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Seismic Induced Events, Acceptable Risks at Nuclear Facilities, and Proposed ANSI/ANS and ASCE Standards

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ABSTRACT

Facilities (including those at Department of Energy - DOE) containing hazardous materials or energy sources in USA are designed and constructed per current applicable seismic design criteria at the Nuclear Facilities. A change in these standards is currently being proposed as federal agencies are in process of transferring to a set of standards being developed by the American Nuclear Standards Institute (ANSI), American Nuclear Society (ANS), and the American Society of Civil Engineers (ASCE). The objective of this paper is to investigate, elaborate and discuss the potential impacts of this transition to the new criteria on the current practice for seismic design of Structures, Systems, and Components (SSCs).

The proposed ANSI/ANS Standard will provide criteria and guidance to select Seismic Design Category (SDC) and Limit State for the SSCs important to safety. An unmitigated consequence analysis considering the uncertainties in estimating failure and the safety consequences of the failure is performed to determine the SDC and the Limit State, which then are used to establish the level of Peak ground Acceleration (PGA) and design response spectra. The SDC placement will be based on the objective of achieving acceptable risk to the public, the environment and workers from seismic induced events. This paper will also address the issue of how a facility designed and constructed in accordance with these new standards may comply with requirements for protection of worker and public safety promulgated by the United States Nuclear Regulatory Commission (NRC) in 10 CFR Part 70.

KEY WORDS: Seismic events, risks, nuclear facilities, ANSI/ANS standards, USNRC, ASCE standards, DOE-NPH standards, seismic design category, 10CFR Part 70, unmitigated consequence analysis, structural deformation limits, site atmospheric dispersion, nuclear materials, mixed oxide fuel, plutonium powder.

INTRODUCTION

The DOE designs and constructs facilities containing hazardous materials or energy sources in accordance with formal seismic design criteria. Currently, acceptable design criteria and procedures for response to natural phenomena hazards are published in DOE Standards -1020, thru –1023, -3009, -1027 [1 thru 6]. A change in these standards/procedures is underway as DOE transfers to a set of procedures developed by the American Nuclear Standards Institute (ANSI), American Nuclear Society (ANS) and American Society of Civil Engineers (ASCE). The objective of this paper is to investigate the potential impacts on DOE practice of transition to the new criteria and procedures for seismic design. Also of interest is the issue of how a facility designed and constructed in accordance with these procedures may comply with requirements for protection of worker and public safety promulgated by the Nuclear Regulatory Commission in 10 CFR Part 70 [7].

BACKGROUND

The ANSI/ANS Standard 2.26 [8] has been developed based on methods used by the U.S. Department of Energy (DOE) for performance categorizing and designing structures, systems, and components (SSCs) in nuclear facilities to withstand the effects of natural phenomena hazards (NPH) [1 thru 4]. The ANSI/ANS Standard 2.26 provides criteria and guidance to select Seismic Design Category (SDC) and Limit State for the SSCs important to safety. The Standard is applicable to both, new nuclear facilities, as well as to existing nuclear facilities. *The SSC placement in a particular SDC is based on the objective of achieving acceptable risk to the public, the environment and workers from seismic induced events.* The SDCs have unmitigated consequence objectives that shall not be exceeded.

The American Society of Civil Engineers (ASCE) Nuclear Standards Committee have developed and issued a Draft of ASCE Standard XXX [9]. This Standard provides seismic design criteria for SSCs, in nuclear facilities that have been placed in SDC -3, -4, and -5 in accordance with the ANSI/ANS Standard. The SDC and Limit State are then used with ASCE-XXX and other applicable DOE NPH Standards to establish the level of peak ground acceleration (PGA) and design response spectra.

The Appendix A to the DOE-STD-3009 [5] specifies a numerical radiological dose value to be used in identifying safety class (SC) for a given SSC in a *non-reactor nuclear facility* at DOE. Worker safety performance requirements are contained in code of federal regulations 10 CFR 20 [10] and 10 CFR 70 [7] for reactor and nonreactor nuclear facilities, respectively. The code of federal regulation 10 CFR 20 specifies a worker dose limit of 5 rem, for occupational normal conditions. The 10 CFR 70 specifies that design accident events leading to an acute *worker dose* of 25 rem must be unlikely, and 100 rem must be highly unlikely. The Evaluation Guideline (EG) for accident conditions per DOE-STD-3009 is 25 rem total effective dose equivalent (TEDE). One of the objectives of this paper is to discuss the details of assigning SDC to a given SSC, in view of ANSI/ANS Standard coupled with applicable DOE Standards, to ensure an uniform and acceptable method which is not only mutually compatible, but clear, concise, and yet not too conservative to achieve the overall safety goals.

UNMITIGATED CONSEQUENCE ANALYSIS, SEISMIC DESIGN CATEGORY AND LIMIT STATE

The unmitigated consequence analysis associated with the failure of the SSC is "***Essential***" to Standard ANSI/ANS 2.26. The qualitative and quantitative values of the critical design parameters at which the safety function fails shall be identified, along with the unmitigated radiological, toxicological and environmental consequences of failure. The analysis shall consider the uncertainties in estimating failure and the safety consequences of the failure *sufficiently* to support the judgment that categorization based on Table 1 of the ANSI/ANS 2.26 Standard, and the design based on ASCE XXX make the facility earthquake risk acceptable.

The unmitigated consequence analysis shall consider only the inherent physical or chemical characteristics of the hazardous material and the energy sources for dispersing the material. Details of basic data compilation requirements and certain caveats that need to be satisfied to perform the unmitigated consequence analysis can be found respectively, in Sections 6.3 and 6.2, of the ANSI/ANS 2.26 Standard.

The SDC of the SSC (important to safety) is based on the unmitigated consequences of SSC failure, as qualitatively described in Table 1 of the ANSI/ANS 2.26. *For a given SDC all three categories (Worker, Offsite public, and Environment) of consequences must be satisfied*. In addition to qualitative requirements of ANSI/ANS 2.26 Table 1, the quantitative thresholds described in Table 3 of ANSI/ANS 2.26 for the Worker and Offsite Public shall be met. An SSC can be placed into one of the five categories of SDC, namely ***SDC-1 through SDC-5***.

SSC's (important to safety) that require seismic design shall be assigned to one of the four Limit States based on the information or data obtained from the facility safety analysis or integrated safety assessment. Limit State is defined as the maximum acceptable displacement, ductility or stress that an SSC can experience during and following an earthquake and still perform its safety function. The guidance for risk informed basis for determining SDC and associated Target Performance Goals are provided in Appendix A of the ANSI/ANS 2.26 Standard. Appendix B provides guidance for proper selection of a Limit State (which is dependent upon specific safety analysis and safety function) of an SSC.

An SSC is assigned one of the four Limit States, namely ***Limit State A through Limit State D***. The structural deformation limits vary from *Significant damage* ~ to *No damage* for Limit State A through D respectively. The safety analysis is the unmitigated consequences analysis. Thus, the first step to design an SSC (in a nuclear facility at DOE) is to satisfy the requirements of overall safety goals as mandated by the standards mentioned above. This requires one to perform the unmitigated consequences analysis.

Note that the ANSI/ANS 2.26 Standard states that guidance provided in ANS 5.10 [11] should be used to support analysis required by ANSI/ANS Standard 2.26. Also consistent with the risk-based process for selecting the earthquake level, the unmitigated consequence analysis should ***strive*** to use "***mean***" values for the parameters related to material release, dispersal, and health. The computed dose consequences shall be the TEDE, and the dose to the public shall be based on the maximally exposed individual off-site. The air and water transport mechanisms should be modeled using "mean" values. The limits of unmitigated consequences of an SSC failure are as shown in Table-1.

Once the SDC and Limit State for an SSC is defined, one can proceed to assign the Target Performance Goals P_F as listed in ASCE XXX Table 1.2-1 and appropriate hazard exceedance probabilities H_D for SSCs placed in SDC 3 through 5 from ASCE XXX Table 1.1-2 to develop site-specific seismic hazard curve and the uniform hazard response spectra that are used for developing the design basis earthquake (DBE) response spectra. The approach developed in ASCE XXX for SSCs placed in SDC-3, SDC-4 and SDC-5, is based on DOE-STD-1020, ASCE 4-98 [12], and the NRC Standard Review Plan NUREG 0800 [13]. For SSCs placed in SDC-1 and SDC-2, the identification of the use of the International Building Code (IBC) 2000 [14] is also specified in ASCE XXX.

In contrast to the proposed ANSI/ANS method of seismic classifications, current DOE procedures focus on offsite individuals and recommend use of conservative values of parameters used to estimate consequences. DOE-STD-3009 [5], the DOE-STD-1027 [6] provides guidance and radiological threshold values for accident analysis techniques and determining the hazard category (HC) of a facility. This Standard is in compliance with DOE Order 5480.23 [15]. Facility hazard analysis indicating: potential for *significant offsite* consequences is assigned a HC 1, potential for *significant onsite* is assigned HC 2, and potential for only *significant localized* consequences as HC 3. The recommended values and technical basis for Airborne Release Fractions (ARFs), Airborne Release Rates (ARRs), and Respirable Fractions (RFs) at DOE Non-Reactor Facilities are per the DOE handbook DOE-HDBK-3010-94 [16].

COMPARISON OF NRC 10 CFR 70 Vs. DOE-STD-3009

- NRC calculates committed effective dose equivalent (rem) as:

$$CEDE = ST * SA * X/Q * RR * DCF \quad \text{where}$$

ST = Source Term (g or grams)
SA = Specific Activity (for a given nuclear material) (Ci/g)
X/Q = Site Atmospheric Dispersion - ground level release (varies from site to site) (sec/m^3)
RR = Respiration rate (m^3/sec)
DCF = Dose Conversion Factor (rem/Ci)

DOE-STD-3009 [5] and DOE-STD-1027 [6] defines *Safety Class* SSCs as those whose preventive or mitigative function is necessary to limit radioactive hazardous material exposure to public. *Safety Significant* SSCs are defined as those whose preventive or mitigative function is a major contributor to defense in depth and/or worker safety as determined from safety analysis.

- DOE-STD-3009 calculates Source Term as:

$$ST = MAR * DR * ARF * RF * LPF \quad \text{where}$$

ST = Source Term (g)
MAR = Material At Risk (g)
DR = Damage Ratio (conservative to assume unity, unless justified otherwise)
ARF = Airborne Release Fractions (from DOE-HDBK-3010 for a given nuclear material)
RF = Respirable Fractions (from DOE-HDBK-3010 for a given nuclear material)
LPF = Leak Path Factor (set to unity for unmitigated release calculations)

$$TEDE \text{ (rem)} = ST * X/Q * BR * DCF$$

BR = Breathing Rate (same as RR above)

Table - 1

Unmitigated Consequence of SSC Failure per ANSI/ANS 2.26

Worker Dose Limits - CEDE	**Offsite Public Dose Limits - CEDE**	**Seismic Design Category**	**P_F Target Performance Goal**	**H_D Hazard Exceedance Probabilities**
25 rem < dose < 100 rem	5 rem < dose < 25 rem	SDC-3	1×10^{-4}	4×10^{-4}
100 rem < dose <500 rem	25 rem < dose < 100 rem	SDC-4	4×10^{-5}	4×10^{-4}
dose > 500 rem	dose > 100 rem	SDC-5	1×10^{-5}	1×10^{-4}

NRC defines an ***unlikely event*** as one with probability of occurrence between 1×10^{-2} / Yr. ~ 1×10^{-5} / Yr., and ***highly unlikely*** event as one with probability of occurrence < 1×10^{-5} / Yr. Note that, although the hazard exceedance probabilities for SDC-3 and SDC-4 are same, they have different target performance goals. In general, DOE facility with PC-3 designation would be equivalent to SDC-3, and that with PC-4 designation would be equivalent to SDC-5.

PRECEDURE TO DEVELOP DBE

Step –1: Perform unmitigated consequence analysis for all SSCs (important to safety) per ANSI/ANS 2.26, and per committed NRC and applicable DOE Standards and assign SDC.

Step – 2: With known SDC, assign Limit State to an SSC, and identify target performance goals and relevant seismic hazard exceedance probabilities.

Step – 3: Develop site-specific seismic hazard curve and the uniform hazard response spectra (UHRS) per ASCE XXX to develop design basis seismic response spectra.

Step – 4: Use ASCE XXX to determine seismic design/analysis methods and criteria for SSCs placed in SDC-3 through -5, and use IBC –2000 for SSCs placed in SDC-1, and SDC-2.

A ***sample example*** is presented below to demonstrate the application of performing unmitigated consequence analysis and assign seismic design categories (Step - 1).

The nature of results produced using the DOE-STD-3009 and ANSI/ANS 2.26 seismic hazard analysis procedures may be investigated using an example facility and a typical DOE site. The system under evaluation in this example is the building structure. The example facility selected is the Mixed Oxide (MOX) Fuel Fabrication Facility (MFFF) planned for one of the DOE site. This facility will contain both plutonium and uranium primarily in the oxide chemical form. The plutonium isotopes have relatively high disintegration rate per unit mass and constitute the major hazard at this facility while the uranium isotopes have low disintegration rate per unit mass and pose smaller hazard if present alone. The nature of the material and the building collapse scenario is such that the major exposure pathway for both onsite and offsite individuals is inhalation of particulate material dispersed through the atmosphere. The primary physical forms of the MAR are powder in cans, bare pellets and pellets in rods and assemblies. *In order to maintain simplicity in this example calculation, credit is not taken for passive confinement by rods or assemblies and all MAR is represented as powder in cans or bare pellets.* The selected site is large with considerable distance between the facility and the site boundary (potentially affected offsite population).

Estimates of risk associated with a facility include identification of hazards, development of release scenarios, estimation of release rate from the facility and estimation of concentration and dose at the point of exposure. In this case, plutonium and uranium particulates are the hazardous material and the scenario is seismically induced collapse of the building with no reliance on mitigating features. The amount of MAR in the MFFF is estimated to be 10,000 kg of plutonium dioxide powder in cans and 100,000 kg of MOX in pellets [17]. In application of the DOE-STD-3009 procedure, bounding values of ARF, RF and LPF are used to estimate the size of the release and are used in conjunction with unfavorable meteorological conditions, those that occur less than 5% of the time, to estimate concentration at the point of exposure. In the ANSI/ANS 2.26 procedure, average (mean) values of ARF, RF, LPF and meteorological conditions are used. Representative values of these parameters are summarized in Table -2 for the two procedures. The joint frequency distribution of meteorological conditions are, those observed at the site [18]. Concentrations per unit source (χ/Q) presented in this table were calculated in accordance with the accident condition dispersion analysis guidance of NRC Regulatory Guide 1.145 [19]. Results of the atmospheric dispersion analysis are summarized in Table -3 for distances of 9,300 meters (offsite receptor) and 100 meters (onsite receptor), respectively. The annual average and 95th percentile values of χ/Q for all directions for the offsite receptor are 2.6×10^{-7} and 7.8×10^{-6} s/m^3, respectively. The annual average corresponds to the 80th percentile of the frequency distribution of χ/Q. The annual average and 95th percentile values of χ/Q for all directions for the onsite receptor are 3.8×10^{-4} and 3.8×10^{-3} s/m^3, respectively. The annual average corresponds to the 50th percentile of the frequency distribution of χ/Q.

The above release and dispersion data can be used with dose conversion factors for Depleted Uranium (DU), plutonium and MOX mixtures to calculate dose per unit of MAR for powder and pellets. The results of this calculation are presented in Table - 4. These unit dose factors may then be used with dose criteria to calculate the amount of material released to produce the specified dose. For hazard classification in accordance with DOE-STD-3009, exceeding a dose of 25 rem for an offsite receptor, merits classification as PC-3. For classification in accordance with ANSI/ANS 2-26, the dose criteria were summarized in Table 1. Material limits determined for the DOE and ANSI/ANS procedures are presented in Table -5 and Table - 6, respectively.

Results of application of the DOE procedure indicate that the MFFF would be classified as PC-3 on the basis of plutonium powder in cans and MOX fuel in pellets. A facility containing only DU would require a large amount of material to be classified as PC-3. Results derived with the ANSI/ANS procedure involve consideration of offsite and onsite receptors and multiple dose levels and are therefore more complex. The results presented in Table A-5 indicate that planned MFFF at this site would be classified as **SDC-3** on the basis of presence of plutonium mixture as powder in cans using the offsite receptor dose as the acceptance criteria. This is in general agreement with the results of the DOE procedure. However, using the onsite receptor dose criteria, the facility would be classified as SDC-4 for MOX in pellets, and possibly as SDC-5 for plutonium powder in cans.

CONCLUSIONS AND RECOMMENDATIONS

As mentioned above, the ANSI/ANS 2.26 guidance recommends use of mean values of parameters, introducing the potential for significant difference in magnitude of estimated dose. *A major difference in the procedure appears in ANSI/ANS specifying acceptance for both workers and offsite individuals, while DOE guidance focuses on offsite individuals.* For the example MFFF, the onsite χ/Q values are ranging from 500 to 1,500 times greater than offsite χ/Q. It should be noted that application of each of the procedures involves subjective judgments that may produce differing results for differing analysts.

The analysis described in this paper indicates that transition to the new system of procedures could have major implications for design of DOE facilities. This is due to the inclusions of dose criteria for workers for accident conditions in the system under development not present in the current system. The current DOE design procedures protect workers by a combination of design features and mitigation measures as elaborated in “defense-in-depth” concept of DOE standards such as DOE-STD-3009. The analysis indicated that facilities designed in accord with criteria for offsite individuals under the current and proposed procedures result in similar seismic design classification.

Potential for excess conservatism in identification of SDC under the proposed system arises if conservative rather than mean values are used for parameters in the dose estimation calculations. Also, the analysis indicates that procedures for design of DOE facilities incorporate sufficient requirements and conservatism that they would comply with the performance requirements of 10 CFR70.61.

Table – 2

Comparison of Accident Analysis Parameters for the MFFF

DESIGN PARAMETER	DOE-STD-3009[1]	ANSI/ANS 2.26[2]	10CFR70[3]
MAR (g)	1	1	1
DR	1	1	1
ARF powder in cans *pellets*	 0.001 -	 $3x10^{-4}$ -	 0.001 -
RF powder in cans *pellets*	 1.0 -	 1.0 -	 1.0 -
RARF powder in cans *pellets*	 0.001 $2x10^{-5}$	 $3x10^{-4}$ $2x10^{-5}$	 0.001 $2x10^{-5}$
LPF	1.0	1.0	1.0
ST (g /g $_{MAR}$) powder in cans *pellets*	 0.001 $2x10^{-5}$	 $3x10^{-4}$ $2x10^{-5}$	 0.001 $2x10^{-5}$
χ/Q (s/m^3) Onsite Offsite	 ------ $7.8x10^{-6}$	 $3.8x10^{-4}$ $2.6x10^{-7}$	 $3.8x10^{-3}$ $7.8x10^{-6}$
BR (m^3/s)	$3.5x10^{-4}$	$3.5x10^{-4}$	$3.5x10^{-4}$

1. DOE-STD-3009 recommends using an unmitigated release calculation to identify safety class SSC. Guidance includes no credit for active safety features, credit for passive safety features, and no credit for leakpath reduction. Maximum MAR, actual DR, bounding ARF and RF, unit LPF and 95th percentile χ/Q are recommended. The evaluation guideline is 25rem for an offsite individual.

2. ANSI/ANS 2.26 recommends use of unmitigated consequence analysis to identify SDC. Use of mean for values of parameters is recommended. Acceptance levels are specified for both workers and offsite individuals for each SDC.

3. NRC practice directs use of conservative values for parameters in deterministic accident analysis. Credit may be taken for all passive features. Acceptance criteria are specified for workers and offsite individuals.

Table – 3

Values of χ/Q (s/m^3)

Offsite (Distance = 9,300 m), Onsite (Distance = 100 m)

Direction	Offsite		Onsite	
	Sector Annual Average	Sector 99.5th Percentile	Sector Annual Average	Sector 95th Percentile
S	1.5e-8	3.7e-7	1.7e-5	7.4e-4
SSW	9.9e-8	4.6e-6	5.9e-5	2.5e-3
SW	1.6e-7	7.8e-6	9.8e-5	3.6e-3
WSW	9.5e-8	4.3e-6	6.4e-5	2.4e-3
W	7.8e-8	4.1e-6	5.2e-5	2.4e-3
WNW	9.5e-8	4.6e-6	5.5e-5	2.5e-3

NW	1.1e-7	4.6e-6	6.3e-5	2.5e-3
NNW	1.3e-7	4.7e-6	7.4e-5	2.5e-3
N	1.7e-7	7.9e-6	9.3e-5	3.8e-3
NNE	1.4e-7	4.7e-6	8.0e-5	2.5e-3
NE	1.4e-7	4.8e-6	8.6e-5	2.5e-3
ENE	1.6e-7	8.0e-6	9.2e-5	3.8e-3
E	8.3e-8	4.1e-6	5.7e-5	2.4e-3
ESE	7.1e-8	4.0e-6	4.8e-5	2.4e-3
SE	5.8e-8	3.7e-6	3.7e-5	2.3e-3
SSE	5.0e-8	3.4e-6	3.1e-3	2.3e-3

Table - 4

Unit Dose Factors Hazard Evaluation (rem/kg mixture)

Location	**DOE-STD-3009**			**ANSI/ANS 2.26**		
	DU	**Pu Mixture**	**MOX**	**DU**	**Pu Mixture**	**MOX**
Onsite Powder in Cans	-	-	-	2.1x10^{-7}	1.16	0.076
Pellets	-	-	-	1.4x10^{-8}	0.077	0.005
Offsite Powder in Cans	1.4x10^{-8}	0.079	0.0052	1.4x10^{-10}	7.9x10^{-4}	5.2x10^{-5}
Pellets	2.8x10^{-10}	0.0016	1.0x10^{-4}	9.5x10^{-12}	5.3x10^{-5}	3.5x10^{-6}

Table - 5

Material Limits for DOE Classification as PC-2 (kg)

Material Form	**DU**	**Pu Mixture**	**MOX**
Powder in Cans	1.8x10^{+9}	315	4,800
Pellets	8.9x10^{+10}	15,600	250,000

Table - 6

Material Limits for ANSI/ANS 2.26 Seismic Design Categories (kg)

Seismic Design Category	**Powder in Cans**			Pellets		
	DU	**Pu Mixture**	**MOX**	**DU**	**Pu Mixture**	**MOX**
SDC-2 Onsite	1.2x10^{+8}	22	330	1.8x10^{+9}	325	5,000
SDC-2 Offsite	3.6x10^{+10}	6,300	96,000	5.3x10^{+11}	94,000	1,430,000
SDC-3 Onsite	4.8x10^{+8}	115	1,320	7.1x10^{+9}	1,300	20,000
SDC-3 Offsite	1.8x10^{+11}	31,600	480,000	2.6x10^{+12}	472,000	7,140,000
SDC-4 Onsite	2.4x10^{+9}	430	6,580	3.6x10^{+10}	64,900	100,000
SDC-4 Offsite	7.1x10^{+11}	127,000	1,920,000	1.0x10^{+13}	1,890,000	2.9x10^{+8}

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