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SUMMARY OF CHANGES TO THE UPCOMING REVISION OF ASCE 43 AND IMPACTS ON THE DESIGN AND ANALYSIS OF NUCLEAR STRUCTURES

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ABSTRACT

ASCE/SEI Standard 43, "Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities," is a consensus US national standard developed by the American Society of Civil Engineers. It provides design criteria for nuclear structures and should be used in conjunction with ASCE/SEI Standard 4. "Seismic Analysis of Safety-Related Nuclear Structures and Commentary". The two standards are performance based and are written to ensure that structures, systems, and components designed and evaluated in accordance with their provisions meet target performance goals that vary as a function of the seismic design basis.

ASCE/SEI 43 was published in 2005, and is currently being revised with the goal of issuing the updated Standard in 2018. This paper presents a summary of the significant changes in the new revision of ASCE 43 and describes the potential impact these changes may have on the design and analysis of nuclear structures. Significant revisions include the characterization of design response spectra, procedures for modeling and analysis, the inclusion of new framing systems, and the addition of a chapter on seismic isolation. The paper will also discuss the integration of ASCE/SEI Standards 4 and 43.

OVERVIEW

ASCE/SEI 43 (hereafter referred to as ASCE 43) consists of a Foreword plus ten Chapters arranged as follows:

Foreword
Chapter 1 – Introduction
Chapter 2 – Earthquake Ground Motion
Chapter 3 – Evaluation of Seismic Demand
Chapter 4 – Structural Capacity
Chapter 5 – Load Combinations and Acceptance Criteria for Structures
Chapter 6 – Ductile Detailing Requirements
Chapter 7 – Special Considerations
Chapter 8 – Seismic Qualification of Equipment and Distributions Systems
Chapter 9 – Quality Assurance Provisions
Chapter 10 – Seismically Isolated Structures

All chapters have been updated. The revisions range from significant to more editorial and clarifying. First, the changes to the chapters will be summarized and then potential impacts to the design of nuclear structures will be discussed.

In general, there has been an attempt to more tightly integrate ASCE 43 and ASCE/SEI 4 (ASCE 2017; hereafter referred to as ASCE 4) by more clearly separating seismic design criteria from seismic analysis topics and removing duplication between the two Standards. In some cases, provisions have been removed, simplified, or provided by simply incorporating other Codes and Standards by reference. An example is reference to ACI 349-13 (ACI 2013a) for strength requirements for concrete and reinforcing steel in Chapter 6 in lieu of independently including such details in this Standard.

SUMMARY OF CHAPTER CHANGES

Chapter 1 introduces one of the more significant changes to the Standard with the inclusion of Seismic Design Category 2 (SDC-2), which is in contrast to ASCE 43-05 (ASCE 2005), which only includes SDC-3 through SDC-5. When ASCE 43-05 was written the expectation was that the majority of nuclear facilities would be categorized as SDC-3 and SDC-4, and thus that the provisions of ASCE 43 (and ASCE 4) would apply to such facilities. This expectation was a natural consequence of the fact that ANSI/ANS2.26 did not provide a numerical target performance goal for SDC-2 Structures, Systems, and Components (SSCs) because it was not anticipated that major nuclear facilities would be categorized or designed as SDC-2. It was thought that SDC-2 SSCs would be designed using ASCE 7 and criteria from the International Building Code (IBC), and would not include facilities with significant nuclear inventory. However, the ASCE 43 Working Group recognizes that there are now many facilities with significant nuclear inventory that are categorized and designed as SDC-2 and thus this situation should be addressed by ASCE 43.

The inclusion of SDC-2 was a straightforward decision by the Working Group, but there was considerable discussion and debate as to whether the associated target performance goal should be set at 4×10^{-4} Annual Frequency of Exceedance (AFE) or if it should be lowered to 2×10^{-4} AFE. The argument for reducing the AFE to 2×10^{-4} is based on the recognition that the risk adjusted ground motion in ASCE/SEI 7 (hereafter referred to as ASCE 7) expressed as MCE_R corresponds to a 1% probability of structural collapse in 50 years (i.e. 2×10^{-4} annual probability of collapse). Thus, in nominal terms, it is difficult to accept a model building code with a more stringent target performance goal (2×10^{-4} annual probability of collapse) than a nuclear standard (4×10^{-4} hazard AFE). That said, such a comparison is anything but direct because the procedures for formulating the performance goals in the two Standards are fundamentally different, namely, performance is judged in ASCE 7 at the system level (building collapse requires the failure of multiple building components) whereas performance is judged in ASCE 43 at the component level. This subject is addressed in Houston et al. (2016) via a case study of a low-rise reinforced concrete shear wall structure.

The argument to lower the target performance goal was ultimately rejected as being based too much on the optics of (tenuous) comparisons between the performance goals of ASCE 43 and ASCE 7. The Working Group also noted that if the target performance goal were set to the lower value of 2×10^{-4}, it would be so close to the SDC-3 target performance goal of 1×10^{-4} that the difference would be nearly indistinguishable in risk space. With this background, the target performance goals for the four SDCs to be included in the next revision of ASCE 43 are shown in Table 1.

Table 1. Target Performance Goals as a Function of Seismic Design Category

	Seismic Design Category (SDC)			
	2	3	4	5
Target Performance Goal (P_F)	4×10^{-4}	1×10^{-4}	4×10^{-5}	1×10^{-5}

The revision of Chapter 2 on Earthquake Ground Motion introduces a different approach to generating Design Response Spectra (DRS) from Uniform Hazard Response Spectra (UHRS). In both cases, the DRS is determined from two UHRS at different hazard annual exceedance frequencies. ASCE 43-05 defines DRS as the product of a Design Factor (DF) and the UHRS at a specified annual exceedance frequency.

$$DRS = DF \text{ x } UHRS_{HD} \quad (1)$$

In equation (1), $UHRS_{HD}$ is the Uniform Hazard Response Spectrum at the mean hazard at a specified exceedance frequency. The hazard exceedance frequencies for SDC-3, -4, and -5 designs are given in Table 2. At spectral frequencies for which the UHRS are defined, the DF is determined from the slope factor (A_R) and a parameter α as follows:

$$A_R = (SA_{0.1HD}/SA_{HD}) \quad (2)$$

In equation (2), SA_{HD} is the spectral acceleration at the mean hazard annual exceedance frequency H_D and $SA_{0.1HD}$ is the spectral acceleration at $0.1H_D$. The DF is then defined according to

$$DF = \max(DF_1, DF_2) \quad (3)$$

$$DF_2 = 0.6(AR)^{\alpha} \quad (4)$$

where DF_1 and α are defined in Table 2.

Table 2. Design Response Spectrum Parameters from ASCE 43-05

SDC	Mean Hazard AFE (H_D)	Target Performance Goal (P_F)	Probability Ratio (R_P)[1]	DF_1	α
3	4 x 10^{-4}	~1 x 10^{-4}	4	0.8	0.4
4	4 x 10^{-4}	~4 x 10^{-5}	10	1.0	0.8
5	1 x 10^{-4}	~1 x 10^{-5}	10	1.0	0.8

[1]The probability ratio (R_P) is defined as H_D/P_F

The working update to ASCE 43 uses a Scale Factor (SF), less than 1.0, rather than a design factor. The new equation defining the DRS in terms of SF is given by

$$DRS = SF \text{ x } UHRS_{Hp} \quad (5)$$

The SF reduces the $UHRS_{Hp}$ defined at the target performance goal AFE to get the DRS instead of the previous method of using a DF, which increased the $UHRS_{HD}$ defined at ten times the target performance goal annual frequency of exceedance to obtain the DRS. This change differs from the previous approach using a DF in that inclusion of SDC-2 in the revised Standard led to an inconsistency in the probability ratios (R_P) used for SDC-2, -3, -4, and -5. Such an inconsistency existed to a lesser degree in ASCE 43-05 as evidenced in Table 2, but inclusion of SDC-2 exacerbated the situation and made it clear that using the previous method would lead to a different format for the DF for SDC-2 than existed in ASCE 43-05. The new SF method uses an R_P of 10 for SDC-2 through SDC-5.

The change in methodology from DF to SF is made for three reasons.

1. The SF approach more clearly indicates the relationship between the DRS and the $UHRS_{HP}$ at the target performance goal AFE. The SF is less than 1.0 and its value decreases with an increasing slope on the seismic hazard curve. This relationship was not obvious with the DF approach.

2. The SF is less sensitive to A_R than is the D_F, particularly over the most likely A_R ranges from 2.0 to 4.0.
3. Some hazard curves at low seismic hazard sites have very low ground motions at mean annual hazard AFEs at ten times the target performance goal (H_D=10*P_F) and at hazard-curve ratios exceeding about 4.5. In such cases the hazard curves cannot be approximated as linear between the H_D=10*P_F and H_{PF} AFEs when plotted on a log-log plot. Because the ratio is based on a linear approximation, this makes the estimate unreliable. To avoid such problems, a lower bound for the SF is introduced. This constraint is more easily expressed in terms of SF than in terms of DF.

When the slope factor is cast in the form

$$A_R = SA_{HPF}/SA_{HD} \tag{6}$$

In equation (6), SA_{HD} is the spectral acceleration at the mean AFE H_D and SA_{HPF} is the spectral acceleration at the mean AFE H_P corresponding to the target performance goal (P_F). The SF for this spectral frequency is given by:

$$SF = \max(SF_1, SF_2, SF_3) \tag{7}$$

$$SF_1 = A_R^{-1.0} \tag{8}$$

$$SF_2 = 0.6(A_R)^{-0.2} \tag{9}$$

$$SF_3 = 0.45 \tag{10}$$

The change in methodology makes essentially no difference in the computed DRS for SDC-4 and SDC-5, and for typical seismic hazard curves makes less than a 5% difference in the DRS for SDC-3. It is easily shown that when R_P=10, the scale factor and the design factor are related according to Equation 10.

$$SF = DF/A_R \tag{11}$$

The revised DRS parameters are shown in Table 3.

Table 3. Revised Design Response Spectrum Parameters

SDC	Mean Hazard AFE (H_D)	Target Performance Goal (P_F)	Probability Ratio (R_P)[1]
2	4×10^{-3}	$\sim 4 \times 10^{-4}$	10
3	1×10^{-3}	$\sim 1 \times 10^{-4}$	10
4	4×10^{-4}	$\sim 4 \times 10^{-5}$	10
5	1×10^{-4}	$\sim 1 \times 10^{-5}$	10

The revision to Chapter 3 illustrates the tighter integration between ASCE 43 and ASCE 4 in that several sections in 43-05 describing linear and nonlinear analytical methods have been moved from Standard 43 and placed more properly in ASCE 4-16. Also moved to ASCE 4 is the table providing effective stiffness values for reinforced concrete members. Chapter 3 provides the first inclusion of steel concrete composite elements in that damping values for such elements are added to the table of damping values for structural elements as a function of response level. Steel-plate concrete composite elements are also introduced in Chapters 4, 5, and 6 as noted below and the technical basis for inclusion of these structural elements is documented in Epackachi et al. (2015a, 2015b, and 2015c), Seo et al. (2016), Varma et al. (2011) and Varma et al. (2013). Requirements for steel-plate composite walls in safety-related nuclear structures are provided in Appendix N9 of ANSI/AISC N690 (AISC 2015).

Chapter 4 now includes steel-plate concrete composite elements as an acceptable structural component for new nuclear facilities. The seismic behavior of this newer framing system for nuclear structures is comparable to reinforced concrete walls provided the reinforcement ratio is similar and the faceplate slenderness ratio (for the SC walls only) comply with limits in Appendix N9 of ANSI/AISC N690. The chapter provides better integration between ASCE 43 and other national codes and standards by removing detail on structural capacities that had been in ASCE 43-05 and instead referring directly to other codes and standards for such information. The design and detailing of reinforced concrete is now by reference to ACI 349-13 with a few exceptions, including new provisions for the out-of-plane shear strength of reinforced concrete walls and slabs. These new provisions update the nominal shear stress of unreinforced concrete in ACI 318-14 (ACI 2014), namely, $2\sqrt{f_c'}$, to account for the effects of section depth, longitudinal reinforcement ratio, and non-exceedance probability on shear strength required of safety-related nuclear structures. Mertz and Whittaker (2018) provide the technical basis for this change, which will affect (and possible increase) the out-of-plane shear reinforcement of reinforced concrete walls and slabs.

The capacity of structural steel components is by reference to ANSI/AISC N690 for carbon steel components, ASCE/SEI 8 for stainless steel components, AISI S100 for cold-formed carbon steel components, and ACI 530/ACI 530.1 (ACI 2013b) for reinforced masonry components. The reference to Section 2108 of the IBC in the context of reinforced masonry has been removed from the Standard.

The design and detailing of carbon steel components is to be performed according to the provisions of ANSI/AISC 341. The revised section on the capacity of structural steel places more emphasis on the LRFD approach and no longer includes individual factors for converting between ASD and LRFD capacities.

The revised Chapter 5 clarifies the delineation between the component level and system level inelastic energy absorption factors (F_μ factors). The provisions give additional guidance on obtaining the component level F_μ factors and describe the required adjustments to the component level F_μ factors for weak or soft stories, high frequency response (greater than the amplified portion of the DRS) and the adjustment for ratcheting. The adjustments to the component level F_μ factors result in the system level F_μ factors.

Table 5-1 of the Standard now includes component level F_μ factors for steel-plate composite walls and buckling restrained braced frames. Consistent with the emphasis on LRFD, axial load limits in Table 5-1 for special steel moment frames are now expressed in terms of the ultimate axial load rather than the axial yield strength. Table 5-2 on allowable drift ratio limits for structural systems now includes limits for steel-plate composite walls.

The commentary to Chapter 5 includes several new sections. The first is a section on developing project-specific system level F_μ factors for existing structures with non-compliant detailing. ASCE/SEI 41-13 (ASCE 2014) is introduced in this context, though it is pointed out that the ASCE/SEI 41 data are developed for different limit states than used in this Standard. The commentary includes a new section that states that the F_μ factors in this Standard are generally conservative even when used in conjunction with Response Level 3 damping, with or without SSI effects.

Finally, the commentary provides two alternate methods of estimating the system F_μ factor. The first is based on an estimate of a permissible inelastic distortion. With this established, response analyses are run using inputs scaled to a level at which the elastically computed demand is equal to the yield (or ultimate) capacity. The input is further scaled until the distortion predicted by the nonlinear response history analysis reaches a maximum permissible value. The F_μ factor is equal to this additional scaling factor. This method may be used to justify an F_μ factor greater than unity for a specific anchorage configuration although in most cases, anchorage F_μ factors are not significantly greater than unity. In the second method, the system ductility is estimated from the ratio of weighted total displacements to a weighted elastically computed displacement when the elastic demand is equal to capacity for the critical story. Once the system ductility has been established, there are several approaches for determining the F_{μ} factor, which are provided in the commentary to Chapter 5.

To reduce detail and redundancy regarding the requirements for steel and concrete structures, Chapter 6 states simply that steel structures shall meet the minimum requirements of ANSI/AISC N690-12, and that steel moment frames shall be detailed in accordance with ANSI/AISC 341. FEMA 350 is no longer included as a reference for detailing of steel moment frames. The commentary on steel structures notes that not only should ANSI/AISC 341 be followed for ductile detailing requirements, but that prequalified special moment frame joints per ANSI/AISC 358 (AISC 2016) should be used.

Similarly, all reinforced concrete structures must meet the minimum requirements of ACI 349-13. In keeping with Chapter 5, Chapter 6 now includes both buckling restrained braced frames and steel-plate concrete composite shear walls, with steel-plate composite shear wall detailing to be in accordance with Supplement 1 of ANSI/AISC N690. The provisions for steel structures now include guidance on the design and analysis of collector items and a new provision that relaxes detailing requirements for Nearly Rigid Platforms and Supports provided that increased loads are considered in the design.

ASCE 43-05 included a provision that weak-axis bending in reinforced concrete walls must be governed by out-of-plane wall flexure. The new revision includes an alternate approach that allows out-of-plane wall shear to limit the strength with respect to weak-axis bending provided that the out-of-plane shear demand is increased by 50% and the F_{μ} factors for flexure and shear are set to unity. There is also a new provision governing the detailing of combined shear wall and frame systems in reinforced concrete. The provisions for transverse joint reinforcement in slab-wall moment frame systems have been modified to remove inconsistencies and to reflect the significant difference between beam-column joints (treated in ACI 349-13) and slab-wall joints that are common in some Department of Energy facilities. Strut-and-tie procedures must be used to design slab-wall moment-resisting connections. Three new subsections have been added to the section on reinforced concrete. The first provides requirements for members not proportioned to resist forces induced by earthquake shaking; the second treats collector elements; and the third gives guidance regarding planes of weakness in the seismic load path.

The Chapter 6 provisions take a more liberal stance on use of adhesive anchors in elevated temperature and/or radiation environments. In ASCE 43-05, this practice was prohibited; now the Standard states that adhesive anchors "…shall be qualified in those environments", with the new commentary on anchorage stating that adhesive anchors that passed tests per ACI 355.4 (ACI 2011) are acceptable for application to nuclear structures.

The procedures for determining sliding and rocking demands for unanchored bodies that were in Chapter 7 of ASCE 43-05 have been moved to ASCE 4-16 because they are analytical procedures that properly belong in ASCE 4. Recognizing that sliding and overturning are not credible failure modes for deeply embedded structures (as defined in the Standard) demonstration of sliding and overturning stability is no longer required for such structures. This change was made to preclude complex checks where no plausible failure mode exists. A related change is that the reduced soil support on the side of a building foundation shall be considered when calculating the side traction for the purposes of sliding checks in embedded structures that are not deeply embedded.

Section 7.5 of the Standard has been condensed to state simply that unreinforced masonry is not an acceptable structural system, but when used as a barrier, shielding, or partition, unreinforced masonry walls shall be designed in accordance with ACI 530.

There are several significant changes to Chapter 8. Qualification by analysis of active electrical equipment is now prohibited, bringing the Standard into alignment with the provisions of Chapter 13 of ASCE 7. More generally, acceptance criteria for qualifying active components by analysis use ratios of demand to capacity and not limiting values of stress as in ASCE 43-05. The chapter also points out that when determining demand on a component for qualification by analysis or by testing, if the input to the component is displacement based, then it can be unconservative to set the F_μ factor equal to 1.0 and an appropriate value of F_μ shall be justified.

Section 8.3 on Qualification by Testing and Experience Data and the associated commentary have been revised significantly to emphasize the differences between qualifications by test versus qualification by test experience data and to also update and clarify the factors to be applied to seismic demand for qualification by test, test experience data, and earthquake experience data required to meet the performance goals of the Standard. The restrictions on the use of factors to be applied to seismic demand are also documented. New sections have been added to the commentary that provide derivations for the factors to be applied to the seismic demand for qualification by testing, test experience data and earthquake experience data in specific situations.

Section 8.3.2.1 of ASCE 43-05 included the following equation for the demand for qualification by test and test experience data:

$$D = D_{NS} + 1.4D_S \tag{12}$$

where D is the total demand, D_{NS} is the non-seismic demand, and D_S is the elastically computed seismic demand. In ASCE 43-05, the factor of 1.4 is described as the equipment capacity factor for qualification by test or test experience spectra that provides the margin to obtain the required confidence level of performance. Sections 8.3.2.1, 8.3.2.2, 8.3.2.3, and the associated commentary sections of the Standard have been revised to clarify the use and interpretation of the equations governing demand for qualification by test, test experience data, and earthquake experience data, respectively. The revised equation for demand for qualification by test is

$$D = D_{NS} + \gamma_{test}D_S \tag{13}$$

The factor γ_{test} is the ratio of the Test Response Spectrum (TRS) to the Required Response Spectrum (RRS) for qualification by testing. If the qualification testing is performed in accordance with IEEE 344, setting the factor γ_{test} to 1.33 will meet the performance goals of this Standard. If testing performed to other procedures and criteria, the value of γ_{test} must be determined by the user so as to meet the performance goals of ASCE 43.

Demand for qualification by test experience data is also given by equation (12), but with γ_{test} replaced by γ_{TES}, where γ_{TES} is the factor to be applied to the Test Experience Spectrum (TES) required to meet the performance goals of this Standard. For non-relay Generic Equipment Ruggedness Spectra (GERS), setting γ_{TES} to 1.33 will meet the performance goals of this Standard. For relay GERS, setting γ_{TES} to 1.75 will meet the performance goals of this Standard. For any component using seismic input other than GERS, γ_{TES} must be shown by the user to meet the performance goals of ASCE 43.

The demand for qualification by earthquake experience data is given by the following equation:

$$D = \gamma_{EED}D_S \tag{14}$$

The factor γ_{EED} is the factor to be applied to earthquake experience data to meet the performance goals of ASCE 43. The seismic demand from earthquake experience data is defined as an Earthquake Experience Spectrum (EES). If the seismic demand D_s is defined by a Seismic Qualification Utility Group (SQUG) reference spectrum (1.5 times the SQUG bounding spectrum), which is an example of an EES, setting γ_{EED} to 1.0 will meet the performance goals of ASCE 43. If the earthquake experience data are based on other than a SQUG reference spectrum, the factor γ_{EED} must be determined by the user so as to meet the performance goals of ASCE 43. Information on the SQUG reference spectrum is documented in SQUG (2001) and in SSRAP (1991).

Table C8-1 of ASCE 43-05 provides a list of standards used for construction and procurement of mechanical and electrical equipment. This table has been removed because unless or until the design approaches and performance goals of the referenced standards can be vetted sufficiently to determine consistency with ASCE 43, it is inappropriate to keep them in the Standard. Also, ASCE 43 addresses only seismic design criteria, where the other codes are more general.

Aside from organizational and editorial revisions, the most significant change to Chapter 9 on quality assurance is the inclusion of detailed provisions on the software quality assurance (SQA).

The Standard specifies requirements for all software used in the analysis and design of SSCs in nuclear facilities, whether acquired or developed. Such software shall be controlled, verified and validated (V&V) prior to the use on a project in accordance with the documented QA program, which shall include a software V&V plan. The plan shall identify significant features of the program that need to be verified, the type of test or benchmark problems, test cases with acceptance criteria and sample problems for installation validation. Acquired computer programs not developed under an approved QA program shall be, as a part of the acquisition process, subject to a dedication activity to provide reasonable assurance that the computer program will perform its intended safety function for SDC-3 to SDC-5. However, such dedication activity (commonly referred to as commercial grade dedication) will not be necessary where the results of such acquired computer programs are verified with the design analysis for each application. All calculations including computer generated ones shall be documented in sufficient detail for a reviewer to determine that the design requirements have been correctly identified and implemented. A graded approach shall be considered for the level of detail and rigor in the documentation.

Chapter 10 is an entirely new chapter on seismically isolated structures, with emphasis on design and on testing of seismic isolation bearings. The text is taken by-and-large from Chapter 12 of ASCE 4-16, with the intent that the design and testing provisions and commentary that will appear in ASCE 43-xx, will be removed from the next revision of ASCE 4. Kumar et al. (2017) show that the analysis and design provisions of ASCE 4-16 and ASCE 43-xx will achieve the target performance goal for SDC-5.

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NOMENCLATURE

AFE	Annual Frequency of Exceedance
A_R	Slope factor, which is a ratio of spectral accelerations corresponding to a tenfold increase in hazard annual exceedance frequency
D	Total demand in the context of equipment qualification
DF	Design Factor from ASCE 43-05
DF_1	Contributing term to the design factor
DF_2	Contributing term to the design factor
D_{NS}	Non-seismic demand in the context of equipment qualification
DRS	Design Response Spectra
D_S	Seismic demand in the context of equipment qualification
γ_{test}	Factor on the seismic demand for qualification by test that is required to meet the target performance goals of this Standard
γ_{TES}	Factor on the seismic demand for qualification by test experience spectra that is required to meet the target performance goals of this Standard
γ_{EED}	Factor on the seismic demand for qualification by earthquake experience data that is required to meet the target performance goals of this Standard
H_D	Mean hazard AFE at ten times the target performance goal
H_{PF}	Mean hazard AFE at the target performance goal
MCE_R	Risk-targeted Maximum Considered Earthquake from ASCE 7

P_F	Target performance goal
R_P	Probability ratio, which is defined as H_D/P_F
RRS	Required Response Spectra
SA	Spectral Acceleration
SA_{HD}	Spectral acceleration from the mean hazard curve at ten times the performance goal AFE
SA_{HPF}	Spectral acceleration from the mean hazard curve at the performance goal AFE
SDC	Seismic Design Category
SF	Scale Factor for determining the
SF_1	Contributing term to the scale factor
SF_2	Contributing term to the scale factor
SF_3	Contributing term to the scale factor
TRS	Test Response Spectra
$UHRS_{HD}$	Uniform Hazard Response Spectra corresponding to an AFE at ten times the target performance goal

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