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NUREG/CR-7193

Evaluations of NRC Seismic-Structural Regulations and Regulatory Guidance, and Simulation-Evaluation Tools for Applicability to Small Modular Reactors (SMRs)

Office of Nuclear Regulatory Research

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ABSTRACT

This report consists of two different evaluations sponsored by the U.S. Nuclear Regulatory Commission (NRC) and performed by Lawrence Berkeley National Laboratory. The first evaluation covers NRC regulatory guidance in the seismic-structural area. The second evaluation covers several seismic-structural simulation tools used in NRC regulatory applications. Each evaluation examines the appropriateness of the regulatory guidance (provided in regulations, guidance, review plans, etc.), or of the simulation tool for its applicability to small modular reactors (SMRs). The objective of each evaluation is to address the following: The bulk of NRC's regulatory work on nuclear power reactor safety has been concentrated for decades on large light-water reactors (LWRs). While the regulations are technology neutral, many of the agency's positions have evolved with large LWRs as the sole technology of interest. Also, the technical analysis tools (computer codes) used in reactor safety guidance, either by the NRC itself or by its licensees and applicants, including structural analysis tools as well as those used to determine ground motion and to analyze soil structure interaction (SSI) effects, have been used to analyze large LWRs. This report examined whether regulatory guidance, or the analysis tools currently used in the seismic-structural area, could benefit from modification to better address small modular reactors (SMRs). It concluded that most documents reviewed do not need any modifications and are acceptable as currently written.

Recommendations for modifications are presented as appropriate. Also, it concluded that the software packages reviewed should yield acceptable results when applied to an SMR. The report can be used to inform the NRC's efforts to update regulatory guidance in support of licensing reviews of SMR applications.

FOREWORD

The current U.S. Nuclear Regulatory Commission (NRC) licensing framework for power reactors was developed primarily to address the safety of large LWRs (light water reactors.) The vast majority of experience over the last 50 years has also been in regulating large LWRs.

In the last several years, small modular reactors (SMRs) have generated sufficient commercial interest to warrant NRC preparations for a review of one or more SMR designs. Therefore, the Office of Nuclear Regulatory Research (RES) initiated a review of existing regulatory guidance in the seismic-structural area. The NRC staff particularly focused on guidance for seismic interactions between smaller modular nuclear units, especially given the multiple configurations possible for SMRs. The SMR units could be built sequentially over many years but the units could be closely located, resulting in multiple interaction and response scenarios.

Advances in the state of knowledge and new abilities to model the seismic input and responses and to model seismic ground motions and soil-structure-interaction effects provide new capabilities to model and analyze the plant. RES wanted to identify whether an SMR design would present any unique or unexpected issues to a reviewer using these new tools for soil structure interaction (SSI) analysis.

The review identified some areas of NRC guidance that could be improved for SMRs. In some technical areas, the current guidance is not appropriate for SMRs, or changes are appropriate to improve clarity or to reduce possible misinterpretations. Also, the review concluded that existing analysis tools can—in the hands of an appropriately skilled practitioner—give proper results. The report can be used to inform the NRC's efforts to update regulatory positions and guidance in support of licensing reviews of SMR applications.

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EXECUTIVE SUMMARY

The existing NRC reactor-safety guidance on seismic-structural evaluations is based largely on the regulation of large light water reactor (LWR) designs. As the NRC prepares to review small modular reactor (SMR) designs of commercial units for the first time, it is important to assess whether the existing guidance and review tools and standards are appropriate for the SMR designs.

Lawrence Berkeley National Laboratory (LBNL) reviewed the NRC guidance documents that have been used in previous NRC licensing reviews in seismic (including soil structure interaction) and structural areas to determine if the documents could be improved for use during review of an SMR application. In addition, LBNL reviewed various software packages to assess whether they had any inherent limitations that could adversely affect the results when used to evaluate an SMR design.

This report has been written in two distinct sections.

In Section 1, fifty-nine (59) documents covering various seismic-structural regulatory-guidance positions were reviewed. Of these, twenty-nine (29) are deemed not to need any improvements; twenty (20) were deemed to need minor or moderate improvements to clarify the NRC position; and ten (10) could benefit from more extensive improvements.

An example of the type of change that was characterized by ‘minor or moderate’ was that in RG 1.57, “Design Limits and Loading Combinations for Metal Primary Reactor Containment System Components,” the value for the load factor to be applied is specified as 1.10. This guidance should be improved to clarify that it is not overly conservative in an SMR design. As another example, RG 1.132, “Site Investigations for Foundations of Nuclear Power Plants,” specifies the spacing of borings at 30 meters, or an area of 900m2 (square meters). This guidance could be modified to specify the resolution needed to ensure appropriate characterization of the subsurface conditions, given the small foot print of an SMR.

An example of a more extensive or important needed revision is for RG 1.29, “Seismic Design Classification.” The design classification system is tailored to LWR designs. Some of the classifications may not be correct for an SMR with its unique design features. A more intense review is required to fully explore this issue. Another example is in RG 1.61, “Damping Values for Seismic Design of Nuclear Power Plants.” The damping values listed may not be correct for the structure, size and mass of an SMR.

In Section 2, thirteen (13) software packages were reviewed. All are deemed to yield acceptable results when used on an SMR design if it can be assumed that the user is properly trained for that package. However, a few specific concerns are identified for two of the software packages.

The Department of Energy (DOE) reported in April 2011 that SASSI software for analyzing soil structure interaction effects could produce unrealistic earthquake responses in some analyses. The unrealistic results manifest for certain types of deeply embedded structures. This is a concern for some proposed SMR designs because they utilize deeply embedded structures. A solution is being pursued by a consortium of SASSI experts and practitioners. Any user of the SASSI program must address this issue when using the software.

The ESSI software is new and uses a different approach than the other packages considered. Specifically it uses a time-domain, non-linear approach, instead of the traditional frequency domain. The review did not reveal any issues with the software. However, users must be aware of this change in modeling philosophy, and build the model accordingly. Given that it is a new package with a different approach, some users or design reviewers may not be confident of its results.

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Dr. Dimitrios Konstantinidis principally worked on the Section 1 evaluation, and Dr. Ziguang Zhou principally worked on the Section 2 evaluation. Dr. Konstantinidis is now on the civil engineering faculty at McMaster University, Hamilton, Ontario, Canada. Dr. Zhou is now at the College of Civil Engineering, Tongji University, Shanghai, China.

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ABBREVIATIONS AND ACRONYMS

ANS	American Nuclear Society
ASCE	American Society of Civil Engineers
ASCII	American Standard Code for Information Interchange (a computer format)
ASME	American Society of Mechanical Engineers
BWR	boiling-water reactor
CFR	U.S. *Code of Federal Regulations*
CQC	Complete Quadratic Combination
CRD	control rod drive
CRDS	control rod drive system
DNFSB	U.S. Defense Nuclear Facilities Safety Board
DOE	U.S. Department of Energy
ESSI	Earthquake Soil Structure Interaction (software program)
FEA	finite element analysis
FEM	finite element method
FNA	finite nonlinear analysis
FSI	fluid-structure interaction
GDC	general design criterion
HVAC	heating, ventilation, and air conditioning
Hz	hertz, a unit of frequency (one cycle per second)
ISG	interim staff guidance
JCNRM	ASME-ANS Joint Committee on Nuclear Risk Management
LBNL	Lawrence Berkeley National Laboratory
LWR	light-water reactor
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NRO	NRC Office of New Reactors
OBE	operating-basis earthquake
PC	personal computer
PDE	partial differential equation
PRA	probabilistic risk assessment
PWR	pressurized-water reactor
RG	NRC Regulatory Guide
SDOF	single degree of freedom
SMR	small modular reactor
SRP	NRC Standard Review Plan
SRSS	square root of the sum of the squares
SSC	structure, system, or component
SSE	safe-shutdown earthquake
SSI	soil-structure interaction
V & V	verification and validation

1. EVALUATION OF NRC SEISMIC-STRUCTURAL REGULATORY GUIDANCE FOR APPLICABILITY TO SMALL MODULAR REACTORS (SMRs)

1.1 Introduction

Lawrence Berkeley National Laboratory (LBNL) performed a project supported by the U.S. Nuclear Regulatory Commission (NRC). The project was entitled, "Soil Structure Interactions for Small Modular Reactors on Individual Foundations." For the first part of the project, covered in this Section, LBNL formed a project team to perform two review and evaluation tasks. The scope of the review and evaluation was limited to NRC regulations, NRC regulatory guidance, and certain consensus codes and standards related to seismic issues. Specifically, the review assessed seismic issues related to structural engineering, geotechnical engineering, and other related engineering areas.

Identification of Applicable NRC Regulations, Reg Guides. etc.
In this Task, the project team identified and reviewed the currently issued NRC regulations, Regulatory Guides, Standard Review Plan sections, industry consensus standards, and other regulatory guidance that are relevant to the areas of seismic engineering, structural engineering, geotechnical engineering, and related topics. Each regulation or document was studied to determine how it had been used for large LWRs (light-water reactors) by industry designers and analysts, and how it had been interpreted by the NRC regulatory staff. In parallel, aspects of NRC risk methodology specific to LWRs were identified. The list of regulations and documents identified as pertinent was compiled into this report.

Evaluation of Applicability to Small Modular Reactors
In this Task, the project team analyzed the regulatory guidance identified in the first Task for applicability to SMR (small modular reactor) design concepts.

In the early stages of this project, the LBNL team (in conjunction with the NRC staff) concluded that identifying specific SMR designs was not necessary—that an evaluation could be performed that would be generically applicable to many of the different types of SMRs. However, this may or may not be true for all SMRs.

1.2 The Work—Three Phases

The first phase of the work reported here in Section 1 involved compiling a list of the relevant NRC regulations and regulatory guides; standard review plan (SRP) sections, etc.; and industry standards. The project team started with a list of NRC documents suggested by the NRC staff and then added other items to it based on the judgment of the team.

The second phase of the work involved the examination and study of each document to determine whether its content, applicability, and application in practice would be different if applied in NRC regulatory processes for an SMR rather than for a current-generation large light-water reactor (LWR). The LBNL team categorized the documents into three categories. For a large fraction of the documents, the LBNL team concluded that there would be no difference. For this reason, the first category consists of documents for which no modification would be needed to accommodate an SMR. For a second category, the LBNL team concluded that the document would be fully applicable to an SMR in a technical sense; however, its efficiency and effectiveness for SMRs could be improved by a small number of modest changes. A third category of documents was identified for which effective use by an SMR would likely require important technical changes. This process resulted in three lists of documents for the three categories.

The third phase of the work involved the detailed evaluation of each of the items in the second and third categories.

1.3 List of Relevant Regulations, Regulatory Guides, ISGs, SRP Sections, and Consensus Codes & Standards

1.3.1 NRC Regulations: General Design Criteria (Parts of 10 CFR 50, Appendix A)

These criteria are from Appendix A, “General Design Criteria for Nuclear Power Plants,” to Part 50, “Domestic Licensing of Production and Utilization Facilities,” of Title 10, “Energy,” of the *Code of Federal Regulations* (10 CFR 50, Appendix A):

- GDC 2 (General Design Criterion 2), “Design Bases for Protection Against Natural Phenomena”

- GDC 4 (General Design Criterion 4) “Environmental and Dynamic Effects Design Basis”

- GDC 5 (General Design Criterion 5), “Sharing of Structures, Systems, and Components”

- GDC 16 (General Design Criterion 16), “Containment Design”

- GDC 50 (General Design Criterion 50), “Containment Design Basis”

1.3.2 Specific NRC Regulations

- Appendix S to 10 CFR 50
  “Earthquake Engineering Criteria for Nuclear Power Plants”

- 10 CFR 100.23
  “Geologic and Seismic Siting Criteria”

- Appendix A to 10 CFR 100
  “Seismic and Geologic Siting Criteria for Nuclear Power Plants”

1.3.3 NRC Regulatory Guides*

- Regulatory Guide (RG) 1.12 (Rev. 2, Mar. 1997)
  “Nuclear Power Plant Instrumentation for Earthquakes”

- RG 1.29 (Rev. 4, Mar. 2007)
  “Seismic Design Classification”

- RG 1.57 (Rev. 1, Mar. 2007)
  “Design Limits and Loading Combinations for Metal Primary Reactor Containment System Components”

- RG 1.60 (Rev. 1, Dec. 1973)
  “Design Response Spectra for Seismic Deign of Nuclear Power Plants”

- RG 1.61 (Rev. 1, Mar. 2007)
  “Damping Values for Seismic Design of Nuclear Power Plants”

- RG 1.92 (Rev. 2, July 2006)
  “Combining Modal Responses and Spatial Components in Seismic Response Analysis”

- RG 1.100 (Rev. 3, Sept. 2009)
  “Seismic Qualification of Electrical and Active Mechanical Equipment and Functional Qualification of Active Mechanical Equipment for Nuclear Power Plants”

- RG 1.122 (Rev. 1, Feb. 1978)
  “Development of Floor Design Response Spectra for Seismic Design of Floor-Supported Equipment or Components”

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[*] Some of these NRC Regulatory Guides are not the very latest revisions but these are the versions that were current when the project began.

- RG 1.132 (Rev. 2, Oct. 2003)
  "Site Investigations for Foundations of Nuclear Power Plants"

- RG 1.136 (Rev. 3, Mar. 2007)
  "Design Limits, Loading Combinations, Materials, Construction, and Testing of Concrete Containments"

- RG 1.138 (Rev. 2, Dec. 2003)
  "Laboratory Investigations of Soils and Rocks for Engineering Analysis and Design of Nuclear Power Plants"

- RG 1.142 (Rev. 2, Nov. 2001)
  "Safety-Related Concrete Structures for Nuclear Power Plants (Other Than Reactor Vessels and Containments)"

- RG 1.166 (Mar. 1997)
  "Pre-Earthquake Planning and Immediate Nuclear Power Plant Operator Post-Earthquake Actions"

- RG 1.167 (Mar. 1997)
  "Restart of a Nuclear Power Plant Shut Down by a Seismic Event"

- RG 1.198 (Nov. 2003)
  "Procedures and Criteria for Assessing Seismic Soil Liquefaction at Nuclear Power Plant Sites"

- RG 1.200 (Mar. 2009)
  "An Approach for Determining the Technical Adequacy of Probabilistic Risk Assessment Results for Risk-Informed Activities"

- RG 1.208 (Mar. 2007)

"A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion"

1.3.4 NRC Interim Staff Guidance

- Design Certification (DC)/Combined License (COL)-ISG-1 (May 19, 2008) "Interim Staff Guidance on Seismic Issues Associated with High Frequency Ground Motion in Design Certification and Combined License Applications"

- DC/COL-ISG-3 (June 11, 2008)
  "PRA Information to Support Design Certification and Combined License Applications"

- DC/COL-ISG-17 (March 24, 2010)
  "Interim Staff Guidance on Ensuring Hazard-Consistent Seismic Input for Site Response and Soil Structure Interaction Analyses"

- DC/COL-ISG-20 (March 15, 2010)
  “Seismic Margin Analysis for New Reactors Based on Probabilistic Risk Assessment”

1.3.5 NRC Standard Review Plan (SRP) Sections (NUREG-0800)

- SRP 2.5
  - 2.5.1 Basic Geologic and Seismic Information
  - 2.5.2 Vibratory Ground Motion
  - 2.5.3 Surface Faulting
  - 2.5.4 Stability of Subsurface Materials and Foundations
  - 2.5.5 Stability of Slopes

- SRP 3.2.1
  - 3.2.1 Seismic Classification

- SRP 3.7
  - 3.7.1 Seismic Design Parameters
  - 3.7.2 Seismic System Analysis
  - 3.7.3 Seismic Subsystem Analysis
  - 3.7.4 Seismic Instrumentation

- SRP 3.8
  - 3.8.1 Concrete Containment
  - 3.8.2 Steel Containment
  - 3.8.3 Concrete and Steel Internal Structures of Steel or Concrete Containments
  - 3.8.4 Other Seismic Category I Structures
  - 3.8.5 Foundations

- SRP 3.9
  - 3.9.1 Special Topics for Mechanical Components
  - 3.9.2 Dynamic Testing and Analysis of Systems, Structures, and Components
  - 3.9.3 ASME Code Class 1, 2, and 3 Components and Component Supports, and Core Support Structures
  - 3.9.4 Control Rod Drive Systems
  - 3.9.5 Reactor Pressure Vessel Internals
  - 3.9.6 Functional Design, Qualification, and Inservice Testing Programs for Pumps, Valves, and Dynamic Restraints
  - 3.9.7 Risk-Informed Inservice Testing
  - 3.9.8 Review of Risk-Informed Inservice Inspection of Piping

- SRP 3.10
  - 3.10 Seismic and Dynamic Qualification of Mechanical and Electrical Equipment

- SRP 19
  - 19.0 Probabilistic Risk Assessment and Severe Accident Evaluation for New Reactors

1.3.6 Consensus Codes and Standards

Note: These consensus codes and standards were selected for review because they are referred to often in various NRC regulatory guidance documents. In each case, this is the latest version of the code or standard referred to in the NRC documents.

- American Society of Civil Engineers (ASCE) 4-98, "Seismic Analysis of Safety-Related Nuclear Structures" (1998)

- ASCE 43-05, "Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities" (2005)

- American Society of Mechanical Engineers (ASME)/American Nuclear Society (ANS) RA-Sa-2009, "Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications"

- ASME Boiler and Pressure Vessel Code (various sections relevant to seismic- structural issues)

1.4 Categorization and Preliminary Evaluation

In this section, the list in Section 1.3 is subdivided into three categories. The three categories are "*no change needed,*" "*modest changes may be desired,*" and "*important changes may be desired*." A rationale is provided for each categorization decision.

1.4.1 Category One, No Changes Needed

The LBNL team's evaluation concluded that a majority of the documents listed in Section 1.3 require no changes to be applicable to a small modular reactor (SMR). The list of documents in this category is presented here as Table 1-1. Table 1-1 also contains the rationale for each item's having been placed into this category.

Two rationales that would place a document in Category One are either (i) the regulation or regulatory position (although directly related to the issue at hand) is technology-neutral vis-à-vis the difference between a large LWR and a small modular reactor or (ii) the regulation or regulatory position is only peripherally related to this difference. [An example of the latter would be the regulatory positions related to which types of seismic strong-motion instruments need to be deployed. The requirements for these instruments are peripherally related to the subject and are unaffected by whether the reactor is an LWR or an SMR.]

Table 1-1 Category One—Documents for Which No Changes Are Needed

Category	Short Descriptor	Name	Rationale for Categorization	Observations/Comments/ Concerns
NRC Regulations	GDC 2	Earthquake Engineering Criteria for Nuclear Power Plants	Technology-neutral	
	GDC 4	Environmental and Dynamic Effects Design Basis	Technology-neutral	
	GDC 5	Sharing of Structures, Systems, and Components	Technology-neutral	
	GDC 16	Containment Design	Technology-neutral	
	GDC 50	Containment Design Basis	Technology neutral	
	10 CFR 50, Appendix S	Earthquake Engineering Criteria for Nuclear Power Plants	Technology-neutral	
	10 CFR 100.23	Geologic and Seismic Siting Criteria	Technology-neutral	
	10 CFR 100, Appendix A	Seismic and Geologic Siting Criteria for Nuclear Power Plants	Technology-neutral	

Table 1-1 Category One—Documents for Which No Changes Are Needed (continued)

Category	Short Descriptor	Name	Rationale for Categorization	Observations/Comments/ Concerns
Regulatory Guides	RG 1.12	NPP Instrumentation for Earthquakes	Technology-neutral	Peripherally related
	RG 1.60	Design Response Spectra for Seismic Design of Nuclear Power Plants	Technology-neutral	
	RG 1.92	Combining Modal Responses and Spatial Components in Seismic Response Analysis	Technology-neutral	Peripherally related The methods for response analysis seem to apply equally to any NPP.
	RG 1.100	Seismic Qualification of Electrical and Active Mechanical Equipment and Function Qualification of Active Mechanical Equipment for Nuclear Power Plants	Technology-neutral	Peripherally related The approaches for qualification of equipment seem to apply equally to any NPP.
	RG 1.166	Pre-Earthquake Planning and Immediate Nuclear Power Plant Operator Post-Earthquake Actions	Technology-neutral	Peripherally related
	RG 1.167	Restart of a Nuclear Power Plant Shut Down by a Seismic Event	Technology-neutral	Peripherally related
	RG 1.200	An Approach for Determining the Technical Adequacy of Probabilistic Risk Assessment Results for Risk-Informed Activities	Technology-neutral	Peripherally related
	RG 1.208	A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion	Technology-neutral	Peripherally related

Table 1-1 Category One—Documents for Which No Changes Are Needed (continued)

Category	Short Descriptor	Name	Rationale for Categorization	Rationale for Categorization
NRO Interim Staff Guidance	DC/COL-ISG-1	Interim Staff Guidance on Seismic Issues Associated with High-Frequency Ground Motion in Design Certification and Combined License Applications	Technology-neutral	
	DC/COL-ISG-3	PRA Information to Support Design Certification and Combined License Applications	Technology-neutral	
	DC/COL-ISG-20	Seismic Margin Analysis for New Reactors Based on Probabilistic Risk Assessment	Technology-neutral	
NUREG-0800 Standard Review Plan (SRP) Sections	SRP 2.5.1	Basic Geologic and Seismic Information	Technology-neutral	
	SRP 2.5.3	Surface Faulting	Technology-neutral	Peripherally related
	SRP 2.5.5	Stability of Slopes	Technology-neutral	Peripherally related
	SRP 3.7.4	Seismic Instrumentation	Technology-neutral	Peripherally related
	SRP 3.9.3	ASME Code Class 1, 2, and 3 Components and Component Supports and Core Support Structures	Technology-neutral	
	SRP 3.9.6	Functional Design, Qualification, and Inservice Testing Programs for Pumps, Valves, and Dynamic Restraints	Technology-neutral	Peripherally related
	SRP 3.9.7	Risk-Informed Inservice Testing	Technology-neutral	Peripherally related
	SRP 3.9.8	Review of Risk-Informed In service Inspection of Piping	Technology-neutral	Peripherally related

Table 1-1 Category One—Documents for Which No Changes Are Needed (continued)

Category	Short Descriptor	Name	Rationale for Categorization	Rationale for Categorization
NUREG 0800 Standard Review Plan (SRP) Sections	SRP 3.10	Seismic and Dynamic Qualification of Mechanical and Electrical Equipment	Technology-neutral	Peripherally related
Continued)	SRP 19.0	Probabilistic Risk Assessment and Severe Accident Evaluation for New Reactors	Technology-neutral	Peripherally related

1.4.2 Category Two, Modest Changes May Be Desired

The LBNL team's evaluation concluded that a small number of the documents may require some modest changes so they can be used in the NRC regulatory process for an SMR. The list of documents in this category is in Table 1-2. Table 1-2 also contains the rationale for each item's having been placed into this category.

The entries in Table 1-2 include the following NRC documents:

RG 1.57
RG 1.122
RG 1.132
RG 1.136
RG 1.138
RG 1.142
RG 1.198
DC/COL-ISG-17
SRP 2.5.2
SRP 2.5.4
SRP 3.7.1
SRP 3.7.2
SRP 3.7.3
SRP 3.8.3
SRP 3.8.4
SRP 3.8.5
SRP 3.9.1
SRP 3.9.2
SRP 3.9.3
SRP 3.9.4

NOTE: "RG" is a "Regulatory Guide" and "SRP" is a "Standard Review Plan Section."

Table 1-2 Category Two—Documents for Which Modest Changes May Be Desired

Category	Short Descriptor	Name	Rationale for Categorization	Observations/Comments/ Concerns
NRC Regulations	None			Regulatory Guides
Regulatory Guides	RG 1.57 *(see Section 1.5.1 for additional discussion)*	Design Limits and Loading Combinations for Metal Primary Reactor Containment System Components	Technology-neutral	(1) The methods for response analysis seem to apply equally to any NPP. (2) The relevance of these load combinations to any specific SMR needs to be checked by both the designer and the NRC. Also, the relevance of the factor of 1.10 for P_{g3} in 1.2.3.(6) needs to be determined for SMRs.
	RG 1.122 *(see Section 1.5.2 for additional discussion)*	Development of Floor Design Response Spectra for Seismic Design of Floor-Supported Equipment or Components	The RG's guidance on development of floor design response spectra may not be fully applicable to a structure like an SMR with its significantly smaller size and mass. However, any changes in the guidance are likely to be modest.	The RG asks for the use of the square root of the sum of the squares (SRSS) to combine floor spectral ordinates (B.2). It appears that this provision was written with a specific piece of equipment in mind that behaves like a system with a single degree of freedom. It ignores structure-equipment interaction and is not generic enough to encompass pieces of equipment with more complex dynamic behavior. Moreover, the use of the SRSS combination rule may not be appropriate if the equipment in question exhibits closely spaced modal frequencies. This is probably because the RG was written before more recent (e.g., Complete Quadratic Combination) modal combination rules that incorporate correlation coefficients were developed.

Table 1-2 Category Two—Documents for Which Modest Changes May Be Desired (continued)

Category	Short Descriptor	Name	Rationale for Categorization	Observations/Comments/ Concerns
Regulatory Guides (continued)	RG 1.132 *(see Section 1.5.3 for additional discussion)*	Site Investigations for Foundations of Nuclear Power Plants	The issues of spacing between borings, minimum depth of penetration of borings, minimum percentage of borings reaching the needed depth, and the extent of subsurface exploration.	Appendix D (Spacing and Depth of Subsurface Explorations and Safety-Related Foundations) calls for 30 m (or area of 900 m^2) between borings under “larger, heavier structures, such as the containment and auxiliary buildings.” This spacing may be too large for SMRs with a small footprint. A smaller boring spacing may be necessary to characterize the subsurface profile. A second concern involves the requirement in Appendix D for boring to a minimum depth of penetration (33 feet below the foundation.) For an SMR that will be deeply or fully embedded, this boring-depth requirement would need to be reevaluated on a case-by-case basis. Additional concerns are the minimum percentage of borings that would be required to reach the maximum required depth and the extent of subsurface exploration that needs to be accomplished to provide reasonable coverage for understanding subsurface stability and for understanding the three-dimensional distribution of geological features.
	RG 1.136 *(see Section 1.5.4 for additional discussion)*	Design Limits, Loading Combinations, Materials, Construction, and Testing of Concrete Containments	The issue of load combinations.	As in RG 1.57, the relevance of these load combinations to any specific SMR needs to be checked by both the designer and the NRC. Also, in C.5.B(3), the relevance to any specific SMR of the 310-kPa pressure load would need to be checked.

Table 1-2 Category Two—Documents for Which Modest Changes May Be Desired (continued)

Category	Short Descriptor	Name	Rationale for Categorization	Observations/Comments/ Concerns
Regulatory Guides (continued)	RG 1.138 *(see Section 1.5.5 for additional discussion)*	Laboratory Investigations of Soils and Rocks for Engineering Analysis and Design of Nuclear Power Plants	The text of this RG seems to be quite generic, but its applicability to an SMR design that is deeply embedded may not be as good a fit as it is for a large LWR to be sited near the surface.	The issue that might require special evaluation is when an SMR design is deeply embedded. This is because the laboratory testing program in RG 1.138 must "work together" with the field sample-taking program usually accomplished under guidance described in other RGs. The sampling program could be different in important ways.
	RG 1.142 *(see Section 1.5.6 for additional discussion)*	Safety-Related Concrete Structures for Nuclear Power Plants (Other than Reactor Vessels and Containments)	The issue of applicability of compressive strength test.	(1) Although the text of this RG refers to certain attributes specific to large LWRs, none of the text is constraining in any way. (2) According to Regulatory Position 5, the frequency for in-process compressive strength tests of concrete is to be 1 test per 100 cu yd. However, the effect of variability in concrete strength may be higher as the size of the structure decreases. Consequently, for an SMR, the testing frequency may need to be higher.
	RG 1.198 *(see Section 1.5.7 for additional discussion)*	Procedures and Criteria for Assessing Seismic Soil Liquefaction at Nuclear Power Plant Sites	The text of this RG seems to be quite generic, but its applicability to an SMR design that is deeply embedded may not be as good a fit as it is for a large LWR to be sited near the surface.	For a deeply embedded SMR, the way liquefaction phenomena might affect the structure could be quite different if the liquefaction layer was close to the bottom of the embedded structure, and all the more so if the layer was located above the bottom of the embedded structure.

Table 1-2 Category Two—Documents for Which Modest Changes May Be Desired (continued)

Category	Short Descriptor	Name	Rationale for Categorization	Observations/Comments/ Concerns
NRO Interim Staff Guidance	DC/COL-ISG-17 *(see Section 1.5.8 for additional information)*	Interim Staff Guidance on Ensuring Hazard-Consistent Seismic Input for Site Response and Soil Structure Interaction Analyses	This ISG seems to be mostly generic and applicable to any site. However, the number of check points called for in ISG-17, and perhaps other aspects of the analysis, may not be applicable to a deeply embedded SMR.	For a deeply embedded SMR, the way ISG-17 suggests that an applicant do this analysis should ensure the development of a consistent seismic input for response and soil-structure interaction (SSI) analyses. The input motions at the foundation level, when convolved up to through the soil column, must bound the free-field performance-based surface response spectrum (PBRS) at the surface. For deeply embedded structures, the number and location of check points may need to be different than those required for a surface-sited large LWR. In particular, for deeply embedded SMR structures, it may be necessary to develop additional PBRS spectra at intermediate depths.
NUREG-0800 Standard Review Plan (SRP) Sections	SRP 2.5.2 *(see Section 1.5.9 for additional discussion)*	Vibratory Ground Motion	The issue of inclined shear-wave propagation being more significant for deeply embedded SMRs	For a deeply embedded SMR, the way an inclined seismic shear wave propagates (the vertical and horizontal components) may be more important for a deeply embedded SMR than for a large LWR at or near the surface, and the analysis method must account for this properly. Specifically, for a deeply embedded SMR, the effect of inclined waves may be more important and the method for determining the GMRS needs to be carefully considered.

Table 1-2 Category Two—Documents for Which Modest Changes May Be Desired (continued)

Category	Short Descriptor	Name	Rationale for Categorization	Observations/Comments/ Concerns
NUREG-0800 Standard Review Plan (SRP) Sections (continued)	SRP 2.5.4 *(see Section 1.5.10 for additional discussion)*	Stability of Subsurface Material and Foundations	For a deeply embedded SMR, the following issues need to be addressed: (1) the construction of the deep excavation, (2) the effect of dewatering, and (3) the adequacy of measuring points to monitor settlement.	For a deeply embedded SMR, the following issues need to be addressed in a way potentially different from how they would be handled for a large LWR at or near the surface: (1) The construction of the deep excavation may affect the surrounding soil properties that are used in the analysis and design of the foundation and plant structures. (2) The effect of dewatering, both during and after construction, considering the higher head and volume of ground water, may be more significant to the structures than its effect for LWRs. (3) Adequate measuring points to monitor settlement throughout the depth of the embedded structure may be needed.
	SRP 3.7.1 SRP 3.7.2 SRP 3.7.3 *(see Section 1.5.11 for additional discussion)*	Seismic Design Parameters Seismic System Analysis Seismic Subsystem Analysis	These three SRP sections seem to be mostly generic and applicable to any site. However, some aspects of them may not be applicable to a deeply embedded SMR.	For a deeply embedded SMR, the guidance in these SRP sections may not be directly applicable. In particular, the development of a consistent seismic input for response and soil structure interaction (SSI) analyses and then for design of a specific structure, system, or component (SSC) can be different than for a large LWR on or near the surface. A number of issues require reevaluation, and the application of these SRP sections without such a reevaluation could lead to a compromise in the design margins. One issue is that the way the soil column interacts with a deeply embedded structure can be quite different, which affects how the seismic energy propagates further into the structure. Design using this type of input, if inappropriate, can then lead to incorrect design solutions. These SRP sections are concerned with design parameters and also with analysis methods. The detailed guidance about analysis methods in SRP sections 3.7.2 and 3.7.3 may also need to be reevaluated for a deeply embedded SMR.

Table 1-2 Category Two—Documents for Which Modest Changes May Be Desired (continued)

Category	Short Descriptor	Name	Rationale for Categorization	Observations/Comments/ Concerns
NUREG-0800 Standard Review Plan (SRP) Sections (continued)	SRP 3.8.3 *(see Section 1.5.12 for additional discussion)*	Concrete and Steel Internal Structures of Steel or Concrete Containments	This SRP section specifically calls out certain features of LWR containments that may or may not be relevant to SMRs, which are likely to have internals with significantly smaller size and mass. However, any changes to the SRP section are likely to be modest.	SRP deals extensively with reactors of different scales and likely different features (pressurized-water reactors [PWRs] and boiling-water reactors [BWRs]).

Table 1-2 Category Two—Documents for Which Modest Changes May Be Desired (continued)

Category	Short Descriptor	Name	Rationale for Categorization	Observations/Comments/ Concerns
NUREG-0800 Standard Review Plan (SRP) Sections (continued)	SRP 3.8.4 *(see Section 1.5.13 for additional discussion)*	Other Seismic Category I Structures	This SRP section seems to have broad applicability to SMRs but, without careful review, a judgment cannot be supported. The text has much that is specific to LWRs but also has sections that can apply broadly to “other” structures. Perhaps more specificity for SMRs is needed. However, any changes to the SRP section are likely to be modest.	Load combinations are given that may have been derived with specific designs in mind. Moreover, the SRP calls for use of damping ratios from tables in RG 1.61 that are not applicable for base-isolated designs (see evaluation of RG 1.61 in Table 3 for more details).
	SRP 3.8.5 *(see Section 1.5.14 for additional discussion)*	Foundations	The treatment of relationships between adjacent structures may not be generic.	The relevance of certain foundation issues needs to be determined for any specific SMR design. Also, computer codes will need to be assessed.

Table 1-2 Category Two—Documents for Which Modest Changes May Be Desired (continued)

Category	Short Descriptor	Name	Rationale for Categorization	Observations/Comments/ Concerns
NUREG-0800 Standard Review Plan (SRP) Sections (continued)	SRP 3.9.1 *(see Section 1.5.15 for additional discussion)*	Special Topics for Mechanical Components	Peripherally related, mostly technology-neutral	Some of the discussion of the SRP review of core supports and reactor internals may not be fully technology neutral. See Section 1.5.15 for a further discussion.
	SRP 3.9.2 *(see Section 1.5.16 for additional discussion)*	Dynamic Testing and Analysis of Systems, Structures, and Components	This SRP section seems to have broad applicability to SMRs but, without careful review, a judgment cannot be supported. However, any changes to the SRP section are likely to be modest.	
	SRP 3.9.3 *(see Section 1.5.17 for additional discussion)*	ASME Code Class 1, 2, and 3 Components and Component Supports, and Core Support Structures	The treatment of core supports may not be generic.	

Table 1-2 Category Two—Documents for Which Modest Changes May Be Desired (continued)

Category	Short Descriptor	Name	Rationale for Categorization	Observations/Comments/ Concerns
NUREG 0800 Standard Review Plan (SRP) Sections (continued)	SRP 3.9.4 *(see Section 1.5.18 for additional discussion)*	Control Rod Drive Systems	The treatment of hydraulic vs. electromagnetic CRD systems vs. other possible systems may not be generic.	
Consensus Codes and Standards	None			

1.4.3 Category Three, Important Changes May Be Desired

The LBNL team's evaluation concluded that a number of the documents may require some important changes in order that they could be used in the NRC regulatory process for an SMR (small modular reactor). The list of documents in this category is in Table 1-3. Table 1-3 also contains the rationale for each item's having been placed into this category.

The entries in Table 1-3 include the following NRC documents:

RG 1.29

RG 1.61

SRP 3.2.1

SRP 3.8.1

SRP 3.8.2

SRP 3.9.5

NOTE: "RG" is a "Regulatory Guide" and "SRP" is a "Standard Review Plan Section."

Table 1-3 Category Three—Documents for Which Important Changes May Be Desired

Category	Short descriptor	Name	Rationale for categorization	Observations/Comments/ Concerns
NRC Regulations	None			
Regulatory Guides	RG 1.29 *(see Section 1.6.1 for additional discussion)*	Seismic Design Classification	The list of SSCs identified in Section C, “Regulatory Position,” of this RG may not be inclusive enough to deal with all of the SSCs in proposed SMRs, with their significantly smaller size and mass and different types of SSCs. Without further study, it is not clear whether the changes would be major or only modest.	RG appears to be technology-specific and applies primarily to LWRs and structures of similar scale.
	RG 1.61 *(see Section 1.6.2 for additional discussion)*	Damping Values for Design of Nuclear Power Plants	It is not entirely obvious that the guidance on damping values applies to all of the constituent parts of an SMR with its significantly smaller size and mass. Without further study, it is not clear whether the changes would be major or only modest.	For base-isolated structures, the typical equivalent damping ratio could be as high as 30 percent or more. The values listed in Tables 1 and 2 for SSE and operating-basis earthquake are very low in comparison. Such restrictive regulation could likely discourage the use of innovative earthquake-protection technologies that adopt high damping to suppress displacements.

Table 1-3 Category Three—Documents for Which Important Changes May Be Desired (continued)

Category	Short descriptor	Name	Rationale for categorization	Observations/Comments/ Concerns
NRO Interim Staff Guidance	None			
NUREG-0800 Standard Review Plan (SRP) Sections	SRP 3.2.1 *(see Section 1.6.3 for additional discussion)*	Seismic Classification	This SPR section specifically calls out certain features of LWRs that may or may not be relevant to SMRs. It also refers in important places to RG 1.29, which itself may not be fully adequate for SMRs. Without further study, it is not clear whether the changes to this SRP section would be major or only modest.	Numerous references are made to RG 1.29, which deals primarily with LWRs.
	SRP 3.8.1 *(see Section 1.6.4 for additional discussion)*	Concrete Containment	This SRP section specifically calls out certain features of LWR containments that may or may not be relevant to SMRs. Without further study, it is not clear whether the changes to this SRP section would be major or only modest.	The concern is frequent references to RG 1.136 where load combinations with unclear origins are cited. These load combinations may have been derived for LWRs.
	SRP 3.8.2 *(see Section 1.6.5 for additional discussion)*	Steel Containment	This SRP section specifically calls out certain features of LWR containments that may or may not be relevant to SMRs. Without further study, it is not clear whether the changes to this SRP section would be major or only modest.	The concern is constant reference to RG 1.57 where load combinations with unclear origins are cited. These load combinations may have been derived for LWRs.

Table 1-3 Category Three—Documents for Which Important Changes May Be Desired (continued)

Category	Short descriptor	Name	Rationale for categorization	Observations/Comments/ Concerns
NUREG-0800 Standard Review Plan (SRP) Sections (continued)	SRP 3.9.5 *(see Section 1.6.6 for additional discussion)*	Reactor Pressure Vessel Internals	This SRP section specifically calls out certain features of reactor “internals” that may or may not be relevant to SMRs. Without further study, it is not clear whether the changes to this SRP section would be major or only modest.	
Consensus Codes and Standards *(see Section 1.7 for additional discussion)*	ASCE 4-98	Seismic Analysis of Safety-Related Nuclear Structures	This standard’s design criteria were developed with large LWRs specifically in mind. It probably applies directly to SMRs, but a careful review would be needed to determine this.	
	ASCE 43-05	Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities	This standard’s design criteria were developed with large LWRs specifically in mind. It probably applies directly to SMRs, but a careful review would be needed to determine this.	

Table 1-3 Category Three—Documents for Which Important Changes May Be Desired (continued)

Category	Short descriptor	Name	Rationale for categorization	Observations/Comments/ Concerns
Consensus Codes and Standards (continued)	ASME-ANS RA-Sa	Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications	This probabilistic risk assessment (PRA) methodology standard was written to address large operating LWRs. The ASME-ANS Joint Committee on Nuclear Risk Management (JCNRM), which revises and maintains the PRA standards, is currently considering changes that would address this issue of the applicability of their current PRA standard(s) to SMRs. It is possible that the JCNRM may support some changes in the future along these lines.	
	ASME B&PV code	Boiler and Pressure Vessel Code	This entire complex set of codes would need to be examined with SMRs in mind. Review of the ASME BPVC was determined to be outside the scope of this project.	

1.5 Evaluation of Each Regulatory Document (from Table 1-2) for Which Modest Changes May Be Desired

1.5.1 Regulatory Guide 1.57, "Design Limits and Loading Combinations for Metal Primary Reactor Containment System Components" (Revision 1, March 2007)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:

Most of the guidance in Regulatory Guide 1.57 seems broadly applicable to any type or size of power reactor. It is mostly technology-neutral. Specifically:

- The methods for response analysis seem to apply equally to any NPP.
- The design limits and the supporting rationale seem to apply equally to any NPP.
- The load-combination requirements seem to be technology-neutral.

Concerns:

(1) The RG text itself contains a warning in the first paragraph of the "Background" (Section B, page 3), as follows:

> *However, the existing industry codes and standards are based on the current class of light-water reactors and, as such, may not adequately address design and construction features of the next generation of advanced reactors.*

One paragraph later, the text says as an additional warning:

> *While this regulatory guide is only directly applicable to light-water reactor metal containments, the principles may be applied to non-light water reactor containments, subject to review by the NRC.*

Moreover, a few specific provisions do not appear to be technology-neutral or at least will require the NRC staff's further evaluation to determine this.

(2) A sentence in the eighth paragraph under "Background" (page 4) states:

> *The effects of natural phenomena other than earthquakes, such as tornadoes, hurricanes, and floods, are not considered in this guide, because a Category I concrete shield building typically protects the steel containment from the effects of tornadoes, hurricanes, and floods occurring outside the shield building.*

This sentence contains the inference that a steel containment covered by this RG is contemplated as "typically" having a surrounding "concrete shield building." This is clearly not technology-neutral, and the entire issue will need to be revisited if an SMR design has a different overall containment design. Therefore, the NRC should consider revising this section to make it applicable to all potential SMR designs.

(3) The following load-combination provisions are for loads arising from metal-water reactions:

  (a) Concerning gas loads, the provision in section 1.2.3.1(6) is for pressure testing of a containment with carbon-dioxide inerting. The equation therein contains a factor of1.10 for the load combination that includes Pg 3 (the pressure from inerting) when pressure testing is conducted. Regulatory Guide 1.7 is referred to for Pg 3. For the much smaller containment of a typical SMR, it is not clear whether this provision including the factor of 1.10 should apply or would need to be revisited.

  (b) Concerning the loads arising from a post-accident hydrogen control system, combined with normal gas loads, the load-combination provision in section 1.2.3.1(5) that includes Pg 3 again would need to be revisited if such a system were to be part of the design of an SMR.

For both of these issues (a) and (b), if review confirms that the issue is important, then the issue could be addressed either by revising the section technically or by including wording that notes a case-by-case review is appropriate if an SMR design is under review.

1.5.2 Regulatory Guide 1.122, "Development of Floor Design Response Spectra for Seismic Design of Floor-Supported Equipment or Components" (Revision 1, 1978)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
The guidance in the RG seems mostly to be broadly applicable to any type or size of power reactor. It is mostly technology-neutral.

Concerns:
One concern is that it is not entirely obvious that the RG's guidance on development of floor design response spectra applies to a structure like an SMR with its significantly smaller size and mass. The NRC should review this technical issue and consider revising the SRP section, if appropriate. However, any changes in the guidance are likely to be modest.

The RG text (Section B.2, page 2) asks for the use of the square root of sum of squares method (SRSS method) to combine floor spectral ordinates. It appears that this provision was written with a specific piece of equipment in mind that behaves like a single degree of freedom system within a much larger structure. It ignores structure-equipment interaction and may not be generic enough to encompass pieces of equipment with more complex dynamic behavior. Also, the use of the SRSS combination rule may not be appropriate if the equipment in question exhibits closely spaced modal frequencies. This is probably because the RG was written before the development of more recent modal combination rules (e.g., complete quadratic combination or CQC) that incorporate correlation coefficients.

Whether this concern is important for floor spectra calculated for a much smaller SMR structure is at least worthy of investigation. The NRC should review this technical issue and consider revising the SRP section technically, if appropriate, or by including wording that notes that a case-by-case review is appropriate if an SMR design is under review. On balance, any required changes to make the SRP text technology-neutral are likely to be modest.

1.5.3 Regulatory Guide 1.132, "Site Investigations for Foundations of Nuclear Power Plants" (Revision 2, October 2003)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
Most of the guidance in the regulatory guide seems broadly applicable to any type or size of power reactor. It is mostly technology-neutral.

Concerns:
One concern involves the spacing between borings called for in the text. Specifically, Appendix D ("Spacing and Depth of Subsurface Explorations and Safety-Related Foundations") calls for 30 m (or an area of 900 m^2) between borings under "larger, heavier structures, such as the containment and auxiliary buildings." This spacing may be too large for SMRs with a small footprint. A smaller boring spacing may be necessary to characterize the subsurface profile, especially if the site is heterogeneous.

Whether this is a concern is not clear, and may require case-by-case evaluation for any specific SMR design to determine if the SRP section is applicable without modification.

A second concern involves the requirement in Appendix D of RG 1.132, "Spacing and Depth of Subsurface Explorations for Safety-Related Foundations," for boring to a minimum depth of penetration (33 feet below the foundation). For an SMR that will be deeply or fully embedded, this boring-depth requirement would need to be reevaluated on a case-by-case basis.

Additional concerns are the minimum percentage of borings that would be required to reach the maximum required depth, and the extent of subsurface exploration that needs to be accomplished, to provide reasonable coverage for understanding subsurface stability and for understanding the three-dimensional distribution of geological features.

1.5.4 Regulatory Guide 1.136, "Design Limits, Loading Combinations, Materials, Construction, and Testing of Concrete Containments" (Revision 3, March 2007)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
Most of the guidance in the regulatory guide seems broadly applicable to any type or size of power reactor. It is mostly technology-neutral.

Concerns:

(1) In section C.5.B(3), the relevance to any specific SMR of the 310 kPa pressure load as a potential challenge to the structure would need to be checked. This is especially true if the SMR design uses a different coolant (e.g., gas or liquid metal) or a different fuel so that zirconium-water reactions as a driver of post-accident internal pressure would not be the concern.

(2) As discussed just above (Section 1.5.1) for RG 1.57, the relevance of some load combinations to any specific SMR needs to be checked. The discussion under RG 1.57 explains the issue. That discussion is repeated here for clarity in italics as follows (copied from above):

There are some load-combination provisions for loads arising from metal-water reactions.

a) *Concerning gas loads, the provision in section 1.2.3.1(6) is for pressure testing of a containment with carbon-dioxide inerting. The equation therein contains a factor of 1.10 for the load combination that includes P_{g3} (the pressure from inerting), when pressure testing is conducted. Regulatory Guide 1.7 is referred to for P_{g3}. For the much smaller containment of a typical SMR, whether this provision including the factor of 1.10 should apply is not clear and would need to be revisited.*

b) *Concerning the loads arising from a post-accident hydrogen control system, combined with normal gas loads, the load-combination provision in section 1.2.3.1(5) that includes P_{g3} again would need to be revisited if such a system were to be part of the design of an SMR.*

1.5.5 Regulatory Guide 1.138, "Laboratory Investigations of Soils and Rocks for Engineering Analysis and Design of Nuclear Power Plants" (December 2003 version)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:

The text of this regulatory guide seems to be quite generic, involving as it does guidance on laboratory testing of soils and rocks retrieved from a field site.

Concerns:

The issue that might require special evaluation is when an SMR design is deeply embedded. This is because the laboratory testing program in RG 1.138, "Laboratory Investigations of Soils and Rocks for Engineering Analysis and Design of Nuclear Power Plants," must "work together" with the field sample-taking program usually accomplished under guidance described in other RGs. The sampling program would be different in important ways for a deeply embedded structure because the coverage of the required samples could usually be quite different. This may mean that blindly following this RG "as if" this were a large LWR near the surface could lead to incorrect insights.

1.5.6 Regulatory Guide 1.142, "Safety-Related Concrete Structures for Nuclear Power Plants (Other than Reactor Vessels and Containments.)" (Revision 2, November 2001)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
Although the text of this regulatory guide refers to certain attributes specific to large LWRs, none of the text is constraining in any way.

Concerns:
According to Regulatory Position 5, the frequency for in-process compressive strength tests of concrete is to be one test per 100 cubic yards. However, the effect of variability in concrete strength may be higher for smaller SMR structures than it would be for a large LWR. Consequently, for an SMR, the testing frequency may need to be higher on a case-by-case basis. The guidance on sampling and testing frequencies in the American Concrete Institute standard ACI-349 may be applicable in such cases.

1.5.7 Regulatory Guide 1.198, "Procedures and Criteria for Assessing Seismic Soil Liquefaction at Nuclear Power Plant Sites" (November 2003 version)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
The regulatory guide is concerned with liquefaction, and most of the guidance (perhaps all of it) seems to be generic and applicable to any site.

Concerns:
For a deeply-embedded SMR, the way liquefaction phenomena might affect the structure could be quite different if the liquefaction layer was close to the bottom of the embedded structure and all the more so if the layer was located above the bottom of the embedded structure. This means that following the guidance in this regulatory guide might not cover fully all of the issue(s) that might affect the structure vis-à-vis liquefaction.

1.5.8 DC/COL-ISG-17 "Interim Staff Guidance on Ensuring Hazard-Consistent Seismic Input for Site Response and Soil Structure Interaction Analyses"

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
This interim staff guidance (ISG) is concerned with hazard-consistent seismic input, and most of the guidance (perhaps all of it) seems to be generic and applicable to any site.

Concerns:
For a deeply-embedded SMR, the way ISG-17 suggests that an applicant do this analysis should ensure the development of a consistent seismic input for response and soil structure interaction (SSI) analyses. The input motions at the foundation level, when convolved up to through the soil column, must bound the free-field performance-based surface response

spectrum (PBRS) at the surface. The surface PBRS at the surface provides a means for checking the adequacy of input motions at the foundation as well as the three deterministic soil columns. For deeply embedded structures, the number and location of check points may need to be different than those required for a surface-sited large LWR. In particular, for deeply-embedded SMR structures, it may be necessary to develop the PBRS at intermediate depths as well to have these available to check that the deterministic soil columns used for SSI analyses meet the required goal.

1.5.9 SRP 2.5.2, "Vibratory Ground Motion" (March 2007 version)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
The SRP section is concerned with developing vibratory ground motions to be used in the design and the safety analysis. Most of this SRP section would be applicable directly for an SMR.

Concerns:
The way an inclined seismic shear wave (both the vertical and horizontal components) propagates may be more important for a deeply-embedded SMR than for a large LWR at or near the surface, and the analysis method must account for this properly. SRP section 2.5.2.5 states, in part, *"Where vertically propagating shear waves may produce the maximum ground motion, a one-dimensional equivalent-linear analysis or nonlinear analysis may be appropriate and is reviewed in conjunction with geotechnical and structural engineering. However, site characteristics (such as a dipping bedrock surface, topographic effects or other impedance boundaries) may require that the analyses are also able to account for inclined waves."* This leads to the caveat that for a deeply embedded SMR, the effect of inclined seismic waves may be more important, and the method for determining the ground motion response spectrum (GMRS) needs to be carefully considered.

1.5.10 SRP 2.5.4, "Stability of Subsurface Material and Foundations" (May 2010 version)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
The SRP section is concerned with understanding the stability of material and foundations in the subsurface. Most of this SRP section would be applicable directly for an SMR.

Concerns:
For a deeply-embedded SMR, the following issues need to be addressed in a way potentially different from how they would be handled for a large LWR at or near the surface. The issues are:

(1) The construction of the deep excavation may affect the surrounding soil properties that are used in the analysis and design of the foundation and plant structures. (See SRP section 2.5.4.5.)

(2) The effect of dewatering, both during and after construction, considering the higher head and volume of ground water, may be more significant to the structures than its effect for LWRs. (See SRP section 2.5.4.6.)

(3) Adequate measuring points to monitor settlement throughout the depth of the embedded structure may be needed. (See SRP section 2.5.4.10.)

1.5.11 SRP 3.7.1 ("Seismic Design Parameters"), 3.7.2 ("Seismic System Analysis"), and 3.7.3 ("Seismic Subsystem Analysis") (March 2007 versions)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
These SRP sections seem to have broad applicability to SMRs, but some of the guidance may not be applicable.

Concerns:
For a deeply-embedded SMR, the technical review approaches in these SRP sections may need to be re-examined. In particular, the development of a consistent seismic input for response and SSI analyses and then for design of a specific SSC can be different than for a large LWR on or near the surface. A number of issues require reevaluation, and the application of these SRP sections without such a reevaluation could lead to a compromise in the design margins. One issue is that the way the soil column interacts with a deeply-embedded structure can be quite different, which affects how the seismic energy propagates further into the structure. Design using this type of input, if inappropriate, can then lead to incorrect design solutions. The staff review, guided by the SRP, needs to identify these if they are present.

These SRP sections are concerned with design parameters and also with analysis methods. The detailed guidance about analysis methods in SRP sections 3.7.2 and 3.7.3 may also need to be reevaluated for a deeply-embedded SMR.

1.5.12 SRP 3.8.3, "Concrete and Steel Internal Structures of Steel or Concrete Containments" (March 2007 version)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
This SRP section deals extensively with reactors and containments of different scales and different features (e.g., existing licensed large PWRs and BWRs.) This means that it is likely that most if not all of it can be used for SMRs without change.

Concerns:
This SRP section's text (throughout both Section I and Section II) specifically calls out certain features of LWR containments that were written with today's large LWR containments (and their typical internal structures) in mind. An SMR is likely not only to have a significantly smaller containment but also (by extension) significantly smaller internal structures.

A section of the SRP on modular walls (in the final paragraph of Section I.1, on page 6) calls for case-by-case evaluation. This provision means that SMRs can in principle be accommodated without a change to the text, albeit without any specific guidance.

Overall, the technical requirements of this SRP section are applicable to SMR internal structures. However, because the text calls out large LWR features and provisions in several places, a reviewer must be cautious to read the intent of the requirements carefully. It would be prudent for the NRC to consider revision of this SRP section to address the concerns as expressed above so that the section can apply to all potential SMR designs.

1.5.13 SRP 3.8.4, "Other Seismic Category I Structures" (March 2007 version)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
This SRP section seems to have broad applicability to SMRs although a careful review would be needed when an evaluation is done for a specific SMR and its several "other" structures.

Concerns:
The text has much that is specific to large LWRs along with sections that can apply broadly to "other" structures. However, the references to large LWRs seem easily adapted without loss of technical validity.

The only specific concern is for load combinations that may have been derived for specific "other structures" for large-LWR-related designs. (See Sections I.3 on page 4 and II.3 on page 9 of the SRP.)

It is also important to be cognizant of the recent issuance by ASME (in 2011) of a new section of the boiler and pressure vessel code (ASME III Division 5) applicable to high- temperature reactors. In preparation for review of an SMR design that may be developed using that code, this SRP section may require revision to cite this new code section as a reference, or perhaps it may need to be significantly re-written to address the code's provisions explicitly.

Overall, perhaps more specificity for SMRs would be needed if a special structure is under review for an SMR that is not under the "umbrella" of one of the several specific structures mentioned here. The NRC should review this technical issue and consider revising the SRP section. However, any changes to the SRP section are likely to be modest.

1.5.14 SRP 3.8.5, "Foundations" (March 2007 version)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
This SRP section seems to have broad applicability to SMRs.

Concerns:
The factors of safety on pages 9-10 may have been derived with large LWRs in mind. If so, revisiting them would be required. The NRC should review this technical issue and consider revising the SRP section technically, if appropriate, or by including wording that notes that a case-by-case review is appropriate if an SMR design is under review. This could be needed

especially for the case of closely spaced individual SMR foundations. However, any changes to make the SRP section technology-neutral would likely be minor.

1.5.15 SRP 3.9.1, "Special Topics for Mechanical Components" (March 2007 version)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
This SRP section seems to have broad applicability to SMRs.

Concerns:
Part of the discussion of the SRP review of core supports and reactor internals was clearly developed with large LWRs in mind. This includes how various transients that could affect loads on core supports and internals are to be treated (see Section II, "SRP Acceptance Criteria," bullet 1 on page 4). These may not be generic. The NRC should review this technical issue and consider revising the SRP section technically, if appropriate, or by including wording that notes that a case-by-case review is appropriate if an SMR design is under review. However, any changes to make the SRP section technology-neutral would likely be minor.

It is also important to be cognizant of the recent issuance by ASME (in 2011) of a new section of the boiler and pressure vessel code (ASME III Division 5) applicable to high- temperature reactors. In preparation for review of an SMR design that may be developed using that code, this SRP section may require revision to cite this new code section as a reference, or perhaps it may need to be significantly re-written to address the code's provisions explicitly.

1.5.16 SRP 3.9.2, "Dynamic Testing and Analysis of Systems, Structures, and Components" (March 2007 version)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
This SRP section seems to have broad applicability to SMRs.

Concerns:
The SRP's text has some discussion of components that are specific to large LWRs (e.g., see Section I.3 on page 4, Section I.4 on page 6 and Section II, "SRP Acceptance Criteria," 1.B on page 10). They are used generally as examples and, to that extent, no problem should exist in applying this SRP section to SMRs. Also, some of the SRP text seems to assume that major components are outside the primary vessel. This text may not be directly applicable to SMR designs in which those same major components are inside the primary vessel (see Section II, "SRP Acceptance Criteria" 2.A, on pages 10-11 and Section III.2A on page 26 as possible examples.) The NRC should review this technical issue and consider revising the SRP section technically, if appropriate, or by including wording that notes that a case-by-case review is appropriate if an SMR design is under review. However, if any changes are needed to make this SRP section technology-neutral, they would likely be minor.

1.5.17 SRP 3.9.3, "ASME Code Class 1, 2, and 3 Components and Component Supports, and Core Support Structures" (March 2007 version)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
This SRP section seems to have broad applicability to SMRs.

Concerns:
The SRP has several references to specific PWR and/or BWR SSCs (this occurs throughout). Although the text is specific in some cases to large LWRs, the SRP section can be used for SMRs with minor adaptations (to make it technology-neutral). This should not present a problem, and there appears to be no ambiguity. The NRC should consider revising this SRP section to accomplish this.

For core designs that are very different from LWR cores (e.g., for a gas-cooled reactor or a liquid-metal reactor), the core support section of this SRP would need to be reviewed for applicability and possibly revised.

It is also important to be cognizant of the recent issuance by ASME (in 2011) of a new section of the boiler and pressure vessel code (ASME III Division 5) applicable to high- temperature reactors. In preparation for review of an SMR design that may be developed using that code, this SRP section may require revision to cite this new code section as a reference or perhaps it may need to be significantly re-written to address the code's provisions explicitly.

1.5.18 SRP 3.9.4, "Control Rod Drive Systems" (March 2007 version)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
This SRP section seems to have broad applicability to SMRs.

Concerns:
This SRP section is definitely not technology-neutral. It contains several sections specific to hydraulic or electromagnetic control rod drive systems (CRDS) that are clearly tailored to a review of CRDS for large PWRs or BWRs. However, the text does contain a sentence (page 2) that states plainly how other technologies would be treated:

> *If other types of CRDS are proposed or if new features that are not specifically mentioned here are incorporated in CRDS of current types, the information supplied for the new systems or new features should be similar to the information described below.*

Given the above, perhaps no modification is needed to the text of this SRP section. Alternatively, if a quite different CRDS technology for an SMR is proposed that will come into widespread use, then perhaps some specific areas of review for that technology should be described in the SRP itself. In that case, the NRC should consider revising this SRP section to accomplish this. Such changes should be minor.

Another possible concern is that this SRP section specifically mentions that "portions of the CRDS are part of the reactor coolant pressure boundary" (see Section I in the first paragraph on page 1 and then elsewhere in subsequent text). This may or may not be true for the CRDS for any specific new SMR design. If review confirms that the issue is important, then it could be addressed either by revising the SRP section technically or by including wording that notes that a case-by-case review is appropriate if an SMR design is under review.

1.6 Evaluation of Each Regulatory Document (from Table 1-3) for Which Important Changes May Be Needed

1.6.1 Regulatory Guide 1.29, "Seismic Design Classification" (March 2007 version)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
Much of this SRP section seems to have broad applicability to SMRs but with some important exceptions.

Concerns:
The classification scheme described in this regulatory guide contains many specific features that are tailored to large-LWR technology, and some of the entries in Section C probably do not apply to SMRs. More importantly, the scope herein is probably not sufficient to cover all of the features of a typical SMR with its smaller overall design, different design features, and reduced mass and size. It is judged that important changes are probably needed to this RG—mainly throughout Section C—but that changes or adaptations may need to be made on an SMR-design-specific basis. This issue could be addressed either by revising the SRP section technically or by including wording that notes that a case-by-case review is appropriate if an SMR design is under review.

1.6.2 Regulatory Guide 1.61, Damping Values for Design of Nuclear Power Plants" (March 2007 version)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
Much of this SRP section seems to have broad applicability to SMRs.

Concerns:
This regulatory guide has structural damping values that may not apply to all of the constituent parts of an SMR with its significantly smaller size and mass (see Section C, Tables 1 and 2). Also, for reactors for which major components (such as large pumps and heat exchangers) are totally submerged inside the vessel, the damping values appropriate for large LWRs may not apply. Modifications to accommodate these concerns could be significant rather than modest in their extent and importance. This issue could be addressed either by revising the SRP section technically or by including wording that notes that a case-by-case review is appropriate if an SMR design is under review.

The other damping values in the SRP, other than for structural damping, seem fully applicable to an SMR. These include damping values for constituent systems like piping (Table 3), electrical systems (Table 4), HVAC (Table 5), and mechanical and electrical components (Table 6).

1.6.3 SRP 3.2.1, "Seismic Classification" (March 2007 version)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
This SRP section seems to have broad applicability to SMRs.

Concerns:
This SRP section contains some specific text applicable to large BWRs that is directed especially toward that technology (see Sections III.4 and IV.5). If an SMR design was a smaller BWR, the applicability of this text to such a design would definitely need reconsideration.

In addition, this section contains numerous cross-references to Regulatory Guide 1.29, which also needs re-evaluation before it can be applied to SMRs (please refer to the discussion of RG 1.29 just above).

1.6.4 SRP 3.8.1, "Concrete Containment" (March 2007 version)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
Some of this SRP section seems to have broad applicability to SMRs

Concerns:
Some of the text in SRP 3.8.1, "Concrete Containment," is clearly written with large LWRs in mind. For example, the following is on page 2:

> *Various geometries have been used for these containments. The geometry most commonly encountered is an upright cylinder topped with a dome and supported on a flat concrete base mat. Although applicable to any geometry, the specific provisions of this SRP section are best suited to the cylindrical-type containment topped by a dome. Reviews of containments with other types of geometry will make the necessary deviations from this SRP section on a case-by-case basis.*

Another possible concern is related to load combinations (see Section II, "SRP Acceptance Criteria", paragraph 3, pages 10-12). For the smaller SMR designs, some of the considerations herein may not apply, but this would need to be evaluated on a case-by-case basis to determine if the SRP section is applicable without modification.

Also, some of the loading discussions in the same part of Section II may need to be reconsidered for the significantly smaller SMR designs.

For both of these concerns, the concern could be addressed either by revising the SRP section technically or by including wording that notes that a case-by-case review is appropriate if an

SMR design is under review. Consideration should be given to moving this guidance into a Regulatory Guide.

1.6.5 SRP 3.8.2, “Steel Containment” (March 2007 version)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
Some of this SRP section seems to have broad applicability to SMRs.

Concerns:
Much of the text in SRP 3.8.2, “Steel Containment,” is not generic but rather is specific to large LWRs. It is possible that a wholesale revision of many sections of the SRP section will be necessary to apply to the steel containment of an SMR, depending on the design. In particular, the long section on load combinations (pages 10 to 15) seems to have been written with large LWRs specifically in mind. This concern could be addressed either by revising the SRP section technically or by including wording that notes a case-by-case review is appropriate if an SMR design is under review.

1.6.6 SRP 3.9.5, “Reactor Pressure Vessel Internals” (March 2007 version)

Evaluation of the applicability to SMRs on individual foundations

Positive findings:
Some of this SRP section seems to have broad applicability to SMRs.

Concerns:
Some of the text in SRP 3.9.5, “Reactor Pressure Vessel Internals,” is not generic but rather is specific to large LWRs. Some of the SRP text seems to assume that major components are outside the primary vessel; this text may not be directly applicable to some SMR designs in which those same major components are inside the primary vessel. A wholesale revision of some sections of the SRP section may be necessary to apply to the internals of an SMR, depending on the design. In particular, Appendix A (covering potential adverse flow effects) was written with large LWRs specifically in mind. How much of this might apply to a specific SMR design is not clear, but a lot of it would need to be rewritten. This concern could be addressed either by revising the SRP section technically or by including wording that notes a case-by-case review is appropriate if an SMR design is under review.

It is also important to be cognizant of the recent issuance by ASME (in 2011) of a new section of the boiler and pressure vessel code (ASME III Division 5) applicable to high-temperature reactors. In preparation for review of an SMR design that may be developed using that code, this SRP section may require revision to cite this new code section as a reference or perhaps it may need to be significantly re-written to address the code’s provisions explicitly.

1.7 Consensus Codes and Standards

In Section 1.3.6, several industry-wide consensus codes and standards were identified as perhaps having been written with large LWRs in mind. This means that their applicability to

SMRs would require evaluation. Those codes and standards include ASCE 4-98, ASCE 43-05, ASME-ANS RA-Sa-2009 (the PRA methodology standard), and certain selected parts of the ASME boiler and pressure vessel code. As noted above, ASME has recently issued a new division to Section III of the boiler and pressure vessel code to address some non-LWR reactor designs.

Each of these consensus standards is long, complex, and written with large LWRs in mind (other than the new division to Section III of the ASME code). An evaluation of where each of them applies to SMRs, where it does not, and where an ambiguity exists was not attempted here.

1.8 Summary for Section 1

The evaluation in Section 1 of this report has presented a categorized list of NRC documents and industry codes and standards relevant to the areas of seismic engineering, structural engineering, geotechnical engineering, and relating topics. The categorization is based on a technical judgment by the Lawrence Berkeley National Laboratory team as to whether or not the document would require changes so that it could be used for SMRs, recognizing that in almost every case the document has been developed and used based on its applicability to current large LWRs.

The categorization placed the various documents into three categories as noted above in Section 1.2. Essentially, the three categories could be described as "*no change needed,*" "*modest and non-controversial changes may be needed,*" and "*important changes may be needed*." A rationale is provided for each categorization decision in Section 1.4, and a detailed evaluation for the second and third categories is found in Sections 1.5 and 1.6, respectively.

Where appropriate, a recommendation is made for a modification so that the document could be used for the safety review of an SMR.

2. EVALUATION OF SEISMIC-STRUCTURAL SIMULATION TOOLS FOR APPLICABILITY TO SMALL MODULAR REACTORS

2.1 Introduction to Section 2

Section 2 of this report provides the results of one part of "Soil Structure Interactions for Small Modular Reactors on Individual Foundations," a project carried out at the University of California's Lawrence Berkeley National Laboratory (LBNL) and sponsored by the U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research.

The evaluation in Section 2 was focused on two tasks:

Identification of Applicable NRC-approved simulation tools

In this task, the project team compiled a library of widely used analysis tools in the areas of structural, geotechnical, and seismic engineering. Each simulation tool was studied to determine how industry designers and analysts have used it for large LWRs and how the NRC regulatory staff has interpreted the results of the simulations. The simulation tools that were identified are those used to evaluate seismic issues as used in structural engineering, geotechnical engineering, and other related engineering areas. A list of the tools and simulations identified has been compiled in this report.

Evaluation of Applicability to Small Modular Reactors

In this task, the project team analyzed each simulation tool identified above for applicability to small modular reactors (SMRs). The areas examined included (a) structural engineering, (b) geotechnical engineering, and (c) seismic engineering including soil-structure interaction. The hazard being studied was large earthquakes.

Limitation: The scope covers the relevant analysis tools that are most widely used in the industry. Some of these tools have been NRC-endorsed for specific purposes, but others have not been endorsed.

Limitation: The LBNL team and the NRC staff agreed that identifying specific SMR designs was not necessary ─ that an evaluation could be performed that would be more generically applicable to all of the different types of SMRs. However, this may or may not be true for all SMR designs.

2.2 The Work – Two Phases

The first phase of the work reported here was the identification of a list of simulation tools (codes) for evaluation in the second phase. The second phase was the evaluation.

2.2.1 The First Phase, Identification

The first phase began with a series of contacts with various industry experts, practicing engineers, and several NRC staff members who either worked on nuclear power plant (NPP) seismic-structural-civil-engineering design and analysis or reviewed designs and analyses done by others. The purpose of this phase was to identify those simulation tools that had been used most commonly in the design and analysis of large LWRs with the application in mind being a submittal for NRC staff regulatory review and approval. In effect, this meant identifying a list of those simulation tools that the staff was sufficiently familiar with and aware of in terms of strengths, limitations, inputs, and results. In other words, this phase involved a search for simulation tools that had been used frequently in industry submittals to the NRC and for which dockets exist containing favorable NRC staff reviews of analyses using the simulation tool. These favorable reviews would reflect the reputation or “pedigree” (formal or informal) the simulation tool enjoys in the community of practitioners.

The LBNL project team had expected that large variations would exist between the “lists” of the various experts (i.e., that little overlap would be evident among the several “lists”). However, this was not the case. Specifically, although some simulation tools are not widely used (i.e., limited perhaps to a single user or a single company), the suite of simulation tools in widespread use turned out to be almost the same list for everyone consulted.

Table 2-1 presents the final list of simulation tools that has been the subject of this evaluation.

In addition, the project team added the new analysis tool called “ESSI” (“Earthquake Soil Structure Interaction”) to its evaluation list. ESSI is under development by a team led by Boris Jeremic at LBNL and the University of California at Davis, and the NRC is supporting its development. Unlike the other analysis tools that were evaluated, ESSI is not in widespread use in the nuclear industry because it is still being developed. However, because the ESSI code is being developed under NRC support as a publicly available code, it is included and therefore may be used in the future in evaluating SMRs. Dr. Jeremic separately evaluated the ESSI code for use with SMRs, and this is covered in a separate discussion below (see Section 2.2.7).

The second part of this identification task was to obtain a working version of each simulation tool that could be loaded into the project team’s in-house computers along with written material (i.e., a “manual”) that would serve to aid the project team as it exercised the simulation tool and evaluated it. This task was ultimately successful, but initial versions of some of the simulation tools the project team found were only available in “student versions” or “trial versions.” These more modest versions were typically sufficient to enable the project team to gain no more than superficial familiarity with the code; however, the project team did succeed in obtaining a more complete version of each simulation tool (see Table 2-1) and in getting it up and running. Again, this applies to all of the analysis tools except the ESSI simulation tool that was evaluated separately (see Section 2.2.7).

Table 2-1 - List of Simulation Tools Evaluated

ABAQUS	NASTRAN
ADINA	SAP 2000
ALGOR	SASSI
ANSYS	SHAKE91
GT STRUDL	SIMQKE-1
LS-DYNA	STARDYNE

Separate evaluation: ESSI

2.2.2 The Second Phase, Evaluation

The LBNL project team subjected each of the various simulation tools (codes) to an independent review. The team studied the manual, loaded the code up onto one of their computers, and performed various reviews of each code's capabilities (the ESSI was evaluated separately; see Section 2.2.7).

For each of the simulation tools that was examined, the project team asked a fundamental question: "Is there something about this code, as it is used for large-LWR design or analysis, that "would not work" for an SMR─some feature that would make it wholly or even partially unusable for the design or analysis of an SMR?"

The project team looked for specific features embedded in the code that might have been present specifically to enable design or analysis of a large LWR but that "would not work" for an SMR. These specific features could include large-LWR-specific or other approximations, scaling effects, specific data, assumptions, or some combination. In addition, the team tried to identify some way that an SMR user of the code might be led astray or might find that the code simply could not be used for a typical SMR design or analysis problem (or could be used only with one or more important compromises).

The approach taken was to search for element types, material models, boundary conditions, or analysis procedures of the analysis tool, if any, that would compel the project team to question the usefulness of the analysis tool for the design or analysis of an SMR. Initially, this meant studying the code manual or descriptive material to understand how the analysis tool had been developed, what physical principles or equations are embedded in it, and how the code produces its "results" or "outputs." This is, of course, the sort of examination and critical evaluation that any new user of any analysis tool must do before beginning to use that tool.

The most important part of the project team evaluation involved examining the physical principles and the equations on which the code is based. A key aspect of that work, in turn, was to understand the approximations embedded in the code itself. Because any analytical tool is only an abstraction of reality developed for a specific purpose, approximations will always be present─sometimes in the "physics," sometimes in the way the binning is done, sometimes in how the input data are specified or used, sometimes in the computational algorithm, or others.

The project team needed to understand these approximations before the SMR evaluation could be undertaken.

A crucial aspect of the SMR evaluation was examining the detailed way in which the code handles scale-dependent features such as dimensional or mass-dependent features. The project team had the benefit of details about one specific SMR design with actual masses and dimensions, but it used the information in a stylized way, not as a specific focus and also not by analysis of that particular SMR *per se*. The team instead tried to focus on the following broader question─if an SMR-type structure on its own foundation were the subject of the code's analysis instead of a large LWR, would any approximations introduced in the code itself make its analyses somehow "less valid," or "less accurate," or "more approximate?"

Clearly, for any specific problem, the analyst must generate a finite element method (FEM) model with the masses, dimensions, configuration(s), and so on. This must be done with great care because every analyst needs to be mindful of the adage "garbage in, garbage out." On this aspect, the team's inquiry was limited to exploring whether creating such an FEM model for an SMR structure with its different masses, dimensions, and so on was fully feasible and did not introduce problems within the parameters of the code and its instructions. It should be noted that this inquiry is different than asking specifically about how the FEM model is to be created (a question that was not important for the project team's purposes).

As the work began, the project team had no idea whether any of these simulation tools might suffer from one or more of these problems if used with an SMR-type design. Therefore, the team was pleasantly surprised when it found no such problems anywhere it looked.

2.2.3 Broad Conclusion

The LBNL project team's overall broad conclusion, reached separately for each of the simulation tools in Table 2-1, is that nothing in any of the codes would preclude a competent user from developing valid results and reaching valid conclusions about an SMR through employing that code for SMR design or analysis.

Of course, there are always *caveats* and warnings to consider. Any user of any simulation tool must be generally competent in understanding the underlying physics and engineering that have gone into the code. A user needs to understand the broad limitations of any code. No code can ever be a completely accurate way to describe any physical problem or situation. As mentioned above, any code is inevitably only an abstraction of the underlying reality developed for a specific purpose─in this case, a design purpose or an analysis purpose.

The next sections will present the project team's evaluations, one code at a time, to support this overall broad conclusion. Some of the discussions in the individual subsections below may seem repetitive because many of the issues and features that the team identified are common to several of the simulation tools. However, the fundamental feature of a code that makes it applicable (or not) to both large LWRs and the much smaller SMRs is the issue of how it scales. That is, the operative question is whether one or more scale-dependent features of the code allow the user to produce "valid" results for a large LWR but not allow for a smaller SMR because of "scaling" issues. The project team did not identify any such features.

There are other reasons why a code that "works" for a large LWR might not "work" for designing or analyzing an SMR-sized problem. As mentioned, specific data embedded in a code, or assumptions or approximations within it, might be a problem. The project team did not identify any such problems.

2.2.4 Analysis of an SMR Adjacent to One or More Others

The general concept behind deploying small modular reactors (SMRs) is that, because they are significantly smaller than a large LWR, a typical electric-generating station site would deploy more than 1─perhaps as many as 5 or 10─on a single site although not all would likely be built at the same time. A common strategy often discussed in the industry is to "stage" the construction of a number of these SMR units over several years, perhaps even over a decade or more.

This strategy presents the following analysis problem─specifically, the seismic-structural analysis of operating SMR #1 while SMR #2 is under construction nearby. Or perhaps SMRs #1, #2, etc. (up to #6) are operating while SMRs #7 and #8 are under construction nearby.

As background, analysis of the seismic safety of a configuration like this is now done routinely for large LWRs. Specifically, both in the United States and abroad, large-LWR sites exist today with one or more operating LWRs and a large construction project underway nearby to build a new large LWR, or sometimes two. The effect of the new plant on the safety of the existing operating unit(s)─both while the construction is underway and later when the new reactor is in operation─is a required analysis that must be done to ensure safety.

The project team's work here has tried to determine whether there is something about the smaller SMRs that would make this analysis problem more difficult or would mean that the analysis tools (codes) would be unable to carry out this analysis for a multiple-SMR site even though the analysis "works" for a multiple-LWR site.

The project team examined several analysis codes with this is mind and determined that the main technical issue for the analyst is "setting up the problem" correctly. After recognizing that this is a challenge for the multiple-LWR analysis problem, the team asked whether it could identify something special about the multiple-SMR problem.

After some deliberation, the project team has concluded that it can't identify anything like that. The codes themselves seem to be as adaptable to the SMR-type multiple unit analysis problems as to the analogous multiple-large-LWR problems. The team did not identify anything in the analysis tools themselves that would be problematical. In addition, the team did not identify any issues with the way the codes make approximations that might not apply to the multiple-SMR problem. Consequently, the team concluded that it need not be concerned about this issue.

One of the analysis tools, SASSI, may be different in this regard (see Section 2.2.6.9 below.) The way soil-structure-interaction (SSI) phenomena occur may be complex enough that the ordinary SSI tools like SASSI may have greater difficulty with the multi-unit analysis problem than is the case for the other analysis tools evaluated here. This issue is too complex to evaluate easily, and therefore the project team believes that the broad conclusion it has reached in the paragraph above about the other analysis tools may not apply to SASSI.

2.2.5 Discussion of Embedment Issues

SMR design concepts covering a very broad range of technologies are being discussed by the various industrial designers and vendors. Some concepts seem to contemplate placing the SMRs at or near the surface, while others discuss either partial embedment or perhaps even complete embedment below the surface. This has led the project team to consider whether the analysis tools being evaluated here would be applicable for analyzing an SMR design with significant or full embedment. (The modest embedments typical of large LWR construction, if used for an SMR, are not seen as an issue.)

No large LWR has ever been fully embedded (i.e., underground) although many of them are embedded partially (but almost never to a significant percentage.) The project team tried to determine whether something about the smaller SMRs would make this analysis problem particularly intractable. Moreover, the team tried to determine whether any specific analysis tool would suffer from an important technical problem if the SMR being analyzed were embedded.

The project team examined the several analysis codes with this in mind. The fact that the analysis would be for an SMR did not give rise to any identifiable technical problems.

The major concern in any analysis of an embedded structure─whether for a large LWR or a smaller SMR─is for the analyst to "set up the problem" appropriately, including the boundary conditions. Although this can be a challenge, it appears to be no different for an SMR than for a large LWR. The codes themselves seem to be as adaptable to an SMR-type embedment analysis problem as to the analogous large-LWR problem. The project team has not identified anything in the analysis tools themselves that would be problematical.

One of the analysis tools, SASSI, may be different in this regard (see Section 2.2.6.9 below). Soil-structure-interaction (SSI) phenomena may be very complex when soil is in direct contact around, for example, the vertical walls of a fully embedded cylindrical structure. Ordinary SSI tools like SASSI may have greater difficulty with a fully embedded structure than is the case for the other analysis tools evaluated here. This issue is too complex to evaluate easily. Consequently, the project team's broad conclusion may not apply to SASSI.

2.2.6 Code by Code Evaluations

Opening Note—Finite Element Method (FEM) Codes

A majority of the simulation tools (codes) that have been evaluated in this review are FEM (finite element method) codes. Therefore, it is worthwhile to provide a short general introduction to the approach to avoid repeating it under the discussion of each individual simulation tool.

The finite element method (FEM) (which in practical applications is often known as the "finite element analysis" [FEA] method) is a numerical technique for finding approximate solutions of partial differential equations (PDE) as well as integral equations under specific boundary conditions. The solution approach is based either on eliminating the differential equation completely (steady-state problems) or rendering the PDE into an approximate system of ordinary differential equations that are then numerically integrated using standard techniques such as Euler's method, Runge-Kutta, etc.

In modern engineering design, it is rare to find a project that does not require some type of finite element analysis. When not actually required, FEA can usually be used to improve a design. The practical advantages of FEA in stress analysis and structural dynamics have made it the accepted design tool for the last three decades. The greatest advantage of FEA is its ability to handle truly arbitrary geometry. Probably its next most important features are its abilities to deal with general boundary conditions and to include nonhomogeneous and anisotropic materials.

These features alone mean that the engineer can treat systems of arbitrary shape that are made up of numerous different material regions. Each material could have constant properties, or the properties could vary with spatial location. To these very desirable features can be added a large amount of freedom in prescribing the loading conditions and in the post-processing of items such as the stresses and strains. For elliptical boundary value problems, the FEA procedures offer significant computational and storage efficiencies that further enhance their use. These classes of problems include stress analysis, heat conduction, electrical fields, magnetic fields, ideal fluid flow, and others. FEA also gives the analyst and designer an important solution technique for other problem classes such as the nonlinear Navier-Stokes equations for fluid dynamics and for plasticity in nonlinear solids.

In a structural simulation, FEM helps tremendously in producing stiffness and strength visualizations and also in minimizing weight, materials, and costs. FEM allows detailed visualization of where structures bend or twist and indicates the distribution of stresses and displacements. FEM software provides a wide range of simulation options for controlling the complexity of both modeling and analysis of a system. Similarly, the desired level of accuracy required and associated computational time requirements can be managed simultaneously to address most engineering applications. FEM allows entire designs to be constructed, refined, and optimized before the design is manufactured.

The LBNL project team has concluded that the partial differential equations (PDEs), integral equations, or boundary conditions used in performing the structural-civil-seismic analysis of SMRs are generally the same as those used for conventional-sized large LWR reactors, considering that SMRs have the size of at least several meters and belong to the same scale of dimensions as conventional larger reactors. Some other problems, such as earth science problems or nano-mechanics problems, may have different scales and even different PDEs or integral equations. However, the analysis of an SMR or of a conventional-sized large LWR reactor uses the same types of PDEs or integral equations. Therefore, to the extent that a code does not contain scale-specific aspects, the broad suite of FEM codes that are used for conventional-sized large LWR reactors can also be used for SMRs.

Opening note—*Descriptions below of a few of the several simulation tools (codes) have been taken almost verbatim, or paraphrased, from the developer's or distributor's literature. The information is included more to provide background information than to support the SMR vs. large-LWR evaluations herein.*

2.2.6.1 ABAQUS

ABAQUS is one of a family of FEM codes. ABAQUS is a high-performance software package developed by Hibbitt, Karlsson & Sorensen, Inc. (now Dassault Systemes) for finite element modeling of structural response. It enables the user to do linear or nonlinear and static or dynamic types of analysis for a large spectrum of engineering problems. The ABAQUS suite of engineering analysis software packages is used throughout the world to simulate the physical response of structures and solid bodies to load, temperature, contact, impact, and other environmental conditions. The software operates on major computers and operating systems from PCs to workstations to supercomputers.

Analysis Type − Designed as a general-purpose simulation tool, ABAQUS can be used to study more than just structural (stress/displacement) problems. It can simulate problems in such diverse areas as heat transfer, mass diffusion, thermal management of electrical components (coupled thermal-electrical analyses), acoustics, soil mechanics (coupled pore fluid-stress analyses), piezoelectric analysis, electromagnetic analysis, and fluid dynamics.

Element Types Used − ABAQUS has an extensive element library to provide a powerful set of tools for solving many different problems. The user can choose an element type that characterizes, among other things, the degree-of-freedom set (displacements and/or rotations, temperatures, etc.); the characteristic shape of the element (line, quadrilateral, brick, etc.); whether the element lies in 2-D space or 3-D space; the response of your system; and the accuracy level of interest.

Material Properties − ABAQUS has an extensive list of material models that can simulate the behavior of most typical engineering materials including metals, rubber, polymers, composites, reinforced concrete, crushable and resilient foams, and geotechnical materials such as soils and rock.

ABAQUS offers a wide range of capabilities for simulation of linear and nonlinear applications. Problems with multiple components are modeled by associating the geometry defining each component with the appropriate material models and specifying component interactions. In a nonlinear analysis, ABAQUS automatically chooses appropriate load increments and convergence tolerances and continually adjusts them during the analysis to ensure that an accurate solution is obtained efficiently.

Evaluation: There seems to be nothing in ABAQUS would preclude a competent user from developing valid results and reaching valid conclusions about an SMR.

2.2.6.2 ADINA

ADINA is one of a family of FEM codes. ADINA comprises a wide variety of solution techniques for static and transient problems that include the robust nonlinear analysis techniques that give this finite-element toolkit its name (ADINA = Automatic Dynamic Incremental Nonlinear Analysis). In addition to its considerable capabilities for structural analysis, ADINA also permits fully coupled fluid-structure interaction simulations that are useful for tsunami analyses. The ADINA system includes a wide variety of capabilities such as integration with solids modeling applications, visual pre- and post-processing tools, and features to support multiphysics simulations involving coupled solid, fluid, and thermal response.

ADINA FSI − Fluid-structure interaction (FSI) occurs when fluid flow causes deformation of the structure. This deformation, in turn, changes the boundary conditions of the fluid flow.

ADINA offers fluid-structure interaction capabilities in one single program for the solution of problems where the fluids are fully coupled to general structures that can undergo highly nonlinear response due to large deformations, inelasticity, contact, and temperature dependency. A fully coupled fluid-structure interaction means that the response of the solid is strongly affected by the response of the fluid and vice versa.

From the fluid point of view, the Navier-Stokes flow can be incompressible, slightly compressible, low-speed or high-speed compressible. From the structural point of view, all available element types can be used (shell, 2-D and 3-D solid, beam, iso-beam, contact surfaces, etc.) as well as all available material models.

Evaluation: There seems to be nothing in ADINA that would preclude a competent user from developing valid results and reaching valid conclusions about an SMR.

2.2.6.3 ALGOR

ALGOR is one of a family of FEM codes. ALGOR, now known as Autodesk Simulation Mechanical or Autodesk Simulation Multiphysics software, is a general-purpose multiphysics finite element analysis software package developed by ALGOR Inc. for use on the Microsoft Windows and GNU/Linux computer operating systems. It is distributed in a number of different core packages to cater to specific applications such as mechanical event simulation and computational fluid dynamics.

Analysis Type: Multiphysics, Linear, Nonlinear, Thermal, Fluid Flow, Electrostatic, Fatigue Analysis, Mass Transfer

Element Types: Beam Elements, Gap Elements, Rigid Elements, Spring Elements, Truss Elements, 2D Elements, Membrane Elements, Plate Elements, Thick Composite Elements, Thin Composite Elements, Brick Elements, Tetrahedral Elements, Incompatible Displacement Modes

Material: Consider actual material behavior for foam, gasket, rubber, plastic, and other nonlinear materials. Choose from a wide range of nonlinear material models to get more accurate results when a part's operation involves twisting, stretching, squashing, or buckling. Learn how a part will likely fail, especially when large deformation occurs.

Evaluation: There seems to be nothing in ALGOR that would preclude a competent user from developing valid results and reaching valid conclusions about an SMR.

2.2.6.4 ANSYS

ANSYS is a general purpose finite element modeling package for numerically solving a wide variety of mechanical problems. These problems include static/dynamic structural analysis (both linear and nonlinear), heat transfer and fluid problems, and acoustic and electromagnetic problems.

The software operates on major computers and operating systems from PCs to workstations to supercomputers. ANSYS features file compatibility throughout the family of products and across all platforms. The multiphysics nature of ANSYS allows the same model to be used for a variety of coupled-field applications such as thermal-structural, magneto-structural, and electrical-magnetic-flow-thermal.

For both new and experienced users, the program offers a growing list of capabilities including advanced structural nonlinearities, electromagnetics, computational fluid dynamics, interactive design optimization, general contact surfaces, adaptive meshing, p-method adaptivity, large strain/finite rotation capability, and parametric modeling. The Motif-based menu system prompts data input and function selections through dialog boxes, pull-down menus, and submenus helping users navigate through the program. Solid modeling features include NURBS-based geometry representation, geometric primitives, and Boolean operations.

Discipline - Any of five physical (engineering) disciplines may be solved by the ANSYS program─structural, thermal, electric, magnetic, and fluid. Note that the user can also solve multi-field problems in ANSYS that consider the effects of the physical phenomena coupled together such as temperature and displacement in a thermal-stress analysis.

Analysis Type - Static, modal, harmonic, transient, spectrum, eigenvalue buckling, and substructuring. Whether the problem is linear or nonlinear will be identified here.

Element Types Used - Over 100 element types are available in ANSYS. The user chooses an element type that characterizes, among other things, the degree-of-freedom set (displacements and/or rotations, temperatures, etc.); the characteristic shape of the element (line, quadrilateral, brick, etc.); whether the element lies in 2-D space or 3-D space; the response of the user's system; and the accuracy level of interest.

Material Properties - Physical properties of a material such as modulus of elasticity or density that are independent of geometry. Although they are not necessarily tied to the element type, the material properties required to solve the element matrices are listed for each element type for your convenience.

Evaluation: There seems to be nothing in ANSYS that would preclude a competent user from developing valid results and reaching valid conclusions about an SMR.

2.2.6.5 GT STRUDL

GT-STRUDL (Georgia Tech STRUctural Design Language) is one of a family of FEM codes. It was developed in 1975 and is a general purpose finite element analysis program for static and dynamic analysis of two- and three-dimensional linear and nonlinear structures. The program continues to be developed by the Georgia Tech Computer-Aided Structural Engineering Center.

Key features of GT-STRUDL include:

- Powerful menu driven graphical Windows® NT/98/2000/ME/XP interface.
- Broad range of nonlinear analysis features, structural definition, and modeling capabilities.
- Library of over 100 member and finite element types.
- Powerful menu-driven mesh generation.
- Built-in Model Wizard for the fast creation of many common structural models.
- Generalized automatic data generation for all classes of structural information.
- Data sheets to define/view/edit/sort information in a spreadsheet format.

- Efficient static and dynamic (response spectrum, transient, harmonic, and steady state) analysis processing.

- Tools to help locate model instabilities.

- Sophisticated and highly efficient equation solvers.

- Comprehensive steel and reinforced concrete structure design according to a variety of design code specifications.

- Offshore platform analysis and design.

- Design provides for a high level of user control of the result dependent and iterative analysis/design/display/evaluation/reanalysis/redesign/decisionmaking process.

- Problem database inquiry and display features for easy database interaction.

- User controlled database management facilities including database storage, retrieval, and updating features.

  - Static and animated displays of deformed structure, mode shapes, and transient response, stress contours.

  - Force and moment diagrams and envelopes.

  - Steel code check pass/fail status and interaction values.

- Display graphical display of results.

<u>Broad range of member and finite-element types for fame and continuous mechanics</u>

GT STRUDL contains a large library of member and finite element types consisting of 7 member types (constant or variable cross-section); over 100 conventional, isoparametric, and hybrid formulation finite element types; and many special transition elements including:

- Plane truss/frame/grid and space truss/frame members.

- Curved plane and space frame member element including internal pressure effects.

- Plate-bending elements to model thin to moderately thick plates (three, four, and eight node triangles and quadrilaterals).

- 3-D solids (6 to 20 node triangular prisms and straight and curved edge bricks).

- Thin shell elements (three and four node triangles and quadrilaterals with five or six degrees-of-freedom per node).

- Axisymmetric elements (four to eight node quadrilaterals) for modeling solids of revolution.

- Large library of special transition elements for plane stress, plane strain, axisymmetric stress (four to eight node quadrilaterals), and 3-D solid (8 to 20 node bricks) problems.

- Special finite element for modeling shear walls and floor slabs where a rotational degree-of-freedom is provided about an axis normal to the element to allow coupling of member rotational degrees-of-freedom with the element (e.g., beam bending may now be coupled with a shear wall).

- Multilevel superelements (i.e., sub-structures defined from user specified collections of members, finite elements, and other superelements) may be defined for large and complex linear static analysis problems.

Evaluation: There seems to be nothing in GT-STRUDL that would preclude a competent user from developing valid results and reaching valid conclusions about an SMR.

2.2.6.6 LS-DYNA

LS-DYNA is one of a family of finite element codes. It is a general-purpose finite element program capable of simulating complex real world problems. The code's origins lie in highly nonlinear, transient dynamic finite element analysis using explicit time integration.

LS-DYNA consists of a single executable file and is entirely command line driven. Therefore, all that is required to run LS-DYNA is a command shell, the executable, an input file, and enough free disk space to run the calculation. All input files are in simple ASCII format and thus can be prepared using any text editor. Input files can also be prepared with the aid of a graphical preprocessor.

Capabilities
LS-DYNA's analysis capabilities include full 2-D & 3-D capabilities; nonlinear dynamics; rigid body dynamics; quasi-static simulations; normal modes; linear statics; thermal analysis; fluid analysis (Eulerian capabilities, Arbitrary Lagrangian-Eulerian, Fluid-Structure Interaction, Navier-Stokes fluids, and compressible fluid solver); FEM-rigid multi-body dynamics coupling (MADYMO, Cal3D); underwater shock; failure analysis; crack propagation; real-time acoustics; implicit springback; multi-physics coupling; structural-thermal coupling; adaptive remeshing; SPH (Smoothed Particle Hydrodynamics); EFG (Element Free Galerkin); radiation transport; and EM (Electromagnetism).

Material Library
LS-DYNA's material library includes metals, plastics, glass, foams, fabrics, elastomers, honeycombs, concrete and soils, viscous fluids, and user-defined materials.

Element Library
LS-DYNA's element library includes beams (standard, trusses, discrete, cables, and welds) (with over 10 beam element formulations); discrete elements (springs and dampers); lumped inertias; lumped masses; accelerometers; sensors; seatbelts; pretensioners; retractors; sliprings; shells (3-, 4-, 6-, and 8-node including 3D shells, membranes, 2D plane stress, plane strain, and axisymmetric solids with over 25 shell element formulations); solids (4- and 10-node tetrahedrons, 6-node pentahedrons, and 8-node hexahedrons, with over 20 solid element formulations); SPH Elements, and thick shells (8-node).

Evaluation: There seems to be nothing in LS-DYNA that would preclude a competent user from developing valid results and reaching valid conclusions about an SMR.

2.2.6.7 NASTRAN

NASTRAN is a finite element analysis (FEA) program that was originally developed with NASA funding in the late 1960s for the aerospace industry. The MacNeal-Schwendler Corporation (MSC) was one of the principal and original developers of the public domain NASTRAN code. NASTRAN source code is integrated in a number of different software packages, which are distributed by a range of companies.

Commercial versions of NASTRAN are currently available from MSC Software, NEi Software (NEi Nastran), and Siemens PLM Software (NX Nastran). In 2006, Siemens AG purchased the former UGS Corp. from private equity concerns and with it their rights to the commercial version of NX NASTRAN.

MSC Nastran offers a complete set of linear static and dynamic analysis capabilities along with unparalleled support for superelements enabling users to solve large, complex assemblies more efficiently. MSC Nastran also offers a complete set of implicit and explicit nonlinear analysis capabilities, thermal and interior/exterior acoustics, and coupling between various disciplines such as thermal, structural, and fluid interaction. New modular packaging also exists.

Evaluation: There seems to be nothing in NASTRAN that would preclude a competent user from developing valid results and reaching valid conclusions about an SMR.

2.2.6.8 SAP2000

SAP2000 is a general purpose finite element analysis program for static and dynamic analysis of two- and three-dimensional linear and nonlinear structures with a particular emphasis on dynamic loading and earthquake loading. The software is developed by Computers and Structures, Inc. Integrated design code features can automatically generate wind, wave, bridge, and seismic loads with comprehensive automatic steel and concrete design code checks per U.S., Canadian, and international design standards.

Advanced analytical techniques allow for step-by-step large deformation analysis, Eigen and Ritz analyses based on stiffness of nonlinear cases, catenary cable analysis, material nonlinear analysis with fiber hinges, multi-layered nonlinear shell element, buckling analysis, progressive collapse analysis, energy methods for drift control, velocity-dependent dampers, base isolators, support plasticity, and nonlinear segmental construction analysis. Nonlinear analyses can be static and/or time history with options for FNA nonlinear time history dynamic analysis and direct integration.

SAP2000 Features

Modeling
Object-Based Graphical Interface; Model Templates with Auto Meshing; Frame, Cable and Tendon Members; Area (Shell) and Solid Objects with Internal Meshing; Editing with Move, Merge, Mirror and Replicate; Accurate Dimensioning with Guidelines and Snapping; Auto Edge Constraints for Mismatched Shell Meshes; Quick Draw Options for Object Creation; Support for

Multiple Coordinate Systems; Powerful Grouping and Selection Options; Automatic Generation of Code Defined Lateral Wind and Seismic Loads; and Transfer of Loads from Area Objects to Framing Systems.

Analysis
Static Analysis with Frame and Shell Objects; Multiple Solvers for Analysis Optimization; Response Spectrum Analysis with Eigen or Ritz Vectors; P-Delta Analysis; Generalized Joint Constraints including Rigid Bodies and Diaphragms; Applied Force and Displacement Loading; Gravity, Pressure and Thermal Loading; Post Tensioning in Frame, Area and Solid Objects; Layered Shell Element; Plane, Asolid and Solid Objects; Dynamic Time History Analysis, including Multiple Base Excitation; Frequency Domain Analysis-Power Spectral Density; Moving Loads (requires Bridge Module); Nonlinear Frame Hinges for Axial, Flexural, Shear & Torsional Behavior; Nonlinear Static Pushover Analysis; Viscous Dampers; Base Isolators; Gap Object for Structural Pounding; and Nonlinear Time History Analysis with the Wilson FNA or Direct Integration Methods.

Design
Steel Frame Design for Numerous Domestic & International Codes; Concrete Frame Design for Numerous Codes; Aluminum Frame Design for AA Codes; Cold-Formed Steel Frame Design for AISI Codes; Design for Static and Dynamic Loads; and Member Selection and Optimization.

Evaluation: There seems to be nothing in SAP2000 that would preclude a competent user from developing valid results and reaching valid conclusions about an SMR.

2.2.6.9 SASSI

SASSI, a System for Analysis of Soil-Structure Interaction, consists of a number of interrelated computer program modules that can be used to solve a wide range of dynamic soil-structure interaction problems in two or three dimensions. The basic methods of analysis adopted by the computer program SASSI2000 are called the flexible volume and the recently developed subtraction methods. These methods are formulated in the frequency domain using the complex response method and the finite element technique.

Complex Response Method: In SASSI, the soil material properties are represented by the complex shear, G*, and complex constrained moduli, M*, defined by the following equations:

$$G^{*} = G\left(1-2\beta_s^2+2i\beta_s\sqrt{1-2\beta_s^2}\right) \cong G\left(1+2i\beta_s\right)$$

$$M^{*} = M\left(1-2\beta_p^2+2i\beta_p\sqrt{1-2\beta_p^2}\right) \cong M\left(1+2i\beta_p\right)$$

where G and M are real numbers corresponding to the shear and constrained moduli, respectively, and β_s and β_p are the critical damping ratios associated with S-wave and P-waves, respectively. Currently, only limited data are available on the ratio between β_s and β_p, and these quantities are therefore usually chosen to be equal in which case the subscripts are dropped and the corresponding Poisson's ratio becomes real number.

Using the complex modulus described above, the spatial variation of damping can be included in the analysis. This is particularly important for SSI systems in which the material damping in the soil and structure is significantly different.

Capabilities and limitations of SASSI 2000

Soil and Structure Idealization

1. The site consists of semi-infinite elastic or viscoelastic horizontal layers on a rigid base or a semi-infinite elastic or viscoelastic half space.
2. The structure(s) are idealized by standard two- or three-dimensional finite elements connected at nodal points.
3. Each nodal point on the structure may have up to six displacement degrees of freedom. The user has the option to delete one or more of the degrees of freedom thereby reducing the size of the problem accordingly.
4. The excavated soil zone(s) are idealized by standard plane strain or three-dimensional solid elements. The finite element models of the structure and excavated soil have common nodes at the boundary.
5. Depending on the method selected for impedance analysis, the interaction between the foundation and the structure occurs at all basement nodes, including those in the basement volume, or occurs only at the common boundary nodes.
6. All the interaction nodes lie on the soil layer interfaces with translational
7. degree-of-freedom. Rotations from the structure are transferred by translation by connecting at several interacting nodes.
8. The mass matrix is assumed to be 50 percent lumped and 50 percent consistent except for the structural beam elements and plate elements where consistent mass matrix and lump mass matrix are used, respectively.
9. Material damping is introduced by the use of complex moduli, which leads to effective damping ratios that are frequency-independent and may vary from element to element.

Discussion of recently discovered validation and verification issues with SASSI

In the course of using SASSI for analysis of seismic soil-structure interaction for various Department of Energy (DOE) nuclear facilities, some technical problems were identified with the code, in particular, certain validation and verification (V&V) issues. These are described in a U.S. Defense Nuclear Safety Board (DNFSB) letter.* The DNFSB letter cited analysis problems for which SASSI supposedly produces unrealistic seismic responses. This discovery has led to an extensive program for the verification and validation of SASSI. The two-phase V&V

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* U.S. Defense Nuclear Facilities Safety Board, letter to D. B. Poneman (Deputy Secretary of Energy, DOE), April 8, 2011, with an attached “DNFSB Staff Issue Report” entitled “Issues Related to the SASSI Computer Software”

program is intended to perform V&V for the SASSI direct method and to provide a technical review of aspects of the subtraction method including analysis problems that have been identified by practitioners. The program is being performed for DOE and could provide guidance to the nuclear power industry as well if the full range of parameters is expanded to encompass those of nuclear power plant sites and structure configurations. The program is being executed by a single firm but with significant contributions from the combined body of SSI experts and SASSI practitioners. The program is continuing at the time of this writing.

Although these issues have not yet been fully resolved, it is apparent that the problem is manifested particularly (or more severely) for the analysis of certain types of embedded structures.

It is still too soon to be able to cite a full “resolution” of this issue for SASSI. Until that occurs, there may be a reason to be wary of using SASSI for an embedded structure, whether it be an SMR, a large LWR, or any other such facility, without great care.

Evaluation: Except for the aforementioned issue of verification and validation for SASSI and except for using SASSI with embedded structures (which issues await a broader resolution), there seems to be nothing in SASSI that would preclude a competent user from developing valid results and reaching valid conclusions about an SMR.

2.2.6.10 SHAKE91

SHAKE91, modified based on SHAKE, has been by far the most widely used program for computing the seismic response of horizontally layered soil deposits. The program computes the response of a semi-infinite horizontally layered soil deposit overlying a uniform half-space subjected to vertically propagating shear waves. The algorithm in the program is based on the continuous solution to the wave equation that was adapted for transient motions using the Fast Fourier Transform techniques of Cooley and Tukey. The analysis is done in the frequency domain and, therefore, for any set of properties, it is a linear analysis. An iterative procedure is used to account for the nonlinear behavior of the soils.

When performing SHAKE91, users need to define the soil properties for each sub-layer(shear-wave velocity, shear modulus, damping, total weight, and thickness) and select the input motions. In addition, the modulus reduction versus shear strain relationship and damping ratio versus shear strain relationship must be specified to represent the soil material properties. An equivalent linear analysis procedure is implemented in SHAKE91 to account for nonlinear response of soil. The outputs of the program are the time histories requested by users. In addition, many associated types of data can be outputted, upon users’ request, such as the maximum shear stress and strain, maximum acceleration, response spectrum, Fourier spectrum, and amplification spectrum.

Evaluation: There seems to be nothing in SHAKE91 that would preclude a competent user from developing valid results and reaching valid conclusions about an SMR.

2.2.6.11 SIMQKE-1

SIMQKE-1 generates statistically independent accelerograms, performs a baseline correlation on the generated motions to ensure zero final ground velocity, and calculates response spectra. One of the options in the program generates ground motions whose response spectra “match,” or are compatible with, a set of specified smooth response spectra. The basis for the spectrum compatible motion generation is the relationship between the response spectrum values for arbitrary damping and the “expected” Fourier amplitudes of the ground motion. The earthquakes are synthesized by superimposing sinusoidal components with pseudo-random phase angles and by multiplying the resulting stationary trace by a user specified function representing the variation of ground motion intensity with time. The program SIMQKE-1 also has the capability to adjust, by iteration, the ordinates of the spectral density function to improve the agreement between computed and specified response spectra. Even without the last step, the average response spectrum (of a set of simulated motions) will match the smooth target spectrum very closely.

SIMQKE-1 uses target response spectra as input that can be developed for nuclear power plants according to NRC’s RG 1.208, “A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion,” or RG 1.60, “Monitoring the Effectiveness of Maintenance at Nuclear Power Plants,” and the outputs are artificial earthquake motions.

Evaluation: There seems to be nothing in SIMQKE-1 that would preclude a competent user from developing valid results and reaching valid conclusions about an SMR.

2.2.6.12 STARDYNE

STARDYNE, now known as STAAD, is a finite element structural analysis and design computer program originally developed by Research Engineers International in Yorba Linda, CA. In late 2005, Research Engineer International was bought by Bentley Systems.

It supports several steel, concrete, and timber design codes. It can make use of various forms of analysis from the traditional first order static analysis, second order p-delta analysis, geometric nonlinear analysis, or a buckling analysis. It can also make use of various forms of dynamic analysis from modal extraction to time history and response spectrum analysis.

Key Feature List:

- Flexible modeling is provided by a state-of-the-art graphical environment and the design supports over 70 international codes and over 20 U.S. codes in 7 languages.
- An array of advanced structural analysis and design features are included such as nuclear certification for 10 CFR Part 50, 10 CFR 21, ASME NQA-1-2000, time history and push over analysis and cable (linear and nonlinear) analysis.
- Concurrent engineering-based user environment for model development, analysis, design, visualization, and verification.
- Full range of structural analysis including static, P-delta, pushover, response spectrum, time history, cable (linear and nonlinear), buckling and steel, concrete and timber design.
- Optional Advanced Analysis engine. A new substantially faster solver that can provide solutions of large structures in a fraction of the time currently required by the standard STAAD engine. The Advanced Solver generally uses less disk and memory.

- Supports truss and beam members, plates, solids, linear and nonlinear cables, and curvilinear beams.

- Advanced automatic load generation facilities for wind, area, floor, and moving loads.

- Efficiencies are gained through the ability to maintain and streamline current workflows with fluent data collaboration. STAAD.Pro integrates with other Bentley products such as STAAD.foundation and ProSteel, and OpenSTAAD is provided for integration with third party programs.

Evaluation: There seems to be nothing in STARDYNE that would preclude a competent user from developing valid results and reaching valid conclusions about an SMR.

2.2.7 ESSI

The NRC ESSI ("Earthquake Soil-Structure Interaction") Program has been under development at LBNL and the University of California at Davis, supported by the NRC, and directed by Prof. Boris Jeremic. It is not yet in widespread use.

The evaluation of ESSI vis-à-vis SMRs was performed separately by Dr. Jeremic.

ESSI is a time domain, nonlinear, parallel finite element program for simulating earthquake-soil-structure interaction of nuclear power plants (NPPs). The program is developed using a number of (open source) libraries that are compiled and linked into an application program. The program uses a number of state-of-the-art methods to analyze nonlinear behavior of soils, rock, concrete, steel, and other materials used. A number of finite elements are available for modeling, namely, solids (8, 20, 20-17, 27 node bricks, etc.) as well as truss, beam, and shell elements. Solid finite elements can model behavior of a single-phase (dry) material and/or behavior of two-phase (fully saturated) material (soil). Special finite elements are available to model gap (opening/closing) and slipping, seismic isolators, etc. Seismic input is performed using the Domain Reduction Method, which provides a way to analytically input body (primary (P) and secondary (S)) and surface (Rayleigh, Love, etc.) seismic waves and provides for analytic radiation damping. The NRC ESSI Program has an extensive ongoing verification and validation suite whose goal is to cover all modeling and simulation components.

The ESSI Program analyzes a finite element model of soil/rock and the NPP using the direct method, where all the components are present in the model at all times and are modeled and simulated using physics-based methods. There is no difference in modeling if the model of the NPP is on the surface, slightly embedded, or fully embedded; all the components are modeled at once. They are fully coupled in the sense that they fully interact through their respective stiffness, damping, and mass matrices at each time step of the simulations, and all of the interactions are fully accounted for at each time step. There is no difference in modeling and simulation that depends on whether a large NPP or an SMR in being modeled because there is no modeling dependence on the dimensions or mass of the structure.

Evaluation: There seems to be nothing in the ESSI analysis program that would preclude a competent user from developing valid results and reaching valid conclusions about an SMR.

2.3 Summary for Section 2

The evaluation in Section 2 of this report has presented an evaluation of simulation tools that can analyze seismic issues as used in structural engineering, geotechnical engineering, and seismic engineering. The evaluation has ascertained whether each simulation tool could be used for the analysis of a small modular reactor (SMR) for regulatory purposes. The evaluation has found that, in every case, there seems to be nothing in the simulation tool that would preclude a competent user from developing valid results and reaching valid conclusions about an SMR.

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11. ABSTRACT (200 words or less)

This report consists of two different evaluations sponsored by the U.S. Nuclear Regulatory Commission (NRC) and performed by Lawrence Berkeley National Laboratory. The first evaluation covers NRC regulatory guidance in the seismic-structural area. The second evaluation covers several seismic-structural simulation tools used in NRC regulatory applications. Each evaluation examines the appropriateness of the regulatory guidance (provided in regulations, guidance, review plans, etc.), or of the simulation tool for its applicability to small modular reactors (SMRs). The objective of each evaluation is to address the following: The bulk of NRC's regulatory work on nuclear power reactor safety has been concentrated for decades on large light-water reactors (LWRs). While the regulations are technology neutral, many of the agency's positions have evolved with large LWRs as the sole technology of interest. Also, the technical analysis tools (computer codes) used in reactor safety guidance, either by the NRC itself or by its licensees and applicants, including structural analysis tools as well as those used to determine ground motion and to analyze soil structure interaction (SSI) effects, have been used to analyze large LWRs. This report examined whether regulatory guidance, or the analysis tools currently used in the seismic-structural area, could benefit from modification to better address small modular reactors (SMRs). It concluded that most documents reviewed do not need any modifications and are acceptable as currently written. Recommendations for modifications are presented as appropriate. Also, it concluded that the software packages reviewed should yield acceptable results when applied to an SMR. The report can be used to inform the NRC's efforts to update regulatory guidance in support of licensing reviews of SMR applications.

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