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Guidelines for the Development of Natural Phenomena Hazards Design Criteria for Surface Facilities

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Guidelines for the Development of Natural Phenomena Hazards Design Criteria for Surface Facilities*

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Abstract

This paper discusses the rationale behind the guidelines, criteria, and methodologies that are currently used for natural phenomena hazard design and evaluation of DOE nuclear and non-nuclear facilities. The bases for the performance goals and usage categories specified in UCRL-15910 are examined, and the sources of intentional conservatism in the analyses, design, and evaluation methods and criteria are identified. Outlines of recent developments/changes in DOE Orders related to Natural Phenomena hazard mitigation are also presented. Finally, the authors recommend the use of DOE methodologies as embodied in UCRL-15910 for design and evaluation of surface facilities of the high level nuclear waste repository site.

Introduction

The Department of Energy (DOE) has developed a methodology for design and evaluation of DOE facilities subjected to Natural Phenomena Hazards (NPH) such as earthquake, wind, tornado, and flood. [Kennedy, et.al., 1990] An important feature of this methodology that makes it applicable to diverse types of facilities is that it uses a graded approach which recognizes the relative risk contributed by various structures, systems, and components (SSCs). This feature makes it possible to specify more stringent design criteria for the SSCs that are more critical to safety. The methodology is based on setting target performance goals which are expressed as the annual probability of exceedance of acceptable behavior limits as a result of natural phenomena hazards. The performance goal for an SSC is set based on the effect of its postulated failure on various factors such as health and safety of people on and off site, risk to the environment, facility mission or production goal, and repair/replacement cost. Performance goals and hazard levels are expressed in numerical probabilistic terms, but design and evaluation procedures are deterministic.

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Other important elements of this methodology include:

1) The use of established safety goals to serve as targets for performance.

2) Adherence to applicable national consensus standards for analysis, evaluation, and construction of facilities.

3) Periodic re-evaluation and upgrading of facility design utilizing the latest information from operational experience and developments in the state-of-the-art.

4) Maintaining a balance among safety, production goals, and cost.

5) Peer review of NPH evaluation of safety-related facilities.

The primary document that is used for implementing this NPH evaluation methodology is UCRL-15910 [Kennedy, et.al., 1990]. Because of the desirable features listed above, and its direct applicability, the authors recommend the use of UCRL-15910 for the design of waste repository surface facilities subjected to NPH loads, including seismic loads. The concept of safety goals in the form of numerical risk targets as embodied in UCRL-15910 is not new. Similar concepts have recently been applied in developing design philosophies for the Uniform Building Code (UBC), DOE's New Production Reactors, and advanced commercial reactors.

This paper briefly describes the current DOE procedure and methodology for NPH design and evaluation of facilities similar to proposed waste repository surface facilities, and discusses the rationale on which the methodology is based. It also presents the recent developments that augment the current methodology, and discusses the application of DOE's NPH criteria to Repository Surface Facility design.

Current Natural Phenomena Hazard Evaluation Procedure for DOE Facilities

DOE'S policy states that structures, systems, and components (SSCs) at DOE facilities shall be designed to withstand the effects of natural phenomena hazards. The most comprehensive document developed to date to implement this policy is UCRL-15910. NPH evaluation of a facility in accordance with this document usually consists of the following procedural steps:

1) Obtain site specific data needed to develop natural phenomena hazard estimates.

2) Document hazard descriptions for each natural phenomena.

3) Classify structures, systems, and components into usage categories.

4) Evaluate natural phenomena loads appropriate for the usage category considered.

5) Identify normal and accident loads.

6) Calculate response to all loads.

7) Combine response to natural phenomena loads with response to normal and accident loads.

8) Compare combined response (demand) with structures, systems, or components capacity.

9) Provide or check for design details such that desirable natural phenomena behavior can be achieved.

10) Redesign or identify where capacity is exceeded.

11) Conduct independent peer review of the natural phenomena design or evaluation.

Developing Hazard Estimates: UCRL-15910 requires consideration of the natural phenomena on a probabilistic basis and refers to existing seismic, wind/tornado, and flood hazard models developed for DOE facilities (Coats and Murray, 1984, Coats and Murray, 1985, and Savy and Murray, 1988, respectively). It also permits and encourages the development and use of site-specific hazard models. Presently, UCRL-15910 specifies hazard annual probabilities of exceedance (HAPE) which form the basis for determining design hazard levels (such as peak ground acceleration levels for seismic hazards). HAPE values are different for different categories of facilities and SSCs, and are dependent on numerical performance goal values and the level of conservatism that is intentionally built into analysis methods and standards, design codes and details, and construction specifications.

The probabilistic characterization of natural phenomena hazards described above for DOE facilities is a departure from that for existing nuclear power plants in which natural phenomena have been defined in a deterministic manner considering the most severe occurrences that have been historically reported. Consideration of natural phenomena hazards on a probabilistic basis enables development of design/evaluation criteria that are based on target performance goals (defined as annual probability of exceedance of acceptable behavior limits due to natural phenomena). This is a rational approach and an improvement over current light water reactor design/evaluation methodology.

Usage Category: As described above, the HAPE value that defines the hazard load depends on the numerical performance goal that is expressed as annual probability of exceedance (APE) of acceptable behavior limits of SSC or facility. The APE value for an SSC or a facility depends on the usage category to which the SSC/facility belongs. Presently, UCRL-15910 provides some basic subjective guidelines for categorizing an SSC or a facility based on the consequences of its postulated failure. Four usage categories have been defined: General Use, Important or Low hazard, Moderate Hazard, and High Hazard. One APE or performance goal value has been assigned as a target for each category or SSC or facility.

This categorization introduces in the design evaluation process the graded approach or the consideration of relative risk potential for various SSCs/facilities, and provides different levels of criteria, such as:

- criteria in which no consideration of natural phenomena is necessary, where safety is not an issue;

- criteria consistent with normal building codes, where life safety of on-site personnel is an issue of importance;

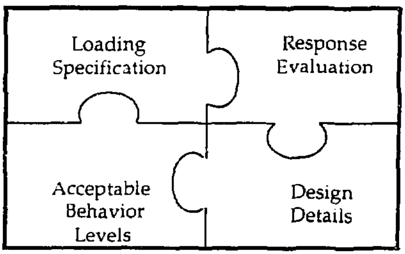
- criteria between those used in normal building codes and those used in nuclear power plants;

- criteria consistent with those used for nuclear power plants, where off-site release of hazardous material must be prevented.

Considering the wide variety of DOE facilities with varying risk potential, it is appropriate to use such a graded approach. Assignment of a probabilistic performance goal to each set of design/evaluation criteria provides a convenient measure of the level of conservatism appropriate to the importance of the safety function or risk potential of SSCs making up DOE facilities. With probabilistic performance goal as a target for deterministic design/evaluation criteria, input loadings from natural phenomena hazards are also determined on a probabilistic basis. Such a use of probabilistic natural phenomena hazard assessments provides a reasonable and modern approach to account for the uncertainty associated with the selection of the worst historically recorded event. It also accounts for potential events in excess of those recorded over the relatively short period of time in which such events have been observed. Using seismic hazard as an example, the following paragraphs present discussions on how the probabilistic performance goals are achieved and how the use of these goals and the use of probabilistic hazard loads are related to the inherent conservatism in the design codes and design details.

Achievement of Performance Goals in UCRL-15910 for Seismic Loads:

Seismic design and evaluation criteria in UCRL-15910 have been developed to attain performance goals by specifying hazard probability (i.e. recurrence period) and by specifying response evaluation methods, acceptance criteria, and design detailing requirements with controlled levels of conservatism. Performance goals have been achieved by consistent specification of all major design or evaluation steps and recognizing their relationship as shown below.



Seismic design evaluation guidelines of UCRL-15910 include the following provisions:

- Lateral Force
- Story Drift/Damage Control
- Detailing for Ductility
- Quality Assurance and Peer Review

Earthquake performance of an SSC depends on the level of the seismic hazard and on conservatism in the response evaluation and acceptance criteria. For example, a performance goal with an APE of 1×10^{-4} can be achieved either by: (1) specifying a conservative evaluation/acceptance approach together with a seismic hazard, at a higher annual probability of exceedance such as 1×10^{-3} or by: (2) specifying a median-centered evaluation/acceptance approach coupled with a 1×10^{-4} annual hazard probability of exceedance. UCRL-15910 uses the former approach because conservative evaluation/acceptance approaches are well established, extensively documented, and commonly practiced while median evaluation/acceptance approaches are controversial, not well understood, and seldom practiced.

Based on this philosophy, the performance goals and earthquake hazard probabilities shown in Table 1 have been recommended in UCRL-15910. The ratio of hazard exceedance probability to performance goal, shown in the last column of Table 1, is a measure of conservatism that must be introduced in the seismic response evaluation approach and/or in the permissible response acceptance criteria.

For General Use category facilities and SSCs, a seismic hazard probability of exceedance of 2×10^{-3}/year is specified that establishes earthquake loading (i.e., peak ground acceleration and input ground response spectrum). This exceedance value is based on the 1988 UBC Zone Map which is probability based (Z coefficient corresponds to 10% probability of being exceeded in 50 years or an annual exceedance probability of 2×10^{-3}).

For High Hazard usage category facilities and SSCs, a seismic hazard probability of exceedance of 2×10^{-4}/year is specified which is consistent with the way peak ground acceleration is determined for Safe Shutdown Earthquake (SSE) in the design of nuclear power plants. The SSE for a nuclear power plant is defined deterministically as the largest historic earthquake or maximum potential earthquake at the site. Based on Lawrence Livermore National Laboratory (LLNL) hazard studies, SSE corresponds to a median annual probability of exceedance of about 2×10^{-4}, and this value has been recommended in UCRL-15910 for High Hazard Usage Category.

Table 1: Performance Goals and Earthquake Hazard Exceedance Probabilities in UCRL-15910

Usage Category	Performance Goal	Hazard Exceedance Probability	Ratio of Hazard to Performance Probability
General Use	$1x10^{-3}$	$2x10^{-3}$	2
Important or Low Hazard	$5x10^{-4}$	$1x10^{-3}$	2
Moderate Hazard	$1x10^{-4}$	$1x10^{-3}$	10
High Hazard	$1x10^{-5}$	$2x10^{-4}$	20

Intentional Conservatism in UCRL-15910 Seismic Evaluation Methodology and Criteria: Seismic design conservatism can be introduced in two ways: (1) in selecting seismic recurrence period (seismic hazard annual probability of exceedance value) and (2) in specifying response evaluation methodology and acceptance criteria. In UCRL-15910, conservatism in selecting hazard exceedance probability has been assured by using values between those adopted in the UBC design methodology and those used in nuclear power plant design. Sources of other intentional conservatism introduced in the evaluation/methodology criteria are listed in Table 2:

Table 2: Sources of Intentional Conservatism in UCRL-15910 Seismic Evaluation Methodology and Criteria

Potential Sources	Median Level Used	Intentional Conservatism in Guidelines [1]	Possible Additional Conservatism
Response spectra amplification	X		
Damping	X		
Analysis methods	X		
Specification of material strengths		X	
Estimation of structural capacity		X	
Load factors		(2)	
Importance factors		(2)	
Limits on inelastic behavior		X	
Soil-structure interaction			X
Effects of a large foundation			X
Effects of foundation embedment			X

NOTES: (1) Controlled to approximately achieve performance only.
(2) General Use and Important or Low Hazard Categories only.

UCRL-15910 response evaluation methods and acceptance criteria are only slightly more liberal than those used for design of nuclear power plants. For reevaluation of existing facilities, UCRL-15910 guidelines have provisions to assure conservatisms. These provisions are similar to those used for reevaluation of nuclear plants which are reviewed by the NRC on a case-by-case basis. Response evaluation methods and acceptance criteria in UCRL-15910 are considered to be more up-to-date than nuclear power plant criteria which were primarily developed in the mid-1970's. For example, UCRL-15910 requires ductile detailing requirements for new designs which are not explicitly required for nuclear plants.

It may be shown that the sources of conservatism listed in Table 2 are sufficient to achieve the performance goals shown in Table 1. From published Probabilistic Risk Assessment (PRA) results for nuclear power plants, it has been estimated that the ratio between seismic hazard probability (i.e. probability of SSE) and probability of seismic induced core damage ranges from 10 to over 200. As shown in Table 3 (taken from Short, et.al., 1990), NRC response evaluation methods and acceptance levels provide sufficient conservatism that performance goals can be met for an annual probability of core damage that is lower than the annual probability of SSE by a median factor of 22 (average is about 66). The UCRL-15910 specified ratio between seismic hazard probability and performance goal is 20 for the High Hazard Category, which is close to the median value of 22. Thus, it is expected that the UCRL-15910 performance goal will be approximately achieved.

Table 3: PRA results showing Seismic Conservatism in Nuclear Power Plants

Plant	SSE (g)	Mean Annual Probability of SSE	Mean Annual Seismic Core Damage Frequency	Conservatism Introduced by Response Evaluation & Acceptance Criteria
Zion	0.17	1.1×10^{-4}	5.7×10^{-6}	19
Indian Pt 2	0.15	7.3×10^{-4}	4.8×10^{-5}	15
Indian Pt 3	0.15	7.3×10^{-4}	3.1×10^{-6}	240
Limerick	0.15	7.0×10^{-4}	5.8×10^{-6}	120
Millstone 3	0.17	2.0×10^{-4}	8.9×10^{-6}	22
Seabrook	0.25	2.2×10^{-4}	2.3×10^{-5}	10
Shoreham	0.20	9.8×10^{-5}	2.6×10^{-6}	38

As shown in Table 2, no intentional conservatism has been introduced in determining spectral amplification. UCRL-15910 recommends that median amplification site-specific response spectra shapes be utilized to obtain the C factor to be used in the UBC base shear equation for ordinary facilities, or as the basis for input excitation to dynamic analyses of High Hazard Category facilities.

No intentional conservatism has been introduced in selecting damping values. Recommended damping is intended to be median level for post yield response. The recommended damping values are based on those given in the Department of

Defense Tri-Service Manual, "Seismic Design of Essential Buildings" [Departments of the Army, Navy, and Air Force, 1986]. These damping values generally correspond to the upper level values given in NUREG/CR-0098 [Reference 6] for "At or just below yield point." According to this NUREG, these values are "the values that should be used in design when moderately conservative estimates are made of the other parameters entering into the design criteria." Future revision of UCRL-15910 will reflect damping values specified in ASCE Standard 4 (ASCE, 1986).

Energy absorption in the inelastic range of response can be very significant. Large hysteretic energy absorption can occur even for structural systems with relatively low ductility such as concrete shear walls or steel braced frames. Limited inelastic energy behavior has been permitted in UCRL-15910. To take credit for inelastic energy absorption capacity, design detailing provisions as given in the UBC are required. Inelastic energy absorption capacity is accounted for by reducing elastic earthquake demand by F_μ, the allowable inelastic demand-capacity ratio. The resulting inelastic earthquake demand is combined with response from concurrent loadings and the overall demand is compared to element capacities. Example values of F_μ from UCRL-15910 are compared with UBC reduction factors, R_w, in Table 4.

Table 4: Comparison of UBC and UCRL-15910 Inelastic Demand-Capability Ratios

Structural System/Element	UCRL-15910 High Hazard F_μ	UCRL-15910 Moderate Hazard F_μ	UBC R_w
Steel Moment Frame	2.5	3.0	12
Steel Diagonal Braced Frame	1.4	1.7	8
Concrete Shear Wall	1.4	1.7	8

The inelastic reduction factors in UCRL-15910 are similar to values given in the DOD Tri-Service Manual, "Seismic Design of Essential Buildings" [Reference 4] and to values given in NUREG/CR-0098, and are consistent with UBC R_w factors when the differences in performance goals and evaluation approaches between general use facilities and moderate or high hazard facilities are considered (see also Appendix A of UCRL-15910). The F_μ values recommended in UCRL-15910 have been developed from these three sources combined with engineering judgment. The use of these values assumes good seismic design detailing such that ductile behavior is reasonably uniform throughout the lateral load carrying system.

Recent Developments

UCRL-15910 contains the framework for a design approach which encompasses relative risk potential (a graded approach), probabilistic performance goals, input loadings based on probabilistic hazard assessments, and integrated response evaluation and permissible response levels. This document has served for several years as the primary guidance document for design and evaluation of DOE facilities subjected to natural phenomena hazards. It has been recently proposed that the four Usage Categories (risk-based groupings) currently in UCRL-15910 be replaced by six SSC performance categories.

A separate document is being developed to establish the methodology for determining performance categories of SSCs. Also, plans are being developed to augment and improve UCRL-15910. Performance Categorization philosophy and the numerical performance goal numbers will be addressed in a new DOE Order 5480.NPH (now in draft form).

The major steps that would be necessary to implement the proposed DOE Order 5480.NPH include the following:

a. Classification of Facilities. Nuclear facilities will be classified as Category 1, 2, or 3, in accordance with the new DOE Order 5480.23, and non-nuclear facilities will be classified as High Hazard, Moderate Hazard, or Low Hazard in accordance with DOE Order 5481.1B. Other facilities not covered by these two orders will be evaluated as non-safety related facilities.

b. Location of site. Site planning must consider all consequences of natural phenomena hazards. For example, seismic hazards must account for : seismicity, geological hazards, foundation hazards, etc. Structures shall not be sited over active geologic faults, in areas of instability subject to landslides, or where soil liquefaction is likely to occur. Combined effects from all these hazards must not result in an annual probability of exceedance equal to or greater than the performance goal assigned.

c. Site data collection and evaluation. In order to establish loadings on facilities resulting from natural phenomena hazards, it will be necessary to collect data on site characteristics including geotechnical, seismological, geological, meteorological, and hydrological information. The level of data collection effort shall depend on the hazard classification of the facility and performance category of the SSCs in the facility. For example, for Hazard Category 1 (High Hazard) facility that contains Performance Category 5 (see Table 5) SSCs, it will be necessary to conduct site-specific studies consisting of extensive field examination. On the other hand, for low-hazard or no hazard facilities consisting of only Performance Category 1 or 2 SSCs, it will generally be sufficient to collect existing site data on characteristics related to natural phenomena (i.e., well logs, existing geologic maps, etc.) and to augment this data with site-specific information, when it is needed.

d. Evaluation of Natural Phenomena Hazards. Natural phenomena hazard design and evaluation requirements include a probabilistic assessment of the likelihood of future NPH occurrence. In addition, deterministic evaluations of natural phenomena hazards are required to supplement and verify probabilistic assessments.

The level of probabilistic natural phenomena hazard assessment to be performed will be appropriate for the performance categories being considered in a manner consistent with the graded approach. For example, for sites containing facilities with SSCs in Performance Category 5, a multi-expert probabilistic natural phenomena hazard assessment shall be performed. For other categories, a probabilistic natural phenomena hazard assessment shall be performed which may be of lesser scope. For sites containing facilities with SSCs in only Performance Categories 1 and 2, it is sufficient to utilize natural phenomena hazard maps from model building codes or national consensus standards. For sites which have site-specific probabilistic NPH assessments, the SSCs in categories 1 and 2 shall be evaluated or designed for the greater of the site specific values or the model code values unless lower site specific values (consistent with applicable industry standards, such as UBC) can be justified.

e. <u>Assignment of performance categories.</u> Performance goals are established in the DOE order as aiming points for performance of structures, system, and components subjected to natural phenomena hazards. After determining a facility hazard category in accordance with 5480.23 or 5481.1B or as a non-safety related facility not covered by these two orders, each SSC in the facility shall be categorized into one of 6 categories based on the consequences of its failure. The categories range from SSCs whose failure would result in unacceptable offsite consequences, to SSCs which are not of a safety or cost concern. Categories and associated performance goals are presented in Table 5.

Table 5: Performance Goals for SSCs

Performance Category	5	4	3	2	1	0
Performance Goal (annual probability of exceedance of acceptable behavior limits)	$<1\times10^{-5}$	1×10^{-5}	1×10^{-4}	5×10^{-4}	1×10^{-3}	N/A

These goals form targets for performance of function or maintenance of structural integrity. Goals and corresponding performance categories should be selected by systems/safety engineers and DOE site managers in a manner that DOE safety policy is met. Economic or programmatic considerations may require use of higher goals for specific SSCs.

As an example to illustrate the categorization process, consider a DOE 5480.23 Category 1 facility which, by definition of the category, has the potential for significant off-site consequences. Certain SSCs in this facility are required to remain structurally intact and/or to continue to function during and/or after a natural phenomena occurrence in order to prevent significant off-site consequences. These SSCs should be placed in Performance Category 4 or 5 depending on the extent and severity of consequences and the type of the facility (such as nuclear reactor facility, non-reactor nuclear facility, etc.). Other SSCs which do not participate in the prevention of off-site consequences can be placed in lower Performance Categories. SSCs that are not needed to prevent either off-site or on-site consequences but may contribute to life safety hazards due to potential structural damage, sliding, or overturning, should be placed in Performance Category 1. SSCs in a facility not needed to prevent off-site or on-site consequences, but needed for emergency actions, should be placed in Performance Category 2. SSCs which are of no safety concern and which can be economically replaced following a natural phenomena hazard occurrence should be placed in

Performance Category 0. Hence, it may be seen that SSCs comprising a 5480.23 Category 1 facility can be placed in a variety of performance categories. The SSCs comprising a 5480.23 Category 3 facility should be placed only in Performance Categories 0, 1, or 2 unless there are economic or programmatic reasons to place them in higher performance categories.

In summary, SSCs comprising DOE facilities shall be designed, evaluated, modified, or upgraded to maintain performance during or after NPHs within constraints of acceptable performance. Acceptable performance shall be defined utilizing a graded approach consistent with facility characteristics such as hazards, safety considerations, mission importance, and cost. For all SSCs comprising DOE facilities, it is necessary to assign appropriate performance categories which specify acceptable annual probabilities of SSC damage or failure.

f. Design and evaluation for the effects of natural phenomena hazards. Specified annual probabilities of exceedance for natural phenomena hazards to establish loadings and deterministic design rules for response evaluation methods, permissible response levels, design detailing requirements, and quality assurance and peer review requirements will be provided in implementing documents. These documents will be in the form of DOE Standards and or guidelines. The response evaluation methods, permissible response levels, and design detailing requirements will invoke national consensus standards wherever possible. The current implementing document for design and evaluation is UCRL-15910 [Reference 5]. It should be noted that the proposed DOE Order 5480.NPH provides only general guidance for categorizing SSCs. Categorizing SSCs is potentially one of the more difficult parts of a NPH evaluation but forms an essential step to implementing the requirements described herein. The remaining portions of the proposed NPH evaluation method, i.e. techniques for respons evaluation and comparison to acceptance criteria are completely general and could be applied to any type of SSC. There are many paths that could be taken to meet a performance goal. Conservatism could be included in any step of an evaluation. The previous section illustrated the achievement of performance goals for earthquake loading by following the current provisions of UCRL-15910.

Application of DOE NPH Criteria for Repository Surface Facilities

The methodology discussed in this paper involves meeting performance goals by choosing consistent loading resulting from a given hazard exceedance probability, response evaluation techniques, acceptance criteria, and design detailing. By choosing the appropriate degree of conservatism (ratio of Hazard to Performance Probability) as shown in Table 1, a performance goal can be met for a given hazard. Note that these conservatism factors will be different for different types of loading. For instance, for flood there is usually little conservatism beyond the design flood height. A flood wall can only stop water at a given elevation, for instance. Therefore, the flood wall design would have a hazard annual probability equal to the performance goal (with conservatism factor equal to 1). Thus, once categories to meet goals are developed, the methodology can be applied.

The determination of categories for SSCs is the remaining item to be specified for surface facilities. In accordance with 10CFR60, the SSCs comprising the surface facilities must limit releases to specified dose rates at the site boundary. Explicit Categorization of SSCs by calculating the contribution of each SSC to the dose may not be practical. But by performing system safety analysis, the severity of the consequence of failure of each SSC can be determined, on the basis of which performance categorization can be performed. DOE's guidelines for such performance categorization is presently under development. These guidelines will recognize that DOE facilities are classified according to inventory and type of material in accordance with DOE order 5480.23 or 5481.1B.

The methodology presented above for DOE facilities does not require performing PRA studies but requires some level of system safety analysis and evaluation. However, since the repository surface facilities, are somewhat unique, the authors recommend that at least a scoping level PRA be performed to identify system vulnerability and potential failure paths at an early design stage. Also, a post-design PRA may be needed to determine the level of conformance to the overall DOE/NRC safety policy.

Conclusion

Rationales for various provisions of current DOE methodology for NPH evaluation, as embodied in UCRL-15910, have been discussed. Also, brief outlines of recently proposed DOE Order 5480.NPH, that specifies the performance categorization of SSCs according to the severity of their failure consequences, have been presented. The applicability of these methodologies to high level waste surface facilities has been discussed. The authors recommend that; since the DOE's NPH evaluation methodology is based on a graded approach and state-of-the-art philosophy, this should be applied to the design/evaluation of SSCs comprising the Surface facilities.

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