β-SOAR: A FLEXIBLE TOOL FOR ANALYZING DISPOSAL OF NUCLEAR WASTE

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The US Nuclear Regulatory Commission (NRC) recently developed a simplified generic analytic model for providing insights into the development of a more efficient and effective regulatory program in response to changes in the U.S. policy for disposal of high-level radioactive waste. The beta Scoping of Options and Analyzing Risks model (β-SOAR) incorporates simplified representations of components common to performance assessments of geologic disposal systems. Three distinct waste forms and four waste package materials are considered in the model. The near field component models radionuclide transport through the waste package internals, surrounding backfill, and the disturbed zone within the geologic host formation. The far field model incorporates three segments, each independently able to represent either sediments or crystalline rock under oxidizing or reducing conditions. System performance is measured in terms of release rates or dose. To highlight the flexibility of the β-SOAR, two simulations are presented. It is assumed that the conditions in the near and far field environments are reducing in the first simulation, and oxidizing in the second simulation. Performance is consistent with that expected for oxidizing versus reducing systems.

I. INTRODUCTION

In an effort to create a more efficient regulatory structure for the back-end of the nuclear fuel cycle, the U.S. Nuclear Regulatory Commission is developing a simplified performance assessment model to provide risk and performance insights on a range of nuclear waste geological disposal options. These efforts are in response to potential policy changes in the ultimate disposition of spent nuclear fuel. The beta Performance Assessment, Scoping of Options and Analyzing Risk (β-SOAR), is intended to support an effective and efficient risk-informed, performance-based licensing program for geologic disposal of HLW. The beta (β) designation in the model name indicates that this initial version of the model and the assigned default input parameters are considered preliminary, yet to undergo rigorous review and validation.

II. OVERVIEW OF PERFORMANCE ASSESSMENT MODELS

A performance assessment (PA) is a systematic analysis that can be used to evaluate complex systems where significant uncertainties exist. In the context of geological disposal of high-level waste, the objective of a PA is to provide risk and performance insights on the disposal system with respect to the risk triplet questions: What can happen? How likely is it? and What are the consequences?

The development of a PA for a geologic disposal system is a phased process making use of iterative modifications and enhancements as insights and knowledge are acquired. Generally, the first step is to conduct a scenario analysis that identifies the potential features, events, and processes (FEPs) and the associated uncertainties that may impact the disposal system. Once identified, the FEPs are incorporated into a quantitative analysis, commonly referred to as the PA. Once developed, the PA is exercised to develop risk and performance insights. As these insights are developed, the PA may be further revised to better capture dominant aspects controlling the risk, which can include either increasing or decreasing model complexity commensurate with the identified insights.

The level of detail necessary for designing a PA is commensurate with the intended application of the model. A distinction between site-specific and scoping PAs should be made. Development of PAs for a specific site can be a more complex endeavor when site-specific data and models for relevant local processes are available. As such, development of site-specific PAs can require significant resources. On the other hand, a generic or scoping PA incorporates data available in the literature and its development often is less labor intensive. Scoping PAs tend to have greater uncertainty in results, but are well suited for initial identification of factors affecting risk, and generation of early performance insights of geologic disposal systems.

The β-SOAR was developed as a scoping PA tool to assist in identifying preliminary risk and performance insights for a range of potential geologic disposal systems. However, the scoping PA has been developed in a manner that allows for potential future modifications that may allow the β-SOAR to be applied to more site-specific applications. The model architecture is such that flexibility allows for the inclusion of more site-specific data and detailed process models, as needed. Site-specific PA analyses can be used to further identify risk and performance insights that could support development of a regulatory framework in an evolving regulatory environment for licensing and regulating permanent disposal of high-level waste.

III. β-SOAR MODEL DEVELOPMENT

The β-SOAR model calculates performance of a hypothetical geologic nuclear waste disposal system. The geologic disposal system is conceptualized as having five main components: the waste form, waste package, disturbed near field, far field natural system and biosphere (Fig. 1). These components are consistent with those used in international performance assessments. Upon waste package failure, radionuclides may be released from the waste form and be transported to the near field via advection and diffusion in the aqueous phase. Additional transport may occur through the far field before any eventual release to the biosphere. The β-SOAR model utilizes two total-system performance metrics: dose to a receptor via ingestion of contaminated water and cumulative radionuclide release.

A few simplifying assumptions should be noted. First, the geologic disposal system is represented by a single representative waste package. Second, the geologic disposal system considers only isothermal conditions. Third, only the expected performance of the geologic disposal system is explicitly considered. However, modifications can be made to the model to consider the impact of disruptive events and are described in an accompanying paper (Ref. 2).

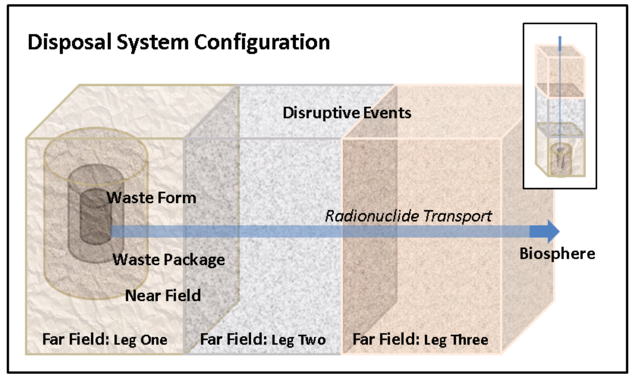

Fig. 1. The conceptualization of the hypothetical disposal system modeled in the β-SOAR.

The β-SOAR model was developed with flexibility to approximate a wide variety of geologic disposal systems as a key consideration. The mathematical code implemented in the β-SOAR utilizes generic representations of physical processes to allow for this flexibility, and is discussed below with respect to each of the five model components. The β-SOAR was developed in a visual-based software environment [GoldSim™ (registered trademark of GoldSim Technology Group LLC)] and extensively utilizes the in-model documentation capabilities. Additionally, the model utilizes a control panel, or dashboard, that allows rapid manipulation of certain key parameters (Fig. 2a-c). A majority of the β-SOAR parameter input values were developed based on a literature review, as documented in the β-SOAR User Guide (Ref. 2).

III.A. β-SOAR Model Components

The source term consists of both the waste form component and waste package component. The waste form component consists of five radionuclide inventories. Three of these inventories are matrix bound; and their release is controlled by the rate of waste form matrix dissolution. Degradation of each of these three waste forms is based on a unique fractional degradation rate. Two of these waste forms include unbound inventories associated with radionuclides accumulated in gaps (e.g., gaps with cladding material) and grain boundaries of the waste form. Radionuclides in the unbound inventory are assumed to be instantly released as soon as the waste package is breached. Note that waste form dissolution and radionuclide release can only occur after waste package failure. In the β-SOAR, three inventories are used to represent spent nuclear fuel, spent mixed-oxide fuel, and glass high-level waste from reprocessing. The two unbound inventories are used to represent the gap and grain boundary radionuclides associated with the spent nuclear and mixed oxide fuels. Additional information on the β-SOAR implementation of waste form degradation is available in the accompanying paper (Ref. 3) while potential future inventory modifications are discussed in another accompanying paper (Ref. 4). The waste package component consists of a representative waste package that encapsulates the waste form where the inventory is weighted based on the proportion of the individual inventories. Two failure mechanisms are conceptualized: distributed and stepwise. The distributed failure mechanism calculates waste package failures as a gradual process over time while the stepwise failure calculates instantaneous waste package failures. The β-SOAR utilizes the distributed and stepwise failure mechanisms to represent general corrosion and localized corrosion, respectively. Each of these failure mechanisms is associated with its own breach area. Additional information on the β-SOAR implementation of waste package degradation is available in the accompanying papers (Ref. 5 and 6).

The near field component consists of the transport region from the waste form to the far field. Three zones are conceptualized: the region inside the waste package, an optional buffer, and the region beyond the buffer to the first far field leg. Aqueous radionuclide transport in the near field occurs via diffusion and, if flowing water is assumed to be present, advection. Solubility limits and equilibrium sorption are considered and are a function of the redox environment and solid media present. Testing of the near field component is discussed in an accompanying paper (Ref. 7).

The far field component consists of three independent transport zones, or legs, each of which can be modified.

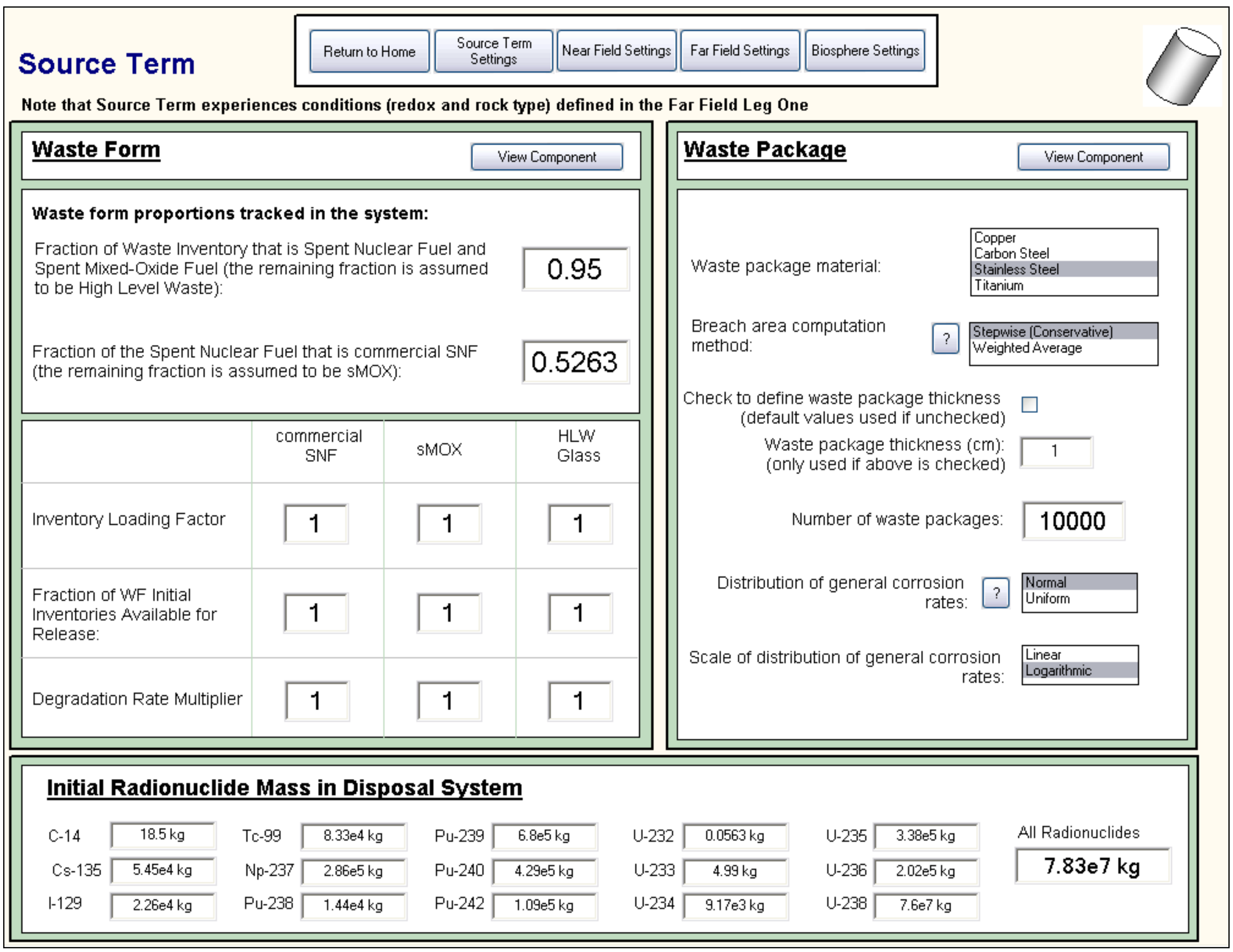

Fig. 2a. The dashboard controls for the waste form and waste package components.

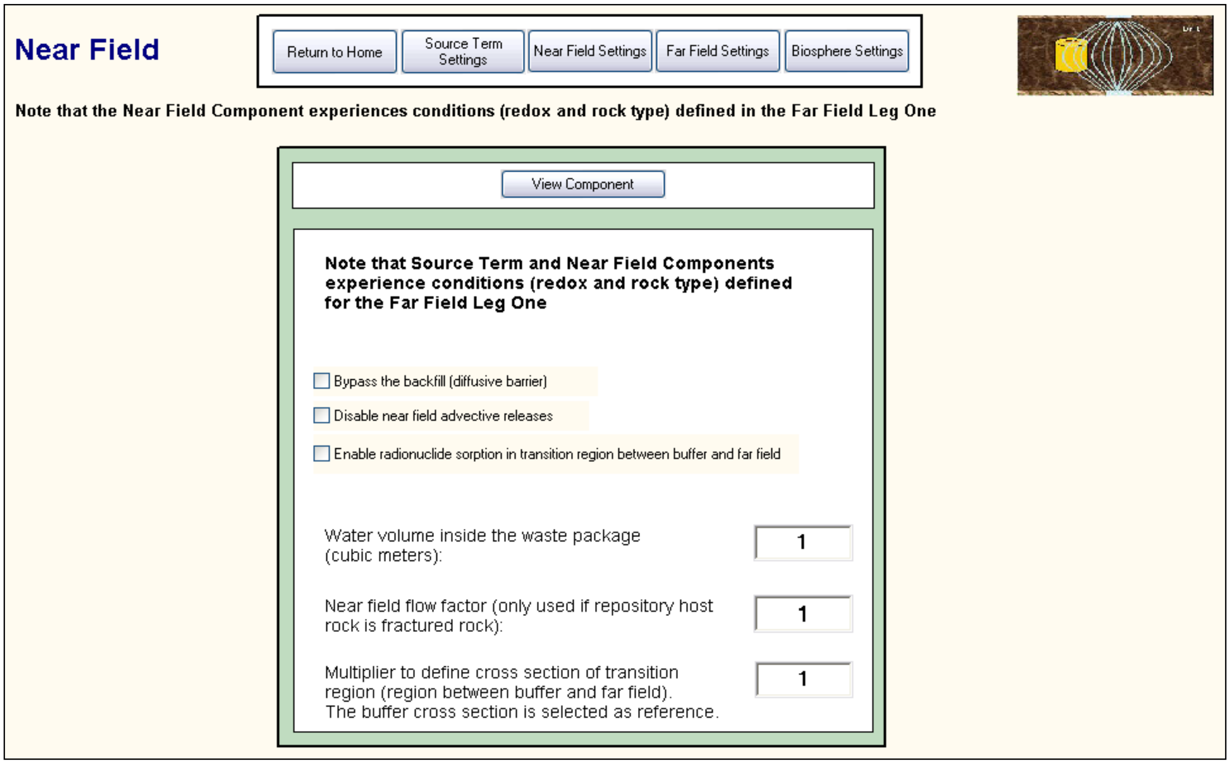

Fig. 2b. The dashboard controls for the near field (disturbed zone) component.

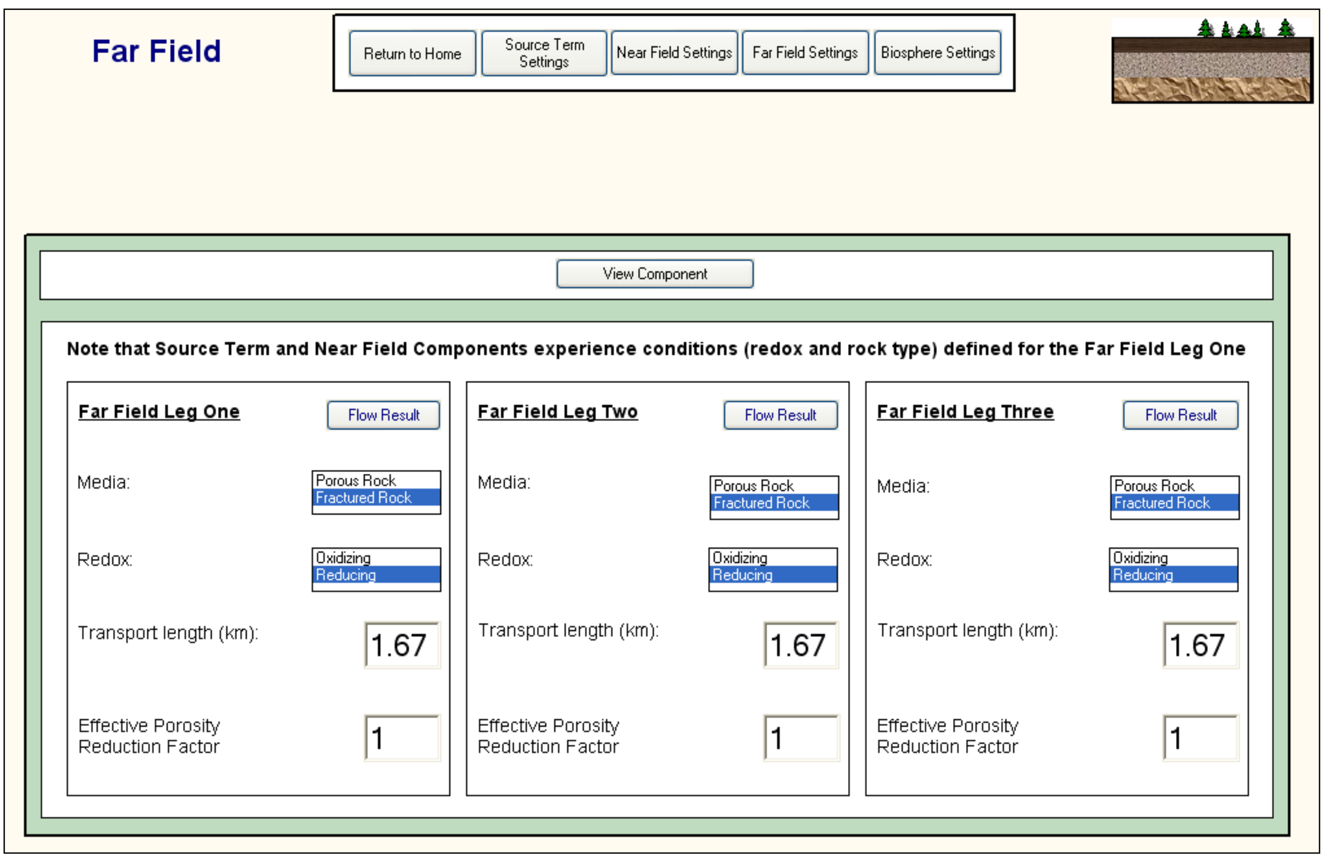

Fig. 2c. The dashboard controls for the far field (natural system) component.

Radionuclide transport through each of these three far field transport legs is governed by a one-dimensional, advective-dispersive equation with linear equilibrium sorption. Each transport leg can represent a fractured or porous media, under oxidizing or reducing conditions. Additionally, the length of each transport leg can be adjusted. The β-SOAR utilizes the porous and fractured media as alluvium and granite, respectively, with a total transport length of five kilometers. Note that the media and redox state defined in the first far field leg is used to define the media and redox state of the near field environment.

The biosphere component consists of the region beyond the third far field leg. Two system performance metrics are calculated in the biosphere component: dose and release. Radionuclides released from the far field are used to either calculate a drinking water ingestion dose or are used to calculate the integrated release. Additional information on the biosphere component is available in an accompanying paper (Ref. 8).

III.B. β-SOAR Model Flexibilities

As stated above, one of the key objectives in model development was to allow for flexibility to model a number of potential geologic disposal systems. Three levels of flexibility have been built into the β-SOAR model. Level-one flexibility is defined as changes that utilize the dashboard to modify the disposal system (Fig. 2a-c). Some changes associated with level-one flexibility include selecting the geologic media, waste package material, and length of the far field legs. Level-one flexibility can be exercised on the free model-viewing software, the GoldSim Player. Level-two flexibility is defined as changes to existing model input parameters. For example, the geologic media currently defined in the β-SOAR is parameterized with granite and alluvium parameters. With the GoldSim development software, a user could modify sorption coefficients and certain other parameters to instead represent basalt and clay. Level-three flexibility is defined by a change to the existing model structure. For example, a more detailed far field component could be developed and added to the β-SOAR.

IV. APPLICATION OF THE β-SOAR MODEL

As a preliminary test of the usefulness of the β-SOAR, two scenarios were simulated to assess the impact of redox on the performance of the geologic disposal system. The first scenario assumed that the near field and three legs of the far field were reducing, while the second scenario assumed that the near field and three far field legs were oxidizing. Apart from redox, the scenarios used default parameter settings. Key parameters in this simulation include a stainless steel waste package, presence of backfill, and a homogeneous, saturated 5-kilometer granite far field.

Dose results, as impacted by redox, are consistent with those found in the international literature (Fig. 3). In a reducing environment, corrosion of stainless steel tends to be slower than in an oxidizing environment. This would result in a later expected failure time in a reducing system, as predicted by the β-SOAR where doses occur earlier in an oxidizing system. Several radionuclides are redox sensitive, having lower mobility in reducing systems, including Tc-99 and the actinides. In the

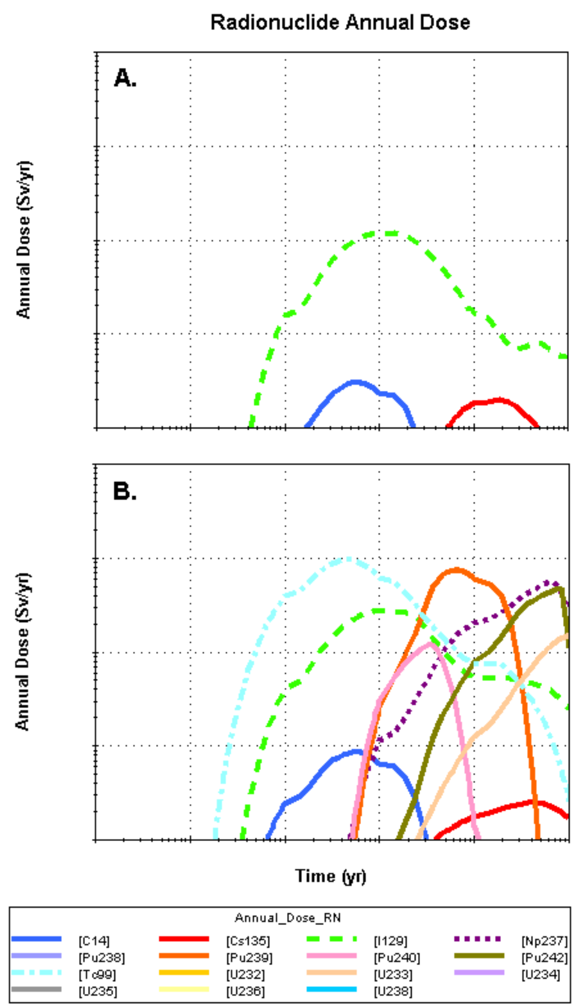

Fig. 3. β-SOAR dose results in a reducing (A.) and oxidizing (B.) geologic disposal system.

reducing system, Tc-99 is not a key contributor, whereas in the oxidizing system, it is the dominant contributor to dose in the early timeframe. A similar trend is seen in the actinides, where there is minimal contribution in a reducing system, but a greater contribution in the later timeframe in the oxidizing system. The timing of contribution of Tc-99 and the actinides to dose in the oxidizing system is generally governed by higher solubility and minimal tendency for Tc-99 to sorb to minerals in the natural environment. I-129 is not a redox-sensitive radionuclide, and minimal impact on dose would be expected based on redox alone. The β-SOAR shows that redox does, in fact, have minimal impact on I-129, identified by similar dose curves.

V. CONCLUSIONS

The β-SOAR was developed as a flexible, scoping PA in an effort to develop risk and performance insights for a range of potential geologic disposal systems. Flexibility to assess a variety of potential geologic disposal options was a key consideration during development of the model. Based on results from initial tests of the scoping tool, performance is consistent with that expected for oxidizing versus reducing systems.

ACKNOWLEDGMENTS

This paper was a joint effort between U.S. NRC and CNWRA staff under contract NRC 02–07–006–000. The NRC and CNWRA staff views expressed herein are preliminary and do not constitute a final judgment or determination of the matters addressed or of the acceptability of any licensing action that may be under consideration at the NRC.

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