COMPLIANCE DETERMINATION STRATEGY
RRT 3.2.3.7 POTENTIALLY ADVERSE CONDITIONS: GASEOUS RADIONUCLIDE MOVEMENT

APPLICABLE REGULATORY REQUIREMENTS:

10 CFR 60.122(c)(24)
10 CFR 60.21(c)(1)(ii)(B)
10 CFR 60.21(c)(1)(ii)(F)

TYPES OF REVIEW:

Acceptance Review (Type 1)
Safety Review (Type 3)
Detailed Safety Review Supported by Analysis (Type 4)

RATIONALE FOR TYPES OF REVIEW:

Acceptance Review (Type 1) Rationale:

This regulatory requirement topic (RRT) is license application-related because, as specified in the license application content requirements of 10 CFR 60.21(c) and the regulatory guide "Format and Content for the License Application for the High-Level Waste Repository" (FCRG), it must be addressed by the U.S. Department of Energy (DOE) in its license application. Therefore, the staff will conduct an Acceptance Review of the license application for this regulatory requirement topic.

Safety Review (Type 3) Rationale:

This regulatory requirement topic is related to containment and waste isolation. It is a requirement for which compliance is necessary to make a safety determination for construction authorization as defined in 10 CFR 60.31 (i.e., regulatory requirements in Subparts E, G, H, and I). Therefore, the staff will conduct a safety review of the license application to determine compliance with this regulatory requirement topic.

The regulatory requirement topic is concerned with a potentially adverse condition, potential for the movement of radionuclides in a gaseous state through air-filled pore spaces of an unsaturated geologic medium to the accessible environment. Three basic sets of issues must be addressed in an evaluation of the potential for gaseous radionuclide transport: i) the potential for radionuclide wastes proposed for Yucca Mountain to exist in a gaseous state, i.e., the volatility and stability of gaseous chemical species of radionuclides in the Yucca Mountain environment; ii) the inventory, distribution, and release rates of gaseous radionuclides from the waste forms and engineered barriers; and iii) the potential for gas phase transport of the radionuclides. It is assumed that uncertainties associated with the second issue (inventory, distribution, and release) will be addressed in other compliance determination strategies which focus on the engineered barrier system.

The proposed repository horizon at Yucca Mountain is located above the saturated zone. Measured porosities of the rocks of Yucca Mountain are commonly in the range of 5 to 20 percent. The porosity

is filled by both gas and liquid phases at liquid saturations typically measured to be 60 to 90 percent (Flint, 1990).

Spent nuclear fuel and associated hardware contain an inventory of radioactive carbon-14. Carbon-14 has been observed to oxidize upon release from spent fuel in an oxidizing environment. The geologic medium of the repository at Yucca Mountain is oxidizing. The radionuclide is likely to exist as a chemically stable gas species, notably $^{14}CO_2$ (and possibly metastable $^{14}CH_4$ or other species) under conditions likely to be present at Yucca Mountain. In the geologic medium $^{14}CO_2$ will mix in the natural carbon system. It will dissolve in the aqueous phase forming HCO_3- and CO_3^{2-}, and it may precipitate in calcite or adsorb on mineral surfaces. Nevertheless, a significant amount of carbon-14 will be maintained in the gas phase. Other radionuclides may exist as volatile gas species. Noble gas radionuclides such as Kr-85, Rn-220, and Rn-222 have a low solubility in water and gas transport would be only slightly retarded. However, they have short half lives and probably pose little risk to performance objectives for overall release. Other volatile radionuclide species have been postulated, e.g. Tc_2O_7, I_2, and SeO_2 containing Tc-99, I-129, and Se-79, respectively. Although, the low vapor pressures of these latter species may preclude significant gaseous transport, the potential requires evaluation.

CO_2 is a ubiquitous natural component of the gas phase in the ambient system at Yucca Mountain. There is a negligible source for ^{14}C in the natural geologic system. Therefore, ^{14}C observed to exist presently in vadose zone gases at Yucca Mountain must have been derived dominantly from its natural atmospheric (cosmogenic) source or from bomb pulse radioactivity remaining in the atmosphere. Transport of ^{14}C to depth may have been in the liquid and/or gas phase, and measured values may be affected by contamination associated with borehole drilling. There is currently strong if not conclusive evidence for gaseous transport of ^{14}C under natural conditions at Yucca Mountain (Thorstenson et al., 1989).

Gas flow and transport of gaseous species through pore spaces of the unsaturated zone at Yucca Mountain will be strongly accelerated by repository heating throughout the 10,000 year period of regulatory concern (Barnard et al., 1992).

Therefore, the potentially adverse condition of the potential for gaseous radionuclide transport through the porous, unsaturated, geologic medium is known to exist for the Yucca Mountain site.

Detailed Safety Review Supported by Analysis (Type 4) Rationale:

The staff considers that there may be high potential risk of noncompliance with applicable regulatory requirements because, for the Yucca Mountain site, there exist Key Technical Uncertainties concerning gas flow and gaseous radionuclide transport and the volatility and stability of chemical species of radionuclides. Therefore, the staff will conduct a Detailed Safety Review Supported by Analysis of the license application to determine compliance with this regulatory requirement topic.

Any finding made under this regulatory requirement topic may be considered highly uncertain due to the Key Technical Uncertainties, discussed below, related to uncertainties in radionuclide volatility, stability, gas flow, and gaseous radionuclide transport in the Yucca Mountain geologic repository system. Gaseous transport of radionuclides could cause a high potential risk of non-compliance with the overall system performance objective specified in 10 CFR 60.112. Gaseous transport of radionuclides also poses a risk of non-compliance with the substantially complete containment performance objective specified in 10 CFR 60.113(a)(1)(ii)(A) and the subsystem requirement for post-containment gradual release (1 part in 10,000 per year) from the engineered barrier system specified in 10 CFR 60.113(a)(1)(ii)(B). However, transport

that would jeopardize these engineered barrier containment performance objectives is assumed to occur in media other than the pore spaces of the geologic medium. Hence, uncertainties with regard to compliance with the engineered barrier system performance objectives are assumed to be addressed in other compliance determination strategies. In other words, the engineered barrier system, including any backfill material, is assumed not to be a geologic medium for the purposes of this compliance determination strategy.

Key Technical Uncertainties associated with radionuclide volatility and stability and gaseous transport are considered to require a Type 4 review because there is a high potential risk of non-compliance with the performance objectives of 10 CFR 60.112. This concern about high risk of non-compliance will necessitate analyses above and beyond those required for a Type 3 review to assure that the uncertainty, and the associated effects on performance assessment, have been minimized to a reasonable extent.

Key Technical Uncertainty Topic: Volatility and stability of chemical species of radionuclides

Description of Uncertainty: Gaseous transport of radionuclides can occur only if the nuclides exist in volatile chemical species. $^{14}CO_2$ is widely recognized as a likely predominant volatile radionuclide species derived from nuclear waste, and carbon dioxide chemistry is generally well understood. However, uncertainty exists with regard to the volatility and stability of other potential C-14 bearing species such as $^{14}CH_4$. Additional uncertainty exists with regard to the volatility and stability of other potential radionuclide carrying species including SeO_2, I_2 and Tc_2O_7. Because the potentially adverse condition of the potential for gaseous transport of radionuclides clearly exists at Yucca Mountain, a detailed review will be required to evaluate uncertainties with regard to the volatility and stability of chemical species of radionuclides. This review will require independent analyses using existing data for environmental conditions projected for the Yucca Mountain repository and for the chemical stability and volatility of potentially volatile radionuclide species.

Performance Objective at Risk: Total System Performance Objective (10 CFR 60.112)

Explanation of Nature of Risk: In the unsaturated repository environment at Yucca Mountain, with thermally induced gas flow expected to be significant, any radionuclide that can exist as a volatile species has a high likelihood of escaping by gaseous transport through the porous geologic medium to the accessible environment at the surface of the earth. This gaseous radionuclide transport would pose a high potential risk of noncompliance with the total system performance objective.

Although chemical data exist for the volatility of many species that could carry radionuclides derived from nuclear waste, difficulties arise in application of these data to the specific waste forms and near-field and far-field environments in a Yucca Mountain repository.

Description of Resolution Difficulty: A survey of possible gaseous species that could carry radionuclides can be made in a practical manner using existing data for vapor pressures. For most radionuclides, and possibly for all cases other than carbon-14, conservative assumptions of vapor pressures over pure oxide compounds of the radionuclides may be adequate to eliminate the potential risk of radionuclide transport. The stability of gaseous species with sufficient volatility to pose a possible risk of noncompliance with the performance objective must be evaluated in the context of the Yucca Mountain repository environment, which will pose numerous difficulties. Gaseous species stability will be affected by metastability and by kinetic processes such as catalysis. Environmental characteristics that may affect radionuclide stability include temperature, mineralogy, radiolysis, surface characteristics, and water

chemistry. It is assumed that uncertainties with regard to these environmental characteristics will be addressed in other compliance determination strategies. However, stability of gaseous species under these conditions constitutes the primary difficulty with regard to resolution of the key technical uncertainty.

For example, methane (CH_4) can exist indefinitely in a metastable state in an oxidizing environment (e.g., atmospheric air contains free oxygen and 0.17 percent methane). The solubility of CO_2 in water is 10 to 30 times greater than the solubility of CH_4, and CO_2 hydrolysis in water creates abundant HCO_3^- and CO_3^{2-}. Solubility in water is the main retardation process for gaseous carbon transport. Consequently, $^{14}CH_4$ transport would be far less retarded than $^{14}CO_2$ transport.

Key Technical Uncertainty Topic: Gas flow and gaseous radionuclide transport

Description of Uncertainty: Transport occurs in the gas phase by advection and diffusion. Large uncertainties exist in predicting gas flow because of the complexity of two-phase nonisothermal flow and the heterogeneity of the system. Nevertheless, conservative assessments must include significant gas flow from the repository horizon to the accessible environment at the surface of the earth throughout the period of regulatory concern. Intrinsic gas phase diffusion coefficients are relatively well known, but tortuosity, gas-filled porosity, gas conductivity, and mechanical dispersion effects are uncertain. Distribution of carbon and other volatile species among solids, solid surfaces, liquid, and gas can be estimated only approximately. The chemistry of the aqueous phase will remain uncertain, and sorption of carbon and other potential species on mineral surfaces has been poorly studied.

The magnitudes and heterogeneity of post-emplacement gas flow is unlikely to be well characterized prior to waste emplacement. For these reasons there will be significant uncertainty in any calculation of gas flow and transport. This uncertainty will require a detailed review, especially of hydrologic properties and independent analyses using existing computer models.

Performance Objective at Risk: Total System Performance Objective (10 CFR 60.112)

Explanation of Nature of Risk: In the unsaturated repository environment at Yucca Mountain, with thermally induced gas flow expected to be significant, any radionuclide that can exist as a volatile species has a high likelihood of escaping by gaseous transport through the porous geologic medium to the accessible environment at the surface of the earth. This gaseous radionuclide transport would pose a high potential risk of noncompliance with the total system performance objective.

Description of Resolution Difficulty: The primary difficulty in resolution of this issue will be to adequately characterize the site in order to develop a model of gas transport adequate for performance assessment. Depending on the placement scheme of the waste, a relatively small vertical zone of high permeability could lead to high releases. Small permeable horizontal layers could also greatly affect gas movement under certain conditions. In addition to the characterization difficulties, the coupling of moisture movement, heat transfer and gas transport is necessary to determine the effect of various infiltration rates and thermal loading schemes on gas movement. Existing models which incorporate this coupling are limited in their ability to allow for inclusion of small physical features and heterogeneity in the modeled stratigraphy.

Advective transport of radionuclides from the repository is due to temperature gradient induced gas flow, which will vary with time and repository loading. Atmospheric pressure changes may also induce gas movement in permeable strata, however, atmospheric pressure induced flow is not expected to result in

significant transport in the geologic medium under repository conditions. Gas flow and gaseous radionuclide transport out of containers may be significantly affected by atmospheric pumping, but this issue is beyond the scope of this compliance determination strategy. Diffusion of gaseous radionuclides is expected to be relatively minor compared to advective movement under expected repository thermal loading conditions. With a cool repository, however, both diffusion and atmospheric pumping could become the most significant transport mechanisms.

Sophisticated computer models of non-isothermal flow incorporating diffusion and time varying boundary conditions exist and are under continuing development. However, the rock characteristics such as the relations between permeability, moisture content, and suction potential for fractured rock can not be directly measured in situ, nor can they be, at present, accurately correlated with other measurable properties. The effects of varying degrees of heterogeneity are also unknown at this time, although they are being investigated.

Summary: The following assumptions have been made in assigning a Type 4 level of review for this compliance determination strategy:

(1) The Yucca Mountain repository site is located in unsaturated rocks.

(2) Demonstrable gaseous radionuclide transport occurs at Yucca Mountain under ambient conditions.

(3) Gaseous transport will be augmented by repository heating.

(4) The potential for gaseous radionuclide transport in the geologic medium of Yucca Mountain exists.

(5) Carbon-14 is a radionuclide component of high-level nuclear waste, and its release to the accessible environment poses a risk of noncompliance with applicable standards and regulations.

Reassessment: The level of review for this section of the license application may have to be reassessed in the future for a variety of reasons which can not all be anticipated. Possible causes requiring reassessment include:

(1) Regulatory changes to performance objectives eliminate carbon-14 release as a potential risk to compliance.

(2) A coherent and defensible model of gas flow for the Yucca Mountain repository fails to emerge from site characterization and performance assessment activities.

(3) Issues related to substantially complete containment and/or gradual release from the engineered barrier system are determined to be of concern for this compliance determination strategy.

REVIEW STRATEGY:

Acceptance Review:

In conducting the Acceptance Review of the potentially adverse condition concerning gaseous radionuclide transport, the reviewer should determine if the content of the license application is complete in technical breadth and depth with respect to the information requested by Section 3.2.3 of regulatory guide "Format

and Content for the License Application for the High-Level Waste Repository" (FCRG). The reviewer should determine whether the license application contains all appropriate information with respect to this potentially adverse condition that the staff needs to support the safety review (described below) and total system and subsystem performance assessments.

The information contained in the license application should be presented in such a way that the assumptions, data, and logic lead to a clear demonstration of compliance with the requirements. The reviewer should not be required to conduct extensive analyses or literature searches. The reviewer should also determine whether an appropriate range of alternative interpretations and models has been described.

Finally, the reviewer should determine if DOE has either resolved all NRC staff objections that apply to this regulatory requirement topic, or provided all information requested in Section 1.6.2 of the FCRG, for unresolved objections. The reviewer should evaluate the effects of any unresolved objections, both individually and in combination with others, on (1) the ability of the reviewer to conduct a meaningful and timely review, and (2) the ability of the Commission to make a decision regarding construction authorization within the three-year statutory period.

Safety Review:

This regulatory requirement topic is limited to consideration of the potential for gaseous transport of radionuclides in an unsaturated porous geologic medium to the accessible environment. This regulatory requirement topic does not address projections of repository performance as required in 10 CFR 60.21(c)(1)(ii)(C). These "projection" analyses will be covered in other review plans. The specific aspects of the license application on which the reviewer will focus are discussed in the FCRG, and the acceptance criteria will be identified in Section 3.0 of review plan 3.2.3.7 in the LARP.

Following the acceptance review, the first step in the NRC review will be to evaluate DOE's analyses to determine if the following basic assumptions have been met:

(1) The Yucca Mountain repository site is located in unsaturated rocks.

(2) Demonstrable gaseous radionuclide transport occurs at Yucca Mountain under ambient conditions.

(3) Gaseous transport will be augmented by repository heating.

(4) The potential for gaseous radionuclide transport in the geologic medium of Yucca Mountain exists.

(5) Carbon-14 is a radionuclide component of high-level nuclear waste, and its release to the accessible environment poses a risk of noncompliance with applicable standards and regulations.

If the above assumptions have been met, the staff review will follow the review strategy described here. If these assumptions are not met, the staff review may require a different review strategy for evaluating DOE's demonstration of compliance with the applicable regulatory requirements. It is expected, however, that any deviation from these assumptions will be known well in advance of the time a license application is submitted, and this strategy shall be revised in accordance with such new information as it becomes available to the staff.

In conducting the Safety Review, the reviewer will, at a minimum, determine the adequacy of the data and analyses to support DOE's demonstrations regarding 10 CFR 60.122(c)(24). Specifically, DOE will need to: (1) provide information to determine whether, and to what degree, the potentially adverse condition is present; (2) provide information to determine to what degree the potentially adverse condition is present, but undetected; (3) assure the sufficiency of the lateral and vertical extent of data collection; and (4) evaluate the information presented under Items (1) and (2) as stated above, with assumptions and analysis methods that adequately describe the presence of the potentially adverse condition and ranges of relevant parameters. The specific aspects of the license application on which the reviewer will focus are discussed below, and the Acceptance Criteria are identified in Section 3.0 of this Review Plan.

DOE will also need to provide an explanation of the measures applied to assess the presence or absence of evidence for the potential for gaseous radionuclide transport. Analyses and models used to predict future conditions and changes in the geologic setting should be supported by an appropriate combination of field tests, in-situ tests, laboratory tests which are representative of field conditions, monitoring data, and natural analog studies. For purposes of determining the presence or absence of this potentially adverse condition, investigations should extend from the surface to a depth sufficient to determine critical pathways for radionuclide migration from the underground facility, and to a depth sufficient to demonstrate a suitable understanding of the potential for gaseous radionuclide transport such that reasonable bounds can be placed on the different conceptual models.

In conducting the safety review, the reviewer should determine whether DOE uses both analyses sensitive to evidence of the potential for gaseous radionuclide transport, and assumptions which are not likely to underestimate the potential for gaseous radionuclide transport. In general, the reviewer should assess the adequacy of DOE's investigations of the potential for gaseous radionuclide transport both within and outside the controlled area, as necessary.

To conduct an effective review, the reviewer will rely on staff expertise and independently-acquired knowledge, information and data such as the results of research activities being conducted by the NRC Office of Regulatory Research, in addition to that provided by DOE in its license application. It is incumbent upon the reviewer to have acquired a body of knowledge regarding these and other critical considerations in anticipation of conducting the review to assure that the gaseous radionuclide transport program of the DOE is sufficient in scope and depth to provide the information necessary for resolution of the concerns.

Finally, the following DOE site characterization program study plans are expected to provide data and analyses needed in this review to address the presence (or absence) of this potentially adverse condition.

Detailed Safety Review Supported by Analysis:

A Detailed Safety Review will be needed to evaluate the Key Technical Uncertainties regarding volatility and stability of radionuclide species and gas flow and gaseous transport. This will ensure that DOE has adequately demonstrated Items (1)-(4), listed in the above discussion of the review strategy for a safety review. Activities performed in the detailed safety review will help assure that DOE has adequately addressed and resolved these Key Technical Uncertainties so that they do not lead to noncompliance with the total system performance objective of 10 CFR 60.112.

Examples of specific review activities that will be required include: (1) review and analysis of the radionuclides considered to have the potential for transport as gaseous species; (2) review and analysis

of chemical species considered to have volatility sufficient to transport radionuclides; (3) review and analysis of data for the hydrologic properties of the geologic setting that affect gas flow and transport; and (4) review and analysis of data for the distribution of volatile radionuclide species among bulk solids, solid surfaces, liquids and gases likely to occur in the Yucca Mountain geologic environment. The analysis should focus on the sensitivity, resolution and detection capabilities of the different techniques; the degree to which the separate techniques can provide independent assessments of the various features and characteristics of concern; and the degree to which the techniques provide information which either corroborates or contradicts results of the other techniques. It may also be appropriate to assess the quality and traceability of data and information by using staff with specific expertise in the review of quality assurance programs.

RATIONALE FOR REVIEW STRATEGY:

In view of the complexity of the Key Technical Uncertainties addressed above, it is appropriate that the NRC conduct the independent activities described in order to (1) develop the licensing tools and technical basis necessary to judge the adequacy of DOE's license application, (2) assure sufficient independent understanding of the basic physical processes taking place at the geologic repository, and (3) maintain independent but limited confirmatory research capability under NRC auspices.

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APPLICABLE REGULATORY REQUIREMENTS FOR EACH TYPE OF REVIEW

Type 1:
10 CFR 60.122(c)(24)
10 CFR 60.21(c)(1)(ii)(B)
10 CFR 60.21(c)(1)(ii)(F)

Type 3:
10 CFR 60.122(c)(24)

Type 4:
10 CFR 60.122(c)(24)

REFERENCES:

U.S. Nuclear Regulatory Commission, "Format and Content for the License Application for the High-Level Waste Repository" (FCRG), Office of Nuclear Regulatory Research.

Barnard, R.W., Wilson, M.L., Dockery, H.A., Gauthier, J.H., Kaplan, P.G., Eaton, R.R., Bingham, F.W., Robey, T.H. (1992) TSPA 1991: An initial total-system performance assessment for Yucca Mountain. Sandia Report SAND91-2795, Albuquerque, NM.

Flint, L.E. (1990) Preliminary permeability and water-retention data for nonwelded and bedded tuff samples, Yucca Mountain, Nevada. U.S.G.S. Open-File Rept. 90-569.

Thornstenson, D.C., Weeks, E.P., Haas, H., and Woodward, J.C. (1989) Physical and chemical characteristics of topographically affected airflow in an open borehole at Yucca Mountain, Nevada. Nuclear Waste Isolation in the Unsaturated Zone Focus '89, Amer. Nucl. Soc., La Grange Park, IL, p. 256-270.