Reinforced Concrete Supporting Pad Design for an ISFSI and Seismic Soil Structure Interactions - a Perspective

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ABSTRACT:

The U. S. Nuclear Regulatory Commission (NRC) has recently updated NUREG 0800 [1], Standard Review Plan (SRP). Chapter 3 of this SRP addresses acceptable methods for the analysis and design of reinforced concrete supporting pads and foundations for nuclear applications, including specifics for soil-structure interaction analysis and modelling. Guidelines in this SRP, among other requirements, stipulate that Soil-Structure Interaction (SSI) analyses be performed using a range of soil properties, three different sets of shear and compression wave velocity profiles using the best-estimate velocity profile and the high and low velocity profiles. The free-field ground surface response spectra need to be developed using 3 independent time histories. Spent nuclear fuel storage, using an NRC approved Dry Cask Storage System (DCSS) is an acceptable means of safe and secured spent fuel management. The Independent Spent Fuel Storage Installations (ISFSIs) are required to satisfy the safety objectives of Title 10 of the Code of Federal Regulations (10 CFR) Part 72 [2]. Regulatory Guides (RGs), NUREGs, SRPs and other guidance documents are available to assist an applicant in complying with the regulations. The ISFSI pads are independent structural units usually rectangular in shape and 0.61m to 0.91m (24 inches to 36 inches) thick constructed of reinforced concrete typically in accordance with ACI 349 Code [3]. The cask storage pad design is based on the maximum loaded weight of storage casks. Spent fuel storage casks in most cases are free standing steel or concrete modules placed on these storage pads that are co-located with the existing nuclear power plants. A conventional cast-in-place reinforced concrete mat foundation structure provides a level and stable surface for placement and storage of the storage casks. The ISFSI pads are designated as important to safety (ITS) and Quality Assurance (QA) Category C.

Guidelines such as ASCE 4-98 [4], “Seismic Analysis of Safety-related Nuclear Structures and Commentary” have been used for many years for modeling and analyzing soil-structure interactions. Developments in the technique of computational modelling (in the time domain); modeling of the vertical springs to model the upper, best and lower bounds of the soil supporting the pads; dynamic soil properties including profile layering; strain-compatible soil properties, and other non-linear dynamic analysis related details have been well established components of SSI analysis for over 20 years now. However, while SSI analysis techniques are well established and ISFSI concrete pads are simple structures, the fact that the casks resting on the pad could slide or tip adds a true nonlinear components to the SSI analysis resulting in a far more complex problem. This paper provides an overview of the SSI analysis methodologies used to evaluate ISFSI pads and some of these additional complexities.

BACKGROUND:

Federal regulations governing the requirements for siting an ISFSI are contained in 10 CFR 72. These regulations require that seismicity at an ISFSI located west of the Rocky Mountain Front be evaluated using the criteria for determining the safe shutdown earthquake at a nuclear power plant, 10 CFR 100 [5] Appendix A. Vibratory ground motion design bases shall be determined by using a "deterministic" approach based upon a single set of earthquake sources.

The regulations for siting nuclear power plants (10 CFR 100.23) were amended in 1997 in order to recognize the inherent uncertainties in geologic and seismologic parameters that must be addressed in determining the seismic hazard at a nuclear power plant site. One of the ways to address these uncertainties is through a probabilistic seismic hazard analysis (PSHA).

A PSHA can be performed for an ISFSI for vibratory ground motions and surface fault displacement. Methodologies used and the results thereof should be detailed. The hazard results are presented as mean hazard curves that incorporate the uncertainty in input data and interpretations. The seismic source model shall use all capable fault sources and all seismic source zones within 100 km (62 miles). Clarification of the PSHA formulation should be provided in the SAR. In addition, sensitivity analyses should be performed to provide further justification of the design basis ground motions. The NRC staff recommended a risk-informed graded approach in changes to 10 CFR Part 72 [2] when determining the appropriate hazard frequency or return period. It was determined that an appropriate design probability level for the ISFSI can be 5 x 10^{-4} per year or a 2,000-yr return period. Refer to RG 3.73 [6] issued in 2003.

Most soil-structure interaction analyses at commercial nuclear power plants have focused on the effect of the foundation on the response of site buildings affixed to *rigid* foundation mats. As such, SSI analysis has been performed using linear elastic models for the structure above the mat and layered continuum models for the soil under the mat. With the increased focus on siting dry storage facilities at nuclear plants, it has become necessary to revisit traditional SSI analyses, and extend the methodology to include *non-rigid* mats (the flexible ISFSI slab) [7, 8] and the non-linear behavior of the large free-standing dry storage casks emplaced on the ISFSI slab (the casks may rock, precess, and slide depending on the severity of the seismic event).

Fundamentals of SSI:

In a classic definition, the process in which the response of the soil influences the motion of the structure and the motion of the structure influences the response of the soil is termed as soil-structure interaction. SSI can have a detrimental effect on the structural response, and neglecting SSI in the analysis may lead to unsafe design for both the superstructure and the foundation. When a structure is subjected to an earthquake excitation, it interacts with the foundation and the soil, and thus changes the motion of the ground. SSI broadly can be divided into two phenomena: a) kinematic interaction and b) inertial interaction.

SSI problems involve the determination of the response of structures on a flexible soil foundation system. The interaction effects related to the stiffness of the structure is known as the kinematic interaction. The mass related effects are called the inertial interaction. Soft soil sediments can significantly elongate the period of seismic waves and the increase in natural period of structure may lead to the resonance with the long period ground vibration. This paper is about the interaction of soil with structure (ISFSI support pad) during a seismic event.

Past and Present Engineering Experience and Applications

Traditionally, past experience has indicated that a “Stick Model” should be used for a Rigid Mat and a Finite Element Model (FEM) should be used for a Flexible Mat. Here, the “Stick Model” refers to the super-structure. For sites that are called Soil Sites, low frequency input i.e. seismic waves with long wavelength generally governs and the soil motion is input as a rigid body motion. For Rock Sites generally high frequency input governs. Present experience indicates that low and high frequency inputs (Long-and Short Wavelengths) can be used for both Soil and Rock Sites.

If the foundation is rigid either a soil spring model with a stick model super-structure (time domain analysis) or a CLASSI [9] model with a stick model super-structure (frequency domain analysis) can be used. If the foundation is flexible, either a SASSI (frequency domain) analysis or an LS-DYNA [10] (time Domain) analysis can be used. But regardless of whether it is a flexible foundation, or a soil or rock site, the control motion is specified at the control point either at the ground surface or rock outcrop by a response spectrum and its associated time-histories.

SOIL STRUCTURE INTERACTION TECHNIQUES:

All SSI methods are divided into two main methods:

1) *The continuum methods* [suitable for simple soil profiles and surface foundations]

2*) The finite element methods* [more versatile and can handle all practical problems]

   a) The complete methods [Not discussed further]

   b) The substructure methods [Discussed further herein]

The substructure methods involve:

- Site response analysis
- Foundation scattering analysis
- Foundation impedance analysis
- Modeling of the structure and solving for the SSI problem

The site response analysis determines ground motion within the supporting soil medium. One would require the soil profile and the dynamic soil properties including soil nonlinear properties, the design motion and the location of the motion in the free-field (control point) [See Figure -1] input time histories and their frequency contents, wave field and wave composition. It is very important to establish the degraded strain-compatible soil properties for a given level of ground excitation. The equivalent linear strain compatible soil properties are developed by initially beginning with the Seed and Idriss curves [11] for damping and shear modulus versus strain, and the application of the iterative process used by the SHAKE [12] program.

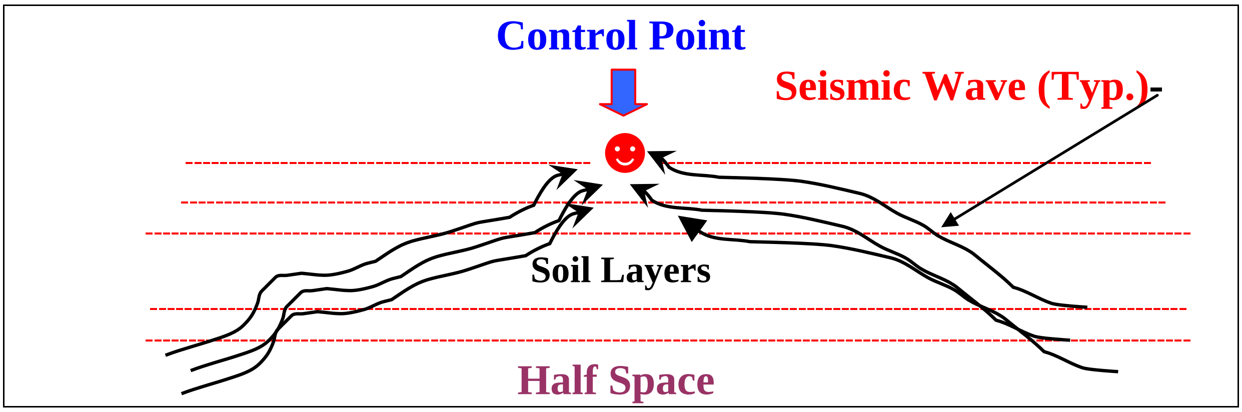

Figure - 1 Free Field Control Point

The scattered motion, if applicable, may include rocking and torsional components in addition to translational motion. The foundation analysis will require knowledge of basic geometry of the foundation, stiffness and effective depth (if any) of the embedment. Most ISFSI pads are typically 0.61m to 0.91m (24 inches to 36 inches) reinforced concrete mat foundation collocated with the reactor within the site boundary. They are normally placed at grade level on top of an engineered fill that is well compacted and adequately supported on a sub-base required to meet various conditions indicated in the Certificate of Compliance (CoC) of a particular cask vendor.

The foundation impedance analysis determines the foundation spring and the damping coefficients. As the impedance functions are highly frequency-dependent the knowledge of frequency and the mode of excitation are required. See Figure -2 for details of the sub-structure methods.

Finally, with all the above information the structural dynamic model and the final solution of the equations of motion are developed. The responses in terms of seismic forces and response motions are generated, that can be used for the actual design of the foundation mat.

The starting point for the analysis is a characterization of the soil properties at the site down to competent rock. For the purposes of the SSI analyses, the soil properties required are those necessary to characterize the soil below the ISFSI pad in terms of representative stiffness, mass, and damping parameters.

The dynamic soil properties must include profile layering, low-strain shear and compression wave velocities, Poisson's ratios, unit weights, and shear modulus reduction and damping relationships. *In accordance with US NRC NUREG 0800[1], Chapter 3.7, which stipulates that SSI analyses be performed using a range of soil properties, three different sets of shear and compression wave velocity profiles should be developed. The best-estimate velocity profile and the high and low velocity profiles should be tabulated.*

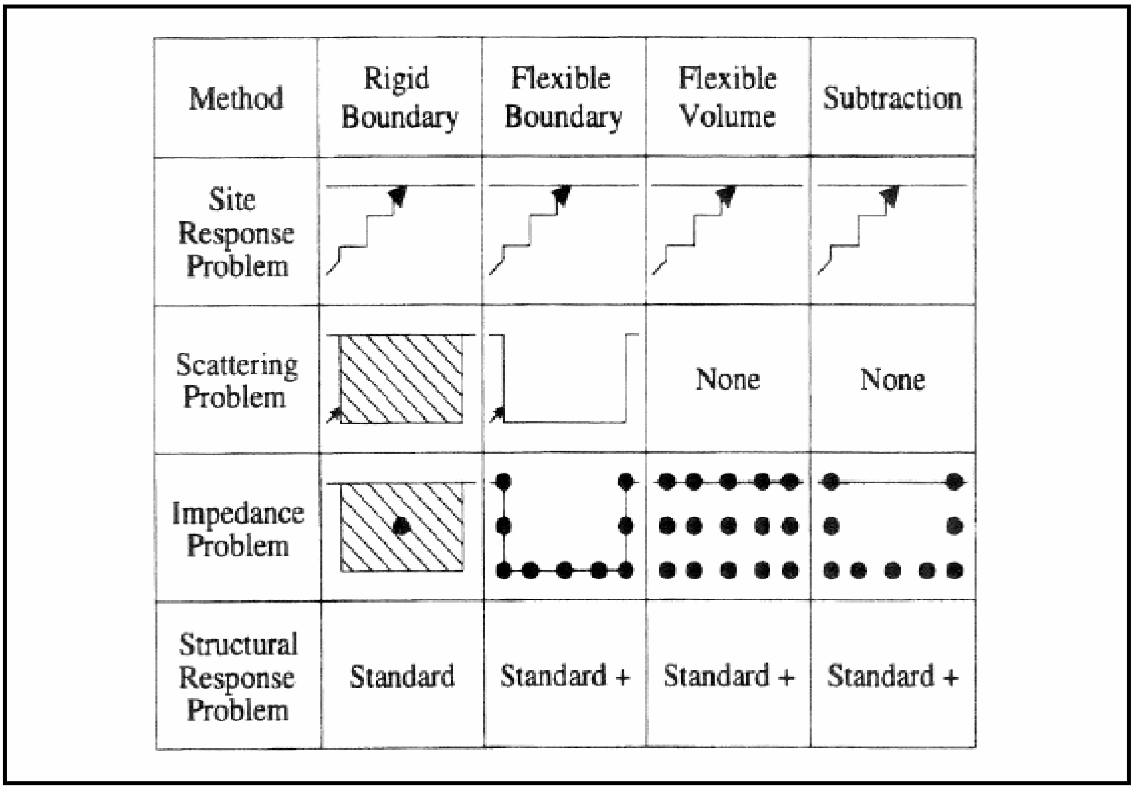

Figure - 2 Substructure Methods

One-dimensional site response analyses should be performed using the three different soil shear wave velocity profiles to determine the response based on the best estimate velocities and the high and low velocities. The strain-compatible shear-wave velocity and damping ratio profiles for these three cases should be listed. Based on the strain-compatible profiles obtained from the one-dimensional site response analyses, idealized horizontally layered soil profiles should be developed for use in the soil-structure interaction analyses based on the System for Analysis of Soil-Structure Interaction (SASSI) [13] or similar continuum model. The dynamic properties for these idealized layers and the details of this idealization should be presented.

The equivalent, single-layer shear modulus, Young's modulus, damping ratio, and unit weight of the soil should be computed as a weighted average of the values within X ft below the surface (X = the minimum width of the cask storage pads). The weighting factors should be assumed to decrease linearly with increasing depth. These equivalent dynamic soil parameters should be computed for a rectangular (or square, as applicable) foundation in accordance with the current revision of NRC SRP 0800 [1] for vertical, horizontal, and rocking modes. Discussion of the static and dynamic engineering properties of the soils underlying the site should be included.

Free standing cask on a flexible pad and effects of SSI - from NUREG/CR-6865 [14]:

If the ground motion is not sufficiently high to cause the cask to lift off the pad or slide relative to the pad, the cask behaves essentially as if it were bonded to the pad. The interaction between the cask and the soil takes place in a manner very similar to typical soil-structure interaction problems involving fixed structures. The deformability of the soil to which the structure is attached reduces the stiffness of the overall system. The cask itself is quite a rigid structure. After the cask begins to tip, it is no longer valid to assume that the cask is bonded to the pad. Before uplift, the cask has a unique fundamental frequency. The frequency of the free vibration of the cask is independent of the vibration amplitude. Once an edge of the cask lifts up from the pad, the frequency of that rocking motion becomes a highly nonlinear function of the amplitude of that motion. As the cask rocks back and forth, energy is absorbed every time the cask impacts the pad. This can be a significant energy dissipation mechanism, and the type of soil underlying the pad can have a noticeable effect on the amount of energy dissipated. This mechanism is believed to be the most important soil-structure interaction effect after the cask begins to tip.

The soil-structure interaction effects and ISFSI pad flexibility are particularly important if the Peak Ground Acceleration [PGA] is below the static tipping threshold. Soil-structure interaction and ISFSI pad flexibility can cause the cask to begin tipping much sooner than it would without this effect [8]. Once the cask has begun to tip, the ISFSI pad flexibility effects appear to have a reduced influence on the cask response. It is important to keep in mind, however, that accurately modeling the point at which tipping first occurs can have a significant effect on the response later on in an analysis, even in a case where the cask would tip without including soil-structure interaction effects in the model.

Details of Soil-Structure Interaction (SSI) Analyses:

The design of Structures, Systems and Components (SSCs) classified as Important to Safety shall consider loadings associated with the ISFSI design basis ground motion, which can be determined by a probabilistic seismic hazard analysis.

The storage pad can be modeled using a three-dimensional, flat-shell finite element model. Gross uncracked stiffness of the storage pad should be used for the model. However, this assumption must be checked based on the bending stress levels in the pad. The finite element mesh can be developed with the consideration that it would produce reasonably refined distribution of internal forces and moments.

The cask pad analysis should be based on the maximum loaded cask weight. Various loading patterns of fully loaded casks should be considered (e.g. 2, 4, 8, etc.). In addition, another load case should consider several loaded casks and one cask being lifted by a cask transporter on the pad. An appropriate dynamic amplification factor should be used for this case to account for any dynamic effect of transporting the cask. Cask loadings should be lumped to points on the outer circular perimeter of each cask. The worst-case loading that produced the largest soil bearing pressure should be computed. Based on a uniform distribution of load (dead weight for the slab, live loads for the casks, and transporter) and the appropriate load combination the maximum soil pressure should be calculated.

Dynamic soil properties should be developed for the subsurface soils at the site based on the geotechnical and geophysical investigations and surveys. The dynamic soil properties include profile layering, low-strain shear and compression wave velocities, Poisson's ratios, unit weights, and shear modulus reduction and damping relationships. Based on the strain-compatible profiles obtained from the one-dimensional site response analyses, idealized horizontally layered soil profiles can be developed for use in the soil-structure interaction analyses based on the SASSI [13] (or similar) code continuum model. Dynamic analysis should be performed for the site-specific PSHA design basis earthquake in the two horizontal directions, and one vertical direction using SASSI [13] (or similar) code to more rigorously account for the effect of soil-structure interaction. The soil impedance functions can be computed numerically within the SASSI computer program based on the free-field profile and dynamic properties of the soil layers underlying the pad.

Coefficient of friction values ranging from 0.2 to 0.8 should be used to account for variations in the coefficient of friction between the pad and casks. The value of 0.2 may represent the lower-bound for sliding displacements of the cask. The value of 0.8 can represent the upper-bound estimate of the cask dynamic forces acting on the pad. These values bound the range of frictional coefficient for concrete to steel interfaces.

The cask stability analysis can be performed using a two step approach. First, the cask/pad/soil system should be modeled using the SASSI (or similar) computer program to include the effects of soil-structure interaction. If the SASSI analysis indicates that sliding and/or tipping occur by investigating the maximum accelerations at the cask center of gravity, then five (5) time-history analyses need to be performed where each time-history is developed from a real earthquake [1].

The storage pad shall be designed to provide adequate strength for accommodating the site-specific seismic loading conditions. From the static and dynamic analyses, pad responses should be obtained and then combined to give the maximum response values in accordance with the applicable load combinations. The combined response values should then be used for checking the structural adequacy of the concrete pad and the soil bearing and sliding stabilities. The checks for dynamic loading conditions should be based on the load combination (Dead Load + Live Load + Soil Load + Earthquake Load) for demand moment and strength reduction factor in accordance with ACI 349 code [3].

Summary of SSI Methodology - excerpts from NRC NUREG 0800 [1]

Soil-Structure Interaction: The earthquake ground motion response spectra (GMRS) are defined in the "free-field," i.e., without the presence of structures, at the ground surface. For sites with soil layers near the surface that will be completely excavated to expose competent material, the GMRS are specified on an outcrop or a hypothetical outcrop that will exist after excavation. Motions at this hypothetical outcrop should be developed as a free surface motion, not as an in-column motion. Competent material is defined as in-situ material having a minimum shear wave velocity of 1,000 feet/second (fps). Because of the deformability of the supporting media (rock or soil), the resulting motions at the foundation mat will differ from the corresponding free-field motions. *This difference between the foundation mat motion and the free-field motion is known as the SSI effect.* As applicable, the modeling methods (including technical bases) used in the seismic system analysis to account for SSI are reviewed. The factors to be considered in accepting a particular modeling method include: (1) the extent of embedment, (2) the layering of the soil/rock strata, and (3) the boundary of soil-structure model. All SSI analyses must recognize the uncertainties prevalent throughout the phenomenon, including:

- The random nature of the soil and rock configuration and material characteristics
- Uncertainty in soil constitutive modeling (soil stiffness, damping, etc.)
- Nonlinear soil behavior
- Coupling between the structures and soil
- Lack of uniformity in the soil profile, which is usually assumed to be uniformly layered in all horizontal directions
- Effects of the flexibility of soil/rock
- Effects of the flexibility of basemat
- The effect of pore water on structural responses, including the effects of variability of ground-water level with time
- Effects of partial separation or loss of contact between the structure (embedded portion of the structure and foundation mat) and the soil during the earthquake

The procedures by which strain-dependent soil properties (damping, shear modulus, pore pressure development), layering, and variation of soil properties are incorporated in the analysis are reviewed. Assumptions for modeling the soil-structure system and computer program validation documents are also reviewed.

To perform a seismic analysis for an SSI system, it may be necessary to have well defined excitation or forcing functions applied at the model boundaries to simulate the design earthquake ground motion. It is therefore required in such cases to generate an excitation system acting at the boundaries such that the response motion of the soil media at the plant site in the free field is identical to the design earthquake ground motion. It is noted that there is enough confidence in the current methods used to perform the SSI analysis to capture the basic phenomenon and provide adequate design information; however, the confidence in the ability to implement these methodologies is uncertain. Therefore, in order to ensure proper implementation, the following considerations should be addressed in performing SSI analysis:

- Perform sensitivity studies to identify important parameters (e.g., potential separation and sliding of soil near the pad, non-symmetry of embedment – if any, location of boundaries) and to assist in judging the adequacy of the final results. These sensitivity studies can be performed by the use of well-founded and properly substantiated simple models to give better insight;
- Through the use of some appropriate benchmark problems, the user should demonstrate its capability to properly implement any SSI methodologies; and
- Perform enough parametric studies with the proper variation of parameters (e.g., soil properties) to address the uncertainties (as applicable to the given site).

Some insights into the upcoming ASCE 04 Standard [4] (Draft 2011 Version):

- Recognizes the significance of seismic input phasing – 5 input histories

- Improves selection of deterministic soil profiles, Lower Bound (LB), Best Estimate (BE), Upper Bound (UB) and others
- Recognizes the spatial correlations between soil layers
- Introduces probabilistic SSI methodologies

Path Forward:

Currently efforts are underway to prepare a Regulatory Guideline (RG) on the Design/Analysis of ISFSI Concrete Pads. A draft outline of such a RG is given below:

<u>For Static Loads</u>

- Modelling Requirements for Static Loads
  - Soil Spring Models (Winkler Foundation)
  - Solid Element Soil Models
- Development of Statically Equivalent Seismic Loads
- Performing Differential Settlement Calculations

<u>Seismic Soil-Structure Interaction (SSI) Analysis</u>

- Linear Methods
  - Soil Spring Models - ASCE Standard 4-98 [4]
  - Developing Strain Compatible Soil Properties
  - Frequency Domain Methods (SASSI) [13]
  - Incorporating Pad Flexibility
- Non-Linear Methods for Cask Rocking and Sliding
  - Coupled Analysis Methods (LS-DYNA) [10]
  - Decoupled Analysis Methods
    - Linear SSI Analysis
    - Non-linear Sliding and Rocking Analysis
      - Time-History Analysis
      - ASCE Standard 43-05 [15] Appendix A Method

Application of NUREG-6865 [14] will also be considered in this RG for Rocking and Sliding Analysis.

CONCLUSIONS:

With the increased focus on siting dry storage facilities for spent nuclear fuel at nuclear plants, it has become necessary to revisit traditional SSI analyses with the view of extending the methodology to include *non-rigid* mats (the flexible ISFSI slab) and the non-linear behavior of the large free-standing dry storage casks emplaced on the ISFSI slab (the casks may rock, precess, and slide depending on the severity of the seismic event). While SSI analysis techniques are well established and ISFSI concrete pads are simple structures, the fact that the casks resting on the pad could slide or tip adds true nonlinear components to the SSI analysis resulting in a far more complex problem. This paper has provided an overview of the SSI analysis methodologies used to evaluate ISFSI pads and some of these additional complexities.

Currently efforts are underway to prepare a RG on the Design/Analysis of ISFSI Concrete Pads. In the interim, for seismic design and analysis of ISFSI pads the guidelines described in NUREG 0800 [1] Chapter 3.7.1 and 3.7.2 can be used (in general) for SSI analysis.

The author of this paper is solely responsible for the opinions, conclusions, recommendations, and overall contents herein and does not necessarily reflect the views of the U. S. Nuclear Regulatory Commission. The author wishes to thank Dr. Gordon Bjorkman of the NRC for his valuable comments on the final draft of this paper.

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