.D Regarding Scientific Evaluation Of Nextera's Aging Management Program For Alkali-Silica Reaction At The Seabrook Nuclear Power Plant(ML19265A019)*. Submitted in NRC Docket No. 50-443). 2019.

[77] Saouma, V.E. *Numerical Modeling of AAR*. 324 pages. CRC Press, 2014.

[78] R. Scott and N. Morgan. *Feasibility and Desirability of Constructing Very Large Centrifuges for Geotechnical Studies*. Tech. rep. Pasadena, CA: California Institute of Technology, 1977.

[79] N. Siddiqui et al. "Reliability analysis of nuclear containment without metallic liners against jet aircraft crash". In: *Nuclear engineering and design* 224.1 (2003), pp. 11–21.

[80] Simpson Gumpertz & Heger-ML16216A243. *SG&H Report 160268-R-01 Development of ASR Load Factors for Seismic Category I Structures (Including Containment) at Seabrook Station. Seabrook, NH Revision 0 (Seabrook FP# 101039)*. 2016.

[81] Simpson Gumpertz & Heger-ML16279A049. *Evaluation and Design Confirmation of As-Deformed CEB, 150252-CA-02," Revision 0, July 2016.* 2016.

[82] F. Sims, J. Rhodes, and R. Clough. "Cracking in Norfork Dam". In: *J. of the American Concrete Institute* (1964).

[83] V. Slowik, C. Kishen, and V. Saouma. "Mixed mode fracture of cementitious bimaterial interfaces; part I: experimental results". In: *Engineering Fracture Mechanics* 60.1 (1998), pp. 83–94.

[84] D. Stark and G. De Puy. "Alkali-silica reaction in five dams in southwestern United States". In: *Special Publication* 100 (1987), pp. 1759–1786.

[85] J. R. Stewart. *Verification Methods and NRC Regulations: A Brief Overview*. Tech. rep. Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2009.

[86] M. Thomas, B. Fournier, and K. Folliard. *Alkali-aggregate reactivity (AAR) facts book*. Tech. rep. United States. Federal Highway Administration. Office of Pavement Technology, 2013.

[87] M. Thomas, B. Fournier, and K. Folliard. *Alkali-Silica Reactivity Field Identification Handbook*. Tech. rep. FHWA-HIF-12-022. United States. Federal Highway Administration. Office of Pavement Technology, 2011.

[88] D. Wald, G. Martinez, and O. Bayrak. "Expansion behavior of a biaxially reinforced concrete member affected by alkali-silica reaction". In: *Structural Concrete* (2017).

[89] D. Wald. "ASR Expansion Behavior in Reinforced Concrete – Experimentation and Numerical Modeling for Practical Application". PhD thesis. Austin, TX: University of Texas, Austin, 2017.

[90] J. Wang and H. Morikawa. "Study on shear behavior of deteriorated RC beams due to alkali-silica reaction". In: *37th Conference on Our World in Concrete and Structures, Singpore*. 2012.

[91] WASH-1400. *An assessment of accident risks in us commercial nuclear power plants*. NTIS, 1975.

[92] E. Wilson. *The Use of the Response Spectrum Method in Earthquake Engineering must be Terminated*. Accessed: 2018-10-12. 2014.

Index

Analytical Evaluation, 18

Bayrak, O., 7
Beam Shear tests, 8
Boeing 737 MAX, 23
Bravo 1 Tunnel, 25
Brookhaven National Laboratory, 25
Building Deformation Aging Management, 12
Building Deformation Assessment, 18

Category I, 18
Chemical Prestressing
  Modelling, 48
Chemical Prestressing, 32
CI, 36
Code-based Approach, 25
Compressive Strength, 37
Concrete Mix, 8
Corroborative Modulus Expansion, 15
crack index, 12
Creep, 33

Dam
  Norfork, x
Detailed Evaluation, 18
Directional Expansions, 16

Edge Effect, 30
Environmental Conditioning Facility, 9

FAA, 23
Factored Load Combinations, 19
Ferguson Structural Engineering Laboratory, 7
Ficititous crack, 31
Force-based Failure Assessment, 43
Francis Bacon, xi

In-plane Shear, 8
Internal Cracks, 38
Internal humidity, 36

Large Scale Testing Program, 8
License Renewal Rule, 5
Loss Of Coolant Accident, 5

Margin For Future Expansion, 41
margin of safety, 51
Mineralogy, 37
MPR Associates, 7

NextEra, 3
NPP
  Seabrook, 3
NRC and NextEra, 23

Out-of-Plane Expansion, 15
Overlayed shell elements, 46

Plastic Capacity, 43

Probability Of Failure, 43

Relative Humidity, 34
Relaxation, 33
Reliability Index, 43
response spectrum
  Response Spectrum method, 50
Role of Reviewers, 24
Root Cause Investigation, 6

Safety Evaluation Report, 5
Screening Evaluation, 18
Seabrook, 3
  Box Limits, 27
  Building Deformation Aging Management, 34
  Building Deformation Assessment, 42
  Finite Element Analysis, 19
  Internal cracking, 32
  Measurement Uncertainties, 41
  Nonlinear Analysis, 46
  Out-of-Plane, 28, 37
  Possible delamination, 31
Seismic loads, 50
Self-straining Loads, 18
Severity Zones, 12
Shear Capacity, 11
Shear Transfer Mechanisms, 28
Shell Elements, 46
Simpson Gumpertz & Heger, 7
Size Effect, 33
Splitting Crack, 30
Stress-based Failure Assessment, 42
Structural Crack, 9
Surface measurements
  Internal cracks, 36

Threshold Factor, 41
Through Thickness Expansion, 15

Verification & Validation, 44
Volumetric Strain, 37

Wetting Zones, 9

Author

ACI 318, 43
ACI 318-71, 19, 21, 25, 43
ACI 365, 22
ACI-ASCE 423.10R-16, 33
Ahmed, Tarig, 11
ASCE 4-16, 22, 51
ASCE/SEI 7, 43
Ashar, Hansraj, 46, 50
ASTM C469, 15, 38
Avrithi, Kleio, 60
Ayyub, Bilal M, 60

Bažant Ž, P., 33
Bažant, Z., 33
Bayrak, O., xix, 4, 7, 9–13, 16, 17, 28, 31, 36
Bayrak, Oguzhan, 11, 32
Bentz, E.C., 33, 34
Bournazel, J.P., 34
Buckingham, E., 26
Buford, A., 37
Burley, Eldon, 11

C-10-ML20043E252, 4
Capra, B., 34
Chana, P.S., 11
Clough, R.A., ix

Darwin, D., 33, 38, 39
De Puy, GW, 34
Deschenes, Dean J, 11, 32
Dolan, C., 33, 38, 39

Ellingwood, B.R., 43, 44, 59, 60
EPRI, 47
Esposito, Rita, 15, 48

Fava, G., 33
Federal Register, 37
FHWA, 13, 36, 38, 40, 48
Folliard, K., 15
Folliard, K.J., 14
Folliard, Kevin J, 11, 32
Fournier, B., 14, 15

Graff, D., 24
Griesser, A., 42

Haberman, S., 5
Hase, Thomas, 38
Hayes, N., 36
Hayward, D.G., 47
Hendriks, Max AN, 15
Hessheimer, M.F. and Dameron, R.A., 47
Hughes, Ifan, 38
Hunkeler, F., 42

Inoue, S., 33
Institution of Structural Engineers, 15, 38

JATR, 23

Kent, D.C., 33
Kishen, C., 30
Korobokis, G.A., 11

Leemann, A., 38, 40, 42
Liaudat, Joaquín, 47
LLNL-ML090500182, 60

Martinez, G.A., xix, 4, 7, 9–12, 16, 17, 28, 31, 36
Merz, C., 42
Miyagawa, Toyoaki, 33, 34
Morgan, N., xxi, 26
Morikawa, Hidenori, 11, 30
MPR-ML16216A242, xix, 7–11, 15, 16
MPR-ML19170A332, 7, 9, 36, 41, 42
Multon, S., 47

NextEra, 5
NextEra-ML12087A194, 18
NextEra-ML121160422, 4, 20
NextEra-ML13151A328, 6, 20
NextEra-ML16216A240, 7, 18, 39, 44
NextEra-ML18141A785, xxi, 8, 14, 16, 17
NextEra-ML19205A489, 32
Nilson, A.H., 33, 38, 39
NRC-CU Grant, 24
NRC-ML 12054A735, 5
NRC-ML12131A431, 6
NRC-ML12160A374, 5
NRC-ML12199A300, 6
NRC-ML18226A205, xix, 15, 16
NRC-ML19261A762, 8
NRC-ML19312B609, 24–28, 38, 39, 46, 59
NUREG-1737, 45

Park, R., 33
Planas, J., 33
Poyet, S., 30

Rashid, Y.R., ix
Regulations, NRC, 45
Rhodes, J.A., ix
Rigden, Stephen, 11

Saouma, V., 30, 45
Saouma, V.E., 24, 30, 33, 47
Saouma-C-10-ML19254F151, xix, 29, 47
Saouma-C-10-ML19254F154, xix, 31, 34, 35, 39, 42, 49
Saouma-C-10-ML19265A019, 39
Scott, R., xxi, 26
Siddiqui, NA, 60
Simpson Gumpertz & Heger-ML16216A243, 19
Simpson Gumpertz & Heger-ML16279A049, xix, xxi, 8, 12, 13, 19–21, 29, 41, 43, 45, 48–50
Sims, F.W., ix
Slowik, V., 30
Sparks, R., 24
Stark, David, 34
Stewart, James R, 44

Thomas, M., 14, 15
Toutlemonde, F., 47

Wald, D., xix, 4, 7, 9–12, 16, 17, 28, 31, 36
Wald, D.M., 4, 7, 9
Wang, Jian, 11, 30
WASH-1400, 60
Wilson, E., 50