COMPLIANCE DETERMINATION STRATEGY

RRT 5.4 ASSESSMENT OF COMPLIANCE WITH THE ENGINEERED BARRIER SYSTEM PERFORMANCE OBJECTIVES

TYPES OF REVIEW:

Acceptance Review (Type 1)
Safety Review (Type 3)
Detailed Safety Review Supported by Analyses (Type 4)
Detailed Safety Review Supported by Independent Tests, Analyses, or Other Investigations (Type 5)

RATIONALE FOR TYPES OF REVIEW:

Acceptance Review (Type 1) Rationale:

This regulatory requirement is considered to be License Application-related because, as specified in the License Application content requirements of relevant parts of 10 CFR 60.21(c)(1)(ii)(C) and the Format and Content Regulatory Guide (NRC, 1990a), it must be addressed by the DOE in its license application. Therefore, the staff will conduct an Acceptance Review of the License Application for this Regulatory Requirement.

Safety Review (Type 3) Rationale:

This regulatory requirement is related to radiological safety and waste isolation. Because this requirement is in 10 CFR Part 60, Subpart E, 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, I and relevant parts of 10 CFR 60.21). Therefore, the staff will conduct a safety review of the license application to determine compliance with this regulatory requirement.

The engineered barrier system (EBS) performance objectives [10 CFR 60.113(a)(1)] stipulate that the EBS shall be designed so that, assuming anticipated processes and events, containment of high-level waste within the waste packages shall be substantially complete during the containment period and that any release of radionuclides from the EBS shall be a gradual process which results in small fractional releases to the geologic setting over long times. To comply with these performance objectives, DOE is expected to develop extensive data to design and construct the EBS and to characterize the environment that the EBS will experience. DOE's compliance demonstration methods are expected to be based largely on predictive mathematical models of varying complexity and credibility and on subjective information obtained through expert elicitation.

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

The staff considers that there may be a high potential risk of non-compliance with this Regulatory Requirement because, for the Yucca Mountain site, there are several Key Technical Uncertainties. Therefore, predictions of the releases of radionuclides from waste packages and the EBS may vary widely and may lead to unwarranted conclusions concerning compliance with the EBS performance objectives. The staff believes that the risk of non-compliance due to the following Key Technical Uncertainties requires that a detailed safety review supported by analyses is justified.

Key Technical Uncertainty Topic:

Prediction of Thermomechanical Effects on Waste Package and Engineered Barrier System

Description of Uncertainty: Heat from emplaced waste packages will induce mechanical stresses in the emplacement borehole, the waste package, backfill, and the underground facility. These thermomechanical stresses may result in the degradation of repository materials (e.g., host rock, backfill, or EBS components). It will be difficult to quantify these stresses and even more difficult to predict the occurrence of fractures. The heat released will also result in elevated temperatures of the container material over a period of hundreds to thousands of years. These elevated temperatures may result in phase transformations or other unexpected changes in the behavior of the container material or other waste package components (Manaktala and Interrante, 1990).

Performance Objectives at Risk : Containment by Waste Packages and Gradual Release from EBS [10 CFR 60.113(a)(1)]

Explanation of Nature of Risk: Impingement of degraded repository materials on the container may: (1) rupture the container, resulting in loss of containment; or (2) contribute to local acceleration of container degradation, resulting in loss of containment or an unpredictable release rate of radionuclides. The phase transformations or property changes of the container material due to long-term exposure to elevated temperatures may result in a container that is more susceptible to penetration by corrosion or mechanical forces.

Description of Resolution Difficulty: DOE is expected to make substantial progress in resolving this Key Technical Uncertainty. In its Site Characterization Plan (SCP) (DOE, 1988a, pp. 8.3.4.2-27 -- 8.3.4.2-28; DOE, 1988b, p. 8.3.5.10-72), DOE recognized the need for obtaining information on thermomechanical effects on waste packages and the EBS. However, it is likely that considerable data gaps will exist and that DOE will use predictive analytical methodologies and expert opinion to resolve these data gaps.

Key Technical Uncertainty Topic:

Prediction of Environmental Effects on the Waste Package and the EBS

Description of Uncertainty: The environment of the waste package and the EBS is expected to change with time. Methodologies for predicting the changing environment are not currently available to the extent necessary to predict effects on long-term performance of the container or the EBS.

To predict the long-term performance of waste packages for containment and the EBS for gradual release, it will be necessary to understand the waste package and EBS environments at the time of emplacement, as well as changes in the environments with time. The major areas of environmental interest most likely to affect uncertainty in waste package life prediction are: (1) Thermohydrology; (2) Geochemistry (water chemistry, pH, Eh, rock chemistry, and trapped, dissolved, or circulating gases); (3) Radiation and Radiolysis; (4) Microbial Effects; and (5) Coupled and Synergistic Effects.

In addition to the above environmental concerns, there are other environmental concerns which may influence the response of the waste packages and EBS. These concerns fall broadly into the following classifications: (1) Hydrology and Climatology; (2) Geology; (3) Tectonics; and (4) Container Internal Corrosion.

Performance Objectives at Risk: Containment by Waste Packages and Gradual Release from EBS [10 CFR 60.113(a)(1)]

Explanation of Nature of Risk: The radioactive contents of the high-level waste (HLW) container provide a unique environment that could interact with and change the existing repository near-field environment and the container material. The interactions could possibly lead to new degradation modes or an acceleration in the rates of degradation observed in the absence of a radiation field, and the ability of the waste package and EBS to contain high-level waste could be compromised as a result. Synergistic effects of two or more of these factors could lead to more severe environmental effects than consideration of the environmental factors separately (Manaktala and Interrante, 1990).

As one example of environmental effects, heat from emplaced waste packages will alter the immediate environment of the waste package and the EBS by increasing the temperature, evaporating water and driving away moisture. A heat-pipe effect may result whereby moisture near the emplacement borehole is evaporated and driven away to the geologic setting, where it may condense and return with a different chemical composition, which might affect the ability to meet the long-term performance objectives of containment and gradual release as well as the overall performance objective.

Description of Resolution Difficulty: DOE's site characterization program should provide extensive data on the environment at Yucca Mountain and DOE's Engineered Barrier System Program should provide extensive data on the EBS. However, it is likely that considerable data gaps will exist and that DOE will use predictive analytical methodologies and expert opinion to resolve these data gaps.

Key Technical Uncertainty Topic:

Prediction of Release Rates of Radionuclides from Partially Failed Waste Packages

Description of Uncertainty: The EBS performance objectives require that DOE design the waste packages to contain radionuclides during the containment period and provide for gradual release of radionuclides from the overall engineered barrier system during the post-containment period. However, the prediction of the release rates of radionuclides from a partially failed waste package is problematic. First, there is a high risk that some significant container degradation modes will be overlooked. Second, for any particular container degradation mode, it will be difficult to accurately predict the size, shape, and distribution of the resulting container perforations and subsequent release from the waste package and the EBS. Third, even if the size, shape, and distribution of the perforations and release could be accurately estimated, estimating the diffusion of radionuclides through the waste package or the engineered barrier system will likely be mathematically intractable, unless simplifying assumptions of uncertain accuracy are used. Fourth, even if the flow rate of air or water effluent streams could be accurately estimated, the concentration of the individual radionuclide species in these effluent streams will likely be uncertain.

Performance Objectives at Risk: Containment by Waste Packages and Gradual Release from EBS [10 CFR 60.113(a)(1)]

Explanation of Nature of Risk: Radionuclide release rates can be significant from partially failed waste packages. Releases through small apertures and cracks in a waste package could affect compliance with the EBS performance objectives (Chambre *et al.*, 1986).

Description of Resolution Difficulty: It is expected that DOE will make substantial progress in resolving this technical uncertainty by analytical studies and experimental testing. However, it is not likely that this uncertainty will be fully resolved. In conducting a degradation analysis of a system, such as the EBS, for which there is no precedent, it is difficult to demonstrate, with reasonable assurance, that each possible degradation mode has been considered. Most existing analytical models that are used to evaluate container degradations predict only the onset of container penetration and do not predict the size, shape, and distribution of the perforations. The calculation of diffusion or fluid flow when a large number of perforations coexist on a waste package, is mathematically intractable and simplifying assumptions are necessary (Chambre *et al.*, 1986; Pescatore and Sastre, 1987). Considerable uncertainties currently exist (and are likely to persist) in modelling the dissolution of radionuclides in air and water effluent streams (Apted *et al.*, 1990). For example, there are inherent uncertainties that arise from solubility measurements. There is also uncertainty in the near-field chemical environment and its evolution over time. There is also uncertainty in determining which solubility-limiting solids will form and the characteristics of these solids.

Detailed Safety Review Supported by Independent Tests, Analyses, or Other Investigations (Type 5) Rationale:

The staff considers that there may be the highest potential risk of non-compliance with this Regulatory Requirement because, for the Yucca Mountain site, the following Key Technical Uncertainty is the most difficult to resolve. Therefore, there might be a high residual risk of non-compliance with the performance objectives specified below because very little can be done to reduce the risk, or compensate for the risk using, for example, favorable site conditions or engineered features. The potential for alternate interpretation and extrapolation of collected data by the license applicant in light of this Key Technical Uncertainty requires a detailed safety review supported by independent tests, analyses, or other investigations.

Key Technical Uncertainty Topic:

Extrapolation of Short-Term Laboratory and Prototype Test Results to Predict Long-Term Performance of Containers and Engineered Barrier Systems

Description of Uncertainty: The length of time specified in the regulations for containment by the waste package (300 to 1,000 years) and for gradual release from the EBS (greater than 1,000 years) exceeds the times commonly required in engineering design and also far exceeds the times that will be available for the testing and analysis of materials. Also, the extremely large number of containers (45,000 to 80,000) implies that scaling up from laboratory and prototype tests to the size of the repository is a unique endeavor. After the repository is closed and sealed, the waste package will be inaccessible. Therefore, a determination of reasonable assurance for containment and subsequent gradual release must come from a very high level of confidence in a scientific understanding of the effects of time and the environment on a repository system composed of an extremely large number of waste packages (Manaktala and Interrante, 1990). The reference material for the container, as described in the SCP (DOE, 1988c, p. 7-25), is a stainless steel, and such steels have been in existence for less than 100 years. By the end of FY93, the license applicant (DOE) will identify the specific material for the container along with further design details. The specific alloy chosen for the container material may be one which, like the stainless steel reference material identified early in the process, has a short service and experience history. Also, for such a material, natural analogs may not exist.

Performance Objectives at Risk: Containment by Waste Packages and Gradual Release from EBS [10 CFR 60.113(a)(1)]

Explanation of Nature of Risk: For some material degradation modes, the rate of degradation decreases with time. For example, in general corrosion, insoluble corrosion products or other protective films are often formed on the material surface which tend to diminish the corrosion rate. For these degradation modes, extrapolation of short term data and analyses to long times will be conservative. However, there are many other degradation modes (e.g., crevice corrosion, pitting corrosion, and waste form dissolution) in which there is an initial incubation period in which little or no degradation occurs, followed by rapidly increasing degradation. For these degradation modes, there is the highest risk that extrapolation of results from short-term tests and analyses will not provide reasonable assurance of complying with the EBS performance objectives of substantially complete containment and gradual release.

Description of Resolution Difficulty: Closure of this issue will be difficult because, currently, there is no rational scientific method for extrapolating relatively short-term data and experience to the long performance periods required for a geological repository. Such a method is needed to provide reasonable assurance that all significant waste package degradation modes have been identified and that predictions of waste package degradation rates will not underestimate the actual degradation rates. However, there can be no assurance that such a method will be available at the time that this safety review is performed. Accordingly, it is expected that a significant amount of expert judgement will be used by DOE in extrapolating short-term data and analysis. These extrapolations by DOE are likely to be highly controversial.

REVIEW STRATEGY:

Acceptance Review (Type 1):

In conducting the acceptance review of this EBS regulatory requirement, the reviewer should determine if the information presented in the license application and its references for demonstrating compliance with the requirement is complete in technical breadth and depth as identified in DG-3003 (NRC, 1990a). The license application and its references should include all appropriate information necessary for the staff to review the predicted performance of the waste package for containment and of the EBS for gradual release.

The information in the license application should be presented in a manner such that the assumptions, data, and logic leading to a demonstration of compliance with the requirement are clear and do not require the reviewer to make extensive analyses and literature searches. The reviewer should also determine that controversial information and appropriate alternative interpretations and models have been described and considered.

Finally, the reviewer should determine if DOE has either resolved all the NRC staff objections to the license application that apply to this requirement or provided information requested in Section 1.6 of DG-3003 for unresolved objections. The reviewer should evaluate the effect of any unresolved objections, both individually and in combinations 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 (Type 3):

In conducting the safety review, the reviewers will, as a minimum, determine the adequacy of the data and analyses presented in the license application to determine DOE's compliance with 10 CFR 60.113(a)(1). The Safety Review will assess whether the waste packages provide substantially complete containment (with reasonable assurance) and whether the waste packages and the other components of the EBS meet the gradual release requirement (with reasonable assurance). Staff's objectives of the Safety Review would be to: (1) understand and evaluate DOE's compliance demonstration logic; (2) conduct a preliminary review of the data base used for compliance demonstration to determine which parts of the data are most uncertain or that may be incomplete; (3) determine whether portions of the data and/or analyses submitted should be subjected to further detailed review (in addition to those areas requiring Type 4 and Type 5 detailed reviews specified below); and (4) determine whether the use of expert opinion (in lieu of experiments or analyses) was appropriate.

The specific aspects of the license application on which the review will focus are discussed in Section 5.2 of DG-3003 and the detailed acceptance criteria will be identified in Section 5.4 of the License Application Review Plan. In general, the reviewers will assess the adequacy of DOE's analyses of the design of the waste packages and the EBS with respect to the performance objectives for containment and gradual release from the EBS. The Safety Review will determine whether or not DOE's assessment shows that all anticipated processes and events have been considered and analyzed. For disposal in the saturated zone, the Safety Review will also determine whether or not DOE's assessment shows that both the partial and complete filling with groundwater of available void space in the underground facility have been considered and analyzed.

The Safety Review will also determine whether or not DOE's assessment shows that: (1) all the favorable conditions and potentially adverse conditions, that are characteristic of the site, have been considered in the demonstration that the EBS performance objectives expressed in 10 CFR 60.113(a)(1) have been met; and (2) the assumptions made in examining each potentially adverse condition are not likely to underestimate the effects of that condition on the EBS performance objectives expressed in 10 CFR 60.113(a)(1). Only anticipated processes and events will be considered in the assessment. (For disposal in the saturated zone, both partial and complete filing with groundwater of available void space in the underground facility shall also be appropriately considered and analyzed.)

In order to conduct an effective review, each reviewer will rely on his own expertise and independently acquired knowledge, information, and data in addition to that provided by the DOE in its license application. Therefore, it is incumbent upon each reviewer to have acquired a body of knowledge regarding critical considerations in anticipation of conducting the safety review to assure that the information provided is sufficient to resolve concerns. At a minimum, each reviewer must be familiar with the experiments and analysis on engineered barrier systems sponsored by DOE (e.g., Chambre *et al.*, 1986; Van Konynenburg *et al.*, 1986; Mallet, 1986; Liebetrau *et al.*, 1987; Zwahlen *et al.*, 1989; Apted *et al.*, 1990; Light *et al.*, 1990; Sadeghi *et al.*, 1990; Wilson, 1991; Zwahlen *et al.*, 1990;

Farmer *et al.*, 1991; Lee *et al.*, 1991; Lee and Choi, 1991; Leider *et al.*, 1991; Pescatore and Sullivan, 1991; and Ueng and O'Connell, 1992) and NRC (e.g., Interrante *et al.*, 1987a, 1987b, 1988a, 1988b, 1989, 1990, and 1991; Manaktala and Interrante, 1990; Wu *et al.*, 1990; and Cragnolino and Sridhar, 1991 and 1992).

Detailed Safety Review Supported by Analyses (Type 4):

A detailed safety review and analysis will be needed for evaluation of the Key Technical Uncertainties related to: (1) Thermomechanical Effects on the Waste Packages and EBS, (2) Environmental Effects on the Waste Packages and EBS, and (3) Prediction of Release Rates of Radionuclides from Partially Failed Waste Packages. This review will make use of data, models, analyses, and methodologies developed by DOE and/or other parties and reviewed and found acceptable by the staff. This will ensure that DOE has adequately demonstrated Items (1)-(4) listed in the previous section (Safety Review, paragraph 1). Probability and uncertainty analyses will be used to identify critical parameters whose associated uncertainties contribute in a major way to demonstration of compliance with the performance objectives. Activities performed in this Detailed Safety Review will help to assure that DOE has adequately addressed and resolved these Key Technical Uncertainties so that they do not lead to non-compliance with the EBS performance objectives.

The Detailed Safety Review of the Key Technical Uncertainty related to thermomechanical effects will require the staff to examine closely the data, analyses, and assumptions used by DOE to analyze thermomechanical effects on the waste packages and the EBS. The staff must assure that all reasonable thermomechanical effects have been considered by DOE and that the models used by DOE are not likely to underestimate the consequences of the thermomechanical effects on the structural integrity of the waste packages and the EBS. Detailed reviews will be supported by the staff's own analyses including the use of data and analytical models not considered by DOE, if appropriate.

The Detailed Safety Review of the Key Technical Uncertainty related to environmental effects will require the staff to examine closely the data, analyses, and assumptions used by DOE to analyze environmental effects on waste packages and the EBS. The staff must assure that all reasonable environmental effects have been considered by DOE and that the models used by DOE are not likely to underestimate the consequences of the environmental effects on the structural integrity of the waste packages and the EBS. Detailed reviews will be supported by the staff's own analyses including the use of data and analytical models not considered by DOE, if appropriate.

The Detailed Safety Review of the Key Technical Uncertainty related to partially failed waste packages will require the staff to examine closely the data, analyses, and assumptions used by DOE to predict radionuclide release rates from partially failed waste packages. The staff must assure that all reasonable release mechanisms have been considered by DOE and that the models used by DOE are not likely to underestimate the release rates. Detailed reviews will be supported by the staff's own analyses including the use of data and analytical models not considered by DOE, if appropriate.

Detailed Safety Review Supported by Independent Tests, Analyses, or Other Investigations (Type 5):

A detailed safety review, independent staff modeling, and the use of the results of staff investigations will be needed for the Key Technical Uncertainty related to the extrapolation of short-term laboratory and prototype test results to predict long-term performance of containers and engineered barrier systems. This will ensure that DOE has adequately demonstrated Items (1) - (4) listed in the section on safety review (Safety Review, paragraph 1).

In order to evaluate this Key Technical Uncertainty, the staff must review the waste package and EBS degradation modes considered by DOE to ensure that anticipated processes and events will not result in any credible degradation modes not analyzed by DOE. In conducting this review, each reviewer must have developed an understanding of the credible degradation modes that have been identified in DOE studies (e.g., Farmer *et al.*, 1991) and in independent NRC studies (e.g., Manaktala and Interrante, 1990).

The staff must also review DOE's data extrapolation procedures to ensure that these procedures are supported by the best available mechanistic models of the long-term performance of the waste package. In conducting this review, the staff must have developed an understanding of the degradation mechanisms that have been identified in DOE studies (e.g., Farmer *et al.*, 1991) and in independent NRC studies (e.g., The Integrated Waste Package Experiments Project).

Finally, the staff must review DOE's formal procedures for the elicitation of expert judgement to ensure that the use of the data and conclusions generated are not likely to result in non-compliance with the EBS performance objectives. In conducting this review, the staff must have developed an understanding of formal elicitation procedures that have been successfully used to address other complex technical issues (e.g., NRC, 1990b).

Contributing Analysts:

NRC Staff: K. Chang, D. Dancer, R. Weller

CNWRA Staff: E. Tschoepe, P.K. Nair

Date of Analyses: 11/16/92

RATIONALE FOR REVIEW STRATEGY (OPTIONAL):

Not applicable.

APPLICABLE REGULATORY REQUIREMENTS:

Type 3

10 CFR 60.113(a)(1)
10 CFR 60.21(c)(1)(ii)(C)

Type 4:

10 CFR 60.113(a)(1)

Type 5:

10 CFR 60.113(a)(1)

REFERENCES:

Apted, M., W. O'Connell, K. Lee, A. MacIntyre, T. Ueng, W. Lee, and T. Pigford, "Preliminary Calculations of Release Rates of Tc-99, I-129, and Np-237 from Spent Fuel in a Potential Repository in Tuff," Lawrence Berkeley Laboratory, Berkeley, California, LBL-31069, June 1990.

Chambre, P., W. Lee, C. Kim, and T. Pigford, "Steady-state and Transient Radionuclide Transport through Penetrations in Nuclear Waste Containers," in J.K. Bates and W.B. Seefeldt, eds., "Scientific Basis for Nuclear Waste Management X," *Materials Research Society Symposium Proceedings*, Boston, Massachusetts, December 1-4, 1986, Vol. 84, 1986, pp. 131-140.

Cragnolino, G. and N. Sridhar, "Integrated Waste Package Experiments" in "Report on Research Activities for Calendar Year 1990," Nuclear Regulatory Commission/Center for Nuclear Waste Regulatory Analyses, NUREG/CR-5817, December 1991.

Cragnolino, G. and N. Sridhar, "Integrated Waste Package Experiments," in "NRC High-Level Radioactive Waste Research at CNWRA, January 1 through June 30, 1992," Center for Nuclear Waste Regulatory Analyses, San Antonio, Texas, CNWRA 92-01S, September 1992.

Farmer, J.C., G.E. Gdowski, and R.D. McCright, "Corrosion Models for Predictions of Performance of High-Level Radioactive-Waste Containers," Lawrence Livermore National Laboratory, Livermore, California, UCID-21756, November 1991.

Interrante, C.G., E. Escalante, and A. Fraker, "Evaluation and Compilation of DOE Waste Package Test Data, Biannual Report: August 1988 - January 1989," Nuclear Regulatory Commission/National Institute of Standards and Technology, NUREG/CR-4735, Vol. 6, November 1990.

Interrante, C.G., E. Escalante, A. Fraker, D. Hall, S. Harrison, W. Liggett, M. Linzer, R. Ricker, J. Ruspi, and R. Shull, "Evaluation and Compilation of DOE Waste Package Test Data, Biannual Report: February 1987 - August 1987," Nuclear Regulatory Commission/National Bureau of Standards, NUREG/CR-4735, Vol. 3, May 1988a.

Interrante, C.G., E. Escalante, A. Fraker, S. Harrison, R. Shull, M. Linzer, R. Ricker, and J. Ruspi, "Evaluation and Compilation of DOE Waste Package Test Data, Biannual Report: August 1986 - January 1987," Nuclear Regulatory Commission/National Bureau of Standards, NUREG/CR-4735, Vol. 2, October 1987b.

Interrante, C.G., E. Escalante, A. Fraker, M. Kaufman, W. Liggett, and R. Shull, "Evaluation and Compilation of DOE Waste Package Test Data, Biannual Report: December 1985 - July 1986," Nuclear Regulatory Commission/National Bureau of Standards, NUREG/CR-4735, Vol. 1, March 1987a.

Interrante, C.G., E. Escalante, A. Fraker, H. Ondik, E. Plante, R. Ricker, and J. Ruspi, "Evaluation and Compilation of DOE Waste Package Test Data, Biannual Report: August 1987 - January 1988," Nuclear Regulatory Commission/National Bureau of Standards, NUREG/CR-4735, Vol. 4, August 1988b.

Interrante, C.G., E. Escalante, A. Fraker, and E. Plante, "Evaluation and Compilation of DOE Waste Package Test Data, Biannual Report: February 1988 - August 1988," Nuclear Regulatory Commission/National Institute of Standards and Technology, NUREG/CR-4735, Vol. 5, October 1989.

Interrante, C.G., A. Fraker, and E. Escalante, "Evaluation and Compilation of DOE Waste Package Test Data, Biannual Report: February 1989 - August 1989," Nuclear Regulatory Commission/National Institute of Standards and Technology, NUREG/CR-4735, Vol. 7, December 1991.

Lee, W.W. and J.S. Choi, "Release Rates from Partitioning and Transmutation Waste Packages," Lawrence Berkeley Laboratory, Berkeley, California, LBL-31255, December 1991.

Lee, W.W., M.M. Sadeghi, P.L. Chambre, and T.H. Pigford, "Waste-Package Release Rates for Site Suitability Studies," Lawrence Berkeley Laboratory, Berkeley, California, LBL-30707, April 1991.

Leider, H.R., S.N. Nguyen, R.B. Stout, and H.C. Weed, "Estimating the Time for Dissolution of Spent Fuel Exposed to Unlimited Water," Lawrence Livermore National Laboratory, Livermore, California, UCRL-ID-107289, December 1991.

Liebetrau, A.M., M.J. Apted, D.W. Engel, M.K. Altenhofen, D.M. Strachan, C.R. Reid, C.F. Windisch, R.L. Erikson, and K.I. Johnson, "The Analytical Repository Source-Term (AREST) Model: Description and Documentation," Pacific Northwest Laboratory, Hanford, Washington, PNL-6346, November 1987.

Light, W.B., E.D. Zwahlen, T.H. Pigford, P.L. Chambre, and W.W. Lee, "C-14 Release and Transport from a Nuclear Waste Repository in an Unsaturated Medium," Lawrence Berkeley Laboratory, Berkeley, California, LBL-28923, June 1990.

Mallet, R.H., "Buckling Design Criteria for Waste Package Disposal Containers," Battelle Memorial Institute, Columbus, Ohio, BMI/ONWI-597, December 1986.

Manaktala, H.K. and C.G. Interrante, "Technical Considerations for Evaluating Substantially Complete Containment of High-Level Waste Within the Waste Package," Nuclear Regulatory Commission/Center for Nuclear Waste Regulatory Analyses, NUREG/CR-5638, December 1990.

Nuclear Regulatory Commission, "Draft Regulatory Guide DG-3003: Format and Content For the License Application for the High-Level Waste Repository," Office of Nuclear Regulatory Research, DG-3003, November 1990a.

Nuclear Regulatory Commission, "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants -- Final Summary Report," NUREG-1150, December 1990b.

Pescatore, C. and C. Sastre, "Mass Transfer from Penetrations in Waste Containers," in M.J. Apted and R.E. Westerman, eds., "Scientific Basis for Nuclear Waste Management XI, *Materials Research Society Symposium Proceedings*, Boston, Massachusetts, November 30 - December 3, 1987, Vol. 112, 1987. pp. 773-782.

Pescatore, C. and T.M. Sullivan, "Modelling of Gaseous $^{14}CO_2$ Release from Perforations in Spent Fuel Disposal Containers, Brookhaven National Laboratory, Brookhaven, New York, BNL-52308, November 1991.

Sadeghi, M.M., T.H. Pigford, P.L. Chambre, and W.W. Lee, "Prediction of Release Rates for a Potential Waste Repository at Yucca Mountain," Lawrence Berkeley Laboratory, Berkeley, California, LBL-27767, October 1990.

Ueng, T.S. and W.J. O'Connell, "Diffusion Releases through One and Two Finite Planar Zones from a Nuclear Waste Package," Lawrence Livermore National Laboratory, Livermore, California, UCRL-ID-109215, July 1992.

U.S. Department of Energy, "Chapter 7, Waste Package," in "Yucca Mountain Site Characterization Plan, Yucca Mountain Site, Nevada Research and Development Area, Nevada," Office of Civilian Radioactive Waste Management, DOE/RW-0198, Vol. III, Part A, December 1988c.

U.S. Department of Energy, "Chapter 8 (Section 3.4.2), Waste Package Program," in "Yucca Mountain Site Characterization Plan, Yucca Mountain Site, Nevada Research and Development Area, Nevada," Office of Civilian Radioactive Waste Management, DOE/RW-0198, Vol. VI, Part B, December 1988a.

U.S. Department of Energy, "Chapter 8 (Section 3.4.5), Performance Assessment Program," in "Yucca Mountain Site Characterization Plan, Yucca Mountain Site, Nevada Research and Development Area, Nevada," Office of Civilian Radioactive Waste Management, DOE/RW-0198, Vol. VII, Part B, December 1988b.

Van Konynenburg, R.A., C.F. Smith, H.W. Culham, and H.D. Smith, "Carbon-14 in Waste Packages for Spent fuel in a Tuff Repository," Lawrence Livermore National Laboratory, Livermore, California, UCRL-94708, October 1986.

Wilson, M.L., "A Simplified Radionuclide Source Term for Total-System Performance Assessment," Sandia National Laboratories, Albuquerque, New Mexico, SAND91-0155, November 1991.

Wu, Y.T., A.G. Journel, L.R. Abramson, and P.K. Nair, "Uncertainty Evaluation Methods for Waste Package Performance Assessment," Nuclear Regulatory Commission/Center for Nuclear Waste Regulatory Analyses, NUREG/CR-5639, January 1991.

Zwahlen, E.D., T.H. Pigford, P.L. Chambre, and W.W. Lee, "Gas Flow in and out of a Nuclear Waste Container," *Transactions of the American Nuclear Society*, 60:109-114 [1989].

Zwahlen, E.D., T.H. Pigford, P.L. Chambre, and W.W. Lee, "A Gas-Flow Source Term for a Nuclear Waste Container in an Unsaturated Medium," American Nuclear Society/American Society of Civil Engineers, *Proceedings of the International High-Level Radioactive Waste Management Conference*, Las Vegas, Nevada, April 8-12, 1990, Vol.1, pp. 418-425.