Designation: ~~C1174 – 07 (Reapproved 2013)~~ C1174 – 17

Standard Practice for ~~Prediction~~Evaluation of the Long-Term Behavior of ~~Materials, Including Waste Forms,~~ Materials Used in Engineered Barrier Systems (EBS) for Geological Disposal of High-Level Radioactive Waste[1]

1. Scope

1.1 This practice ~~describes~~ addresses how various test methods and data analyses can be used to develop models for the ~~prediction~~evaluation of the long-term alteration behavior of ~~materials, such as~~materials used in engineered barrier system (EBS) ~~materials and waste forms, used in the geologic~~ for the disposal of spent nuclear fuel (SNF) and other high-level nuclear waste in a geologic repository. The alteration behavior of waste ~~form~~forms and EBS materials is important because it affects the retention of radionuclides ~~by the disposal system. The waste form and EBS materials provide a barrier to release either directly (as~~within the disposal system either directly, as in the case of waste forms in which the radionuclides are initially ~~immobilized),~~immobilized, or ~~indirectly (as~~indirectly, as in the case of EBS containment materials that restrict the ingress of groundwater or the egress of radionuclides that are released as the waste forms ~~and EBS materials degrade).~~degrade.

~~1.1.1 Steps involved in making such predictions include problem definition, testing, modeling, and model confirmation.~~

~~1.1.2 The predictions are based on models derived from theoretical considerations, expert judgment, interpretation of data obtained from tests, and appropriate analogs.~~

~~1.1.3 For the purpose of this practice, tests are categorized according to the information they provide and how it is used for model development and use. These tests may include but are not limited to the following:~~

~~1.1.3.1 Attribute tests to measure intrinsic materials properties,~~

~~1.1.3.2 Characterization tests to measure the effects of material and environmental variables on behavior,~~

~~1.1.3.3 Accelerated tests to accelerate alteration and determine important mechanisms and processes that can affect the performance of waste form and EBS materials,~~

~~1.1.3.4 Service condition tests to confirm the appropriateness of the model and variables for anticipated disposal conditions,~~

~~1.1.3.5 Confirmation tests to verify the predictive capacity of the model, and~~

~~1.1.3.6 Tests or analyses performed with analog materials to identify important mechanisms, verify the appropriateness of an accelerated test method, and to confirm long-term model predictions.~~

1.2 The purpose of this practice is to provide a scientifically-based strategy for developing models that can be used to estimate material alteration behavior after a repository is permanently closed (that is, the post-closure period) because the timescales involved with geological disposal preclude direct validation of predictions.

1.3 ~~The purpose of this practice is to provide methods for developing models that can be used for the prediction of materials behavior over the long periods of time pertinent to the service life of a geologic repository as part of the basis for performance assessment of the repository.~~ This practice also addresses uncertainties in materials behavior models and the impact on the confidence in the EBS design criteria, the scientific bases of alteration models, and repository performance assessments using those models. This includes the identification and use of conservative assumptions to address uncertainty in the long-term performance of materials.

1.3.1 Steps involved in evaluating the performance of waste forms and EBS materials include problem definition, laboratory and field testing, modeling of individual and coupled processes, and model confirmation.

1.3.2 The estimates of waste form and EBS material performance are based on models derived from theoretical considerations, expert judgments, and interpretations of data obtained from tests and analyses of appropriate analogs.

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[1] This practice is under the jurisdiction of ASTM Committee C26 on Nuclear Fuel Cycle and is the direct responsibility of Subcommittee C26.13 on Spent Fuel and High Level Waste.

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1.3.3 For the purpose of this practice, tests are categorized according to the information they provide and how it is used for model development, support, and use. These tests may include but are not limited to: accelerated tests, attribute tests, characterization tests, confirmation tests, and service condition tests.

~~1.3 This practice also addresses uncertainties in materials behavior models and their impact on the confidence in the performance assessment.~~

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory requirements prior to use.*

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C859 Terminology Relating to Nuclear Materials

C1285 Test Methods for Determining Chemical Durability of Nuclear, Hazardous, and Mixed Waste Glasses and Multiphase Glass Ceramics: The Product Consistency Test (PCT)

C1682 Guide for Characterization of Spent Nuclear Fuel in Support of Interim Storage, Transportation and Geologic Repository Disposal

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E178 Practice for Dealing With Outlying Observations

E583 Practice for Systematizing the Development of (ASTM) Voluntary Consensus Standards for the Solution of Nuclear and Other Complex Problems (Withdrawn 1996)[3]

2.2 *ANSI Standard:*[4]

ANSI/ASME NQA-1 Quality Assurance Program Requirements for Nuclear Facility Applications

2.3 *U.S. Government Documents:*

~~DOE/RW-0333P, Assurance Requirements and Description, USDOE OCRWM, latest revision~~

~~Code of Federal Regulations, Title 10, Part 60, Disposal of High-Level Radioactive Wastes in Geologic Repositories, U.S. Nuclear Regulatory Commission, January 1997~~[5][5]

NOTE 1—The U.S. government documents listed in 2.3 and referenced in this practice are only included as examples of local regulations that, depending on the location of the disposal site, may or may not be appropriate. Users of this practice should adhere to the regulatory documents and regulations applicable in the licensing location. The references listed below are explicit examples of local regulations.

Code of Federal Regulations, Title 10, Part 63, Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada, U.S. Nuclear Regulatory Commission, latest revision

~~Code of Federal Regulations Title 40, Part 191, Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes, July 2002~~[5]

Public Law 97-425, Nuclear Waste Policy Act of 1982, as amended

NUREG–0856, Final Technical Position on Documentation of Computer Codes for High-Level Waste Management (1983)

2.4 *International Documents:*

SKI Report 99:2 Regulatory Perspectives on Model Validation in High-Level Radioactive Waste Programs: A Joint NRC/SKI White Paper, Swedish Nuclear Power Inspectorate, March 1999[6]

IAEA SSR-5 Disposal of Radioactive Waste – Specific Safety Requirements, International Atomic Energy Agency (IAEA), Vienna, Austria, 2011[6]

IAEA GSG-3 The Safety Case and Safety Assessment for the Predisposal Management of Radioactive Waste, International Atomic Energy Agency (IAEA), Vienna, Austria 2013[6]

SSMFS 2008:37 Swedish Radiation Safety Authority Regulatory Code – General Advice, Swedish Radiation Safety Authority, Stockholm, January 30, 2009[7]

Finland Government Decree (736/2008) on the Safety of Disposal of Nuclear Waste, Radiation and Nuclear Safety Authority in Finland (STUK) Helsinki, November 27, 2008[8]

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The last approved version of this historical standard is referenced on www.astm.org.

[4] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

[5] Available from U.S. Government Printing Office, Superintendent of Documents, 732 N. Capitol St., NW, ~~Mail Stop: SDE,~~ Washington, DC ~~20401,~~20401-0001, http://www.access.gpo.gov.

[6] Available from International Atomic Energy Agency (IAEA), Vienna International Centre, PO Box 100, A-1400 Vienna, Austria, www.iaea.org.

[7] Available from Swedish Radiation Safety Authority (SSMFS), Solna Strandvag 96, 171 16 Stockholm, www.stralsakerhetsmyndigheten.se.

[8] Available from Finlex, www.finlex.fi/en/.

3. Terminology

~~3.1 *Definitions:*~~

~~3.1.1 Terminology used in this practice is per existing ASTM definitions, or as understood per the common English dictionary definitions, except as described below.~~

3.1 ~~*Regulatory*~~ *Definitions*[9]~~and Other Published Definitions—~~—Definitions used in this practice are as currently existing in Terminology C859~~of the particular terms below are based on the referenced Code of Federal Regulations, 10 CFR 63 and/or 10 CFR Part 60 which is pertinent to this standard and is under jurisdiction of the Nuclear Regulatory Commission (NRC). If precise regulatory definitions are needed, the user should consult the appropriate governing reference.~~, or as commonly accepted in dictionaries of the English language, except for those terms defined below for the specific usage of this practice.

~~3.2.1 *disposal*—the emplacement in a repository of high-level radioactive waste, spent nuclear fuel, or other highly radioactive material with no foreseeable intent of recovery, whether or not such emplacement permits the recovery of such waste.~~

~~3.2.2 *engineered barrier system (EBS)*—the waste packages and the underground facility, which means the underground structure including openings and backfill materials.~~

~~3.2.3 *geologic repository*—a system which is intended to be used for, or may be used for, the disposal of radioactive wastes in excavated geologic media. A geologic repository includes the geologic repository operations area, and the portion of the geologic setting that provides isolation of the radioactive waste.~~

~~3.2.4 *important to safety*—refers to those engineered features of the geologic repository operations area whose function is: *(1)* To provide reasonable assurance that high level waste can be received, handled, packaged, stored, emplaced, and retrieved without exceeding regulatory requirements for Category 1 design basis events; or *(2)* To prevent or mitigate Category 2 design basis events that could result in doses equal to or greater than the regulatory values to any individual located on or beyond any point on the boundary of the site.~~

~~3.2.5 *important to waste isolation*—refers to those engineered and natural barriers whose function is to provide reasonable assurance that high-level waste can be disposed without exceeding the regulatory requirements.~~

~~3.2.6 *high-level radioactive waste, (HLW)*—includes spent nuclear fuel and solid wastes obtained on conversion of wastes resulting from the reprocessing of spent nuclear fuel and other wastes as approved by the NRC for disposal in a deep geologic repository.~~

~~3.2.7 *waste form*—the radioactive waste materials and any encapsulating or stabilizing matrix in which it is incorporated.~~

~~3.2.8 *waste package*—the waste form and any containers, shielding, packing and other absorbent materials immediately surrounding an individual waste container.~~

~~3.2.9 *data*—information developed as a result of scientific investigation activities , including information acquired in field or laboratory tests, extracted from reference sources, and the results of reduction, manipulation, or interpretation activities conducted to prepare it for use as input in analyses, models or calculations used in performance assessment, integrated safety analyses, the design process, performance confirmation, and other similar work.~~

~~3.2.10 *scientific investigation*—any research, experiment, test, study, or activity that is performed for the purpose of investigating the material aspects of a geologic repository, including the investigations that support design of the facilities, the waste package and performance models.~~

~~3.2.11 *technical information*—information available from drawings, specifications, calculations, analyses, reactor operational records, fabrication and construction records, other design basis documents, regulatory or program requirements documents, or consensus codes and standards that describe physical, performance, operational, or nuclear characteristics or requirements.~~

~~3.2.12 *risk-informed*—refers to an approach to the licensing of a geologic repository based on the understanding that some risk will always exist and that the engineered barrier system and natural barrier system are designed to perform such that the risk is acceptable.~~

~~3.2.13 *risk-significant*—pertaining to an engineered barrier system material that has been determined to have a significant effect on the performance of the repository during the regulatory compliance period after closure.~~

~~3.2.14 *boundary dose risk*—the quantitative estimate of the expected annual dose to an individual at the repository site boundary over the compliance period weighted by the probability of occurrence.~~ ~~**(10 CFR 63.113)**~~

3.2 *Regulatory and Other Published Definitions*—Definitions of the particular terms below are generally consistent with the usage of these terms in the context of geological disposal of radioactive materials. If precise regulatory definitions are needed, the user should consult the appropriate governing reference.

3.2.1 *backfill*—the material used to refill excavated portions of a repository after waste has been emplaced.

3.2.2 *buffer*—any substance placed around a waste package in a disposal facility to serve as a barrier to restrict the access of groundwater to the waste package; and to reduce by sorption and precipitation the rate of eventual migration of radionuclides from the waste.

3.2.3 *data*—information developed as a result of scientific investigation activities, including information acquired in field or laboratory tests, extracted from reference sources, and the results of reduction, manipulation, or interpretation activities conducted

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[9] See *Compilation of ASTM Standard Definitions,* available from ASTM Headquarters, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

to prepare it for use as input in analyses, models, or calculations used in performance assessment, integrated safety analyses, the design process, performance confirmation, and other similar activities and evaluations.

3.2.4 *disposal—in high-level radioactive waste management*, the emplacement in a geologic repository of high-level radioactive waste, spent nuclear fuel, or other highly radioactive material with no foreseeable intent of recovery, whether or not such emplacement permits the recovery of such waste.

3.2.5 *engineered barrier system (EBS)*—the man-made, engineered materials placed within a repository (for example, waste forms, waste packages, waste canisters, backfill, buffer materials) that are designed to prevent or inhibit migration of radioactive material from the repository.

3.2.6 *geologic repository—in high-level radioactive waste management*, a system which is used for, or may be used for, the disposal of radioactive wastes in excavated geologic media.

3.2.6.1 *Discussion—*

A geologic repository includes the geologic repository operations area, and the portion of the geologic setting that provides isolation of the radioactive waste.

3.2.7 *high-level radioactive waste (HLW)—*generally composed of highly radioactive materials produced as a byproduct of the reactions that occur inside nuclear reactors that are disposed of in a deep geologic repository, such as spent nuclear fuel, and wastes resulting from the reprocessing of spent nuclear fuel.

3.2.8 *risk-informed*—refers to an approach that uses the results and findings of risk or performance assessments to focus attention on those attributes of a geologic repository commensurate with their importance to safety.

3.2.9 *scientific investigation*—any research, experiment, test, study, or activity that is performed for the purpose of investigating the material aspects of a geologic repository, including the investigations that support design of the facilities, such as EBS post-closure performance models.

3.2.10 *technical information*—information available from drawings, specifications, calculations, analyses, reactor operational records, fabrication and construction records, other design basis documents, regulatory or program requirements documents, or consensus codes and standards that describe physical, performance, operational, or nuclear characteristics or requirements.

3.2.11 *waste form*—the radioactive waste in its physical and chemical form after treatment or conditioning, or both, (resulting in a solid product) prior to packaging.

3.2.12 *waste package*—the waste form and any containers, shielding, packing, and other absorbent materials immediately surrounding an individual waste container.

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 The following definitions are defined only for the usage in this ~~standard,~~practice, and for the explanation of the analyses contained herein.

3.3.2 *accelerated test*—for the prediction of long-term behavior of materials, a test that results in an increase either in the rate of an alteration ~~mode~~process or in the extent of reaction ~~progress,~~progress when compared with expected service conditions. ~~Changes in the expected alteration mechanism(s) caused by the accelerated test conditions, if any, must be accounted for in the use of the accelerated test data.~~

3.3.2.1 *Discussion—*

Changes in the expected alteration mechanism(s) caused by the accelerated test conditions, if any, must be accounted for in the use of the accelerated test data.

3.3.3 *alteration*—~~any change in the form, state, or properties of a material.~~a measurable or visible change in a material affecting its chemical, physical, or radiological properties.

3.3.4 *alteration mechanism*—the series of fundamental chemical or physical processes by which alteration occurs.

3.3.5 *alteration mode—for the prediction of long-term behavior of materials,* a particular form of alteration, for example, ~~dissolution or passivation.~~general corrosion, localized corrosion.

3.3.6 *analog*—for the prediction of long-term behavior of materials, a material, process, or system whose composition and environmental history are sufficiently similar to ~~that~~those anticipated for the ~~materials~~ materials, processes, or systems of interest to permit use of insight gained regarding its condition or behavior to be applied to ~~a~~the material, process, or system of interest.

3.3.7 *attribute test*—for the prediction of long-term behavior of materials, a test conducted to provide material ~~properties~~ property data that are required as input to behavior models, but ~~that~~ are not themselves responses to the ~~environment. Examples are~~environment, such as density, thermal conductivity, mechanical properties, radionuclide content of waste forms, ~~etc.~~and so forth.

3.3.8 *behavior*—the response of a material to the environment in which it is placed.

3.3.9 *bounding model*—for the prediction of long-term behavior of materials, a model that yields values for dependent variables or effects that are expected to be either always greater than or always less than those expected for the variables or effects ~~to be~~ being bounded.

3.3.10 *characterization test*—~~in high-level radioactive waste management, any test or analysis conducted principally to furnish information used to determine parameter values for a model or develop a mechanistic understanding of alteration. Examples include polarization tests, solubility measurements, etc.~~for the prediction of long-term behavior of materials, a test conducted to establish alteration mechanisms for important processes, measure the effects of environmental variables on material changes (alteration) over time, and develop model parameter values.

3.3.11 *confirmation test*—~~a test in~~for the prediction of long-term behavior of materials, a test for which results are not used in the initial development of a model or the determination of parameter values for a model but are used for comparison with ~~the~~ predictions of that model for model validation.

3.3.12 *degradation*—any change in a material that adversely affects the ~~behavior~~ability of that material ~~or its ability~~ to perform its intended function; adverse alteration.

3.3.13 *empirical model*—a model ~~based only on~~ representing observations or data from ~~experiments,~~experiments without regard to mechanism or theory. An empirical model may be developed ~~from a direct fit of the experimental data such as a~~ by representing experimental data through regression analysis or may be developed ~~as a model which encompasses~~ to bound all the observed ~~data points; that is, a bounding model.~~data.

3.3.14 *extrapolation*—the act of ~~predicting~~estimating long-term material behavior beyond the range of data collected ~~by empirical observation in short-term tests.~~based on trend determined by empirical observation.

3.3.15 *in situ test*—tests conducted within a geological environment representing a potential repository. A special underground laboratory, called an underground research laboratory (URL), may be built for in situ testing or tests may be carried out in an actual repository excavation. In situ tests can be used to measure the full range of initial repository environmental properties and material interactions and under natural conditions.

3.3.16 ~~*in-situ test*—~~*mechanistic model*—~~a test conducted in the geologic environment in which a material or waste form will be emplaced.~~model derived using accepted fundamental laws governing the behavior of matter and energy to represent an alteration process (or processes).

3.3.17 *model*—a ~~simplified~~ representation of a system or phenomenon, based on a set of hypotheses (assumptions, data, simplifications, ~~and/or~~and idealizations) that describe the system or explain the phenomenon, often expressed mathematically.

~~3.3.17 *predict*—declare in advance the behavior of a material on the basis of a model.~~

~~3.3.18 *mechanistic model*—model derived from accepted fundamental laws governing the behavior of matter and energy. It corresponds to one end of a spectrum of models with varying degrees of empiricism.~~

~~3.3.19 *pyrophoric*—capable of igniting spontaneously under temperature, chemical, or physical/mechanical conditions specific to the storage, handling, or transportation environment~~

~~3.3.20 *semi-empirical model*—a model based partially on a mechanistic understanding and partially on empirical fits to data from experiments.~~

~~3.3.21 *service condition test*—a test with a material that is conducted under conditions in which the values of the independent variables characterizing the service environment are within the range expected in actual service.~~

3.3.18 *model validation*—the process through which model ~~predictions~~ calculations and results are compared with independent measurements or analyses of the modelled property to provide confidence that a model ~~accurately predicts~~adequately represents the alteration behavior of waste package/EBS materials under particular sets of credible environmental conditions. This provides confidence in the capability of the model to ~~predict~~estimate alteration behavior under conditions or durations that have not been tested directly. ~~An alteration model that has been demonstrated to provide bounding results under all credible environmental conditions, and is used to provide bounding values for the alteration behavior, may be regarded as validated for its intended usage.~~

3.3.18.1 *Discussion—*

Modelling the behavior of an engineered system in a geological disposal facility involves temporal scales and spatial scales for which no comparisons with system level tests are possible: models cannot be ‘validated’ for that which cannot be observed. ‘Model validation’ in these circumstances implies showing that there is a basis for confidence in the model(s) by means of detailed external reviews and comparisons with appropriate field and laboratory tests, and comparisons with observations of tests and of analogous materials, conditions and geologies at the process level. Although the term validation has been used in a geological disposal context, the term “validation” has typically been qualified regarding the limitations of its use in the context of geologic disposal. Thus, the term ‘validation’ is used sparingly in this practice and when used is referring to the activities taken to provide support for and confidence in models used for estimating the performance of materials for geologic disposal applications. Section 21 provides further discussion on model validation (support for and confidence in models).

3.3.19 *predict*—estimate the future behavior of a material by using a model.

3.3.20 *semi-empirical model*—a model based partially on a mechanistic understanding of an alteration process (or processes) and partially on empirical representations of observations using data from experiments.

3.3.21 *service condition test*—a test that is conducted under conditions in which the values of the independent variables are within the range expected for the actual service environment.

3.3.22 *service condition tests*—for the prediction of long-term behavior of materials, a test conducted to determine what material properties and alteration processes are likely to be important under environmental conditions expected during the performance period.

4. Summary of Practice

4.1 This practice covers the general approach for proceeding from the statement of a problem in ~~prediction of~~estimating the long-term behavior of materials, through the development, ~~validation,~~support, and confirmation of appropriate models, to formulation of the material performance models. Fig. 1~~actual predictions.~~ depicts the various steps in developing a model through to confirmation of the models during operations and the types of testing that could be used to support model development. This general depiction of model development and testing is used to provide an overall perspective for the contents and discussion presented in this practice and is not intended to be applied in an overly restrictive manner. For example, certain tests (for example, service conditions tests) are depicted as supporting model formulation; however, this should not be interpreted that these types of test would also not be able to provide support for other steps in model development (for example, model support and confidence). The figure is intended to correlate the types of tests and steps of model development in a general sense. Clearly, some tests may assist multiple modeling needs and purposes. The final step in model development (that is, long-term estimates of material performance) is correlated to a performance confirmation program that is expected to be implemented during the operational period and, at least in part, allow for monitoring of the actual materials in the repository environment (for example, waste packages with high-level waste emplaced in the repository drifts). The double arrows in Fig. 1 are used to represent the iterative nature of testing and model development. Although the steps in model development process can also be iterative, the vertical arrows in Fig. 1 are used to represent the progress of model development to its final step (estimating performance of the materials). Fig. 2 provides a more detailed depiction of the iterative nature and model development and testing.

5. Significance and Use

5.1 This practice supports the development of ~~materials~~material behavior models that can be used to ~~predict alterations in materials over the very long time periods pertinent to the operation~~ estimate performance of the EBS materials during the post-closure period of a high-level nuclear waste ~~repository; periods of time~~ repository for times much longer than can be tested directly. ~~Under the very extended service periods relevant to geological disposal—much longer periods than those encountered in normal engineering practice—equilibrium or steady state conditions may be achieved and models for reaction kinetics may be replaced by models, if justified, describing equilibrium extents of alteration.~~ This practice is intended for ~~use for waste form materials and materials~~ modeling the degradation behaviors of materials proposed for use in an EBS ~~that is~~ designed to contain radionuclides ~~released from high-level nuclear waste forms as they degrade~~ over tens of thousands of years and more. ~~Various U.S. Government regulations pertinent to repository disposal in the United States are as follows:~~There is both national and international recognition of the importance of the use and long-term performance of engineered materials in geologic repository design. Use of the models developed following the approaches described in this practice is intended to address established regulations, such as:

5.1.1 U.S. Public Law 97–425, the Nuclear Waste Policy Act of 1982, provides for the deep geologic disposal of high-level radioactive waste through a system of multiple barriers. ~~The radiation release limits are to be set by the U.S. Environmental Protection Agency (EPA) (40 CFR 191). Licensing of such disposal will be done by the~~ These barriers include engineered barriers designed to prevent the migration of radionuclides out of the engineered system, and the geologic host medium that provides an additional transport barrier between the engineered system and biosphere. The regulations of the U.S. Nuclear Regulatory Commission ~~(NRC).~~for geologic disposal require a performance confirmation program to provide data through tests and analyses, where practicable, that demonstrate engineered systems and components that are designed or assumed to act as barriers after permanent closure are functioning as intended and anticipated.

5.1.2 ~~The analyses described in this Standard Guide can be used to support the demonstration of compliance of the EBS components and design to the applicable requirements of 10 CFR 60 (pertaining to any HLW repository in the U.S.) and 10 CFR 63 (pertaining to the planned HLW repository at Yucca Mountain, NV).~~IAEA Safety Requirements specify that engineered barriers shall be designed and the host environment shall be selected to provide containment of the radionuclides associated with the wastes.

~~5.1.2.1 10 CFR 60.135 and 60.113 require that the waste form be a material that is solid, non-particulate, non-pyrophoric, and non-chemically reactive, and that the waste package contain no liquid, particulates, chemically reactive or combustible materials and that the materials/components of the EBS be designed to provide – assuming anticipated processes and events - substantially complete containment of the HLW for the NRC-designated regulatory period.~~

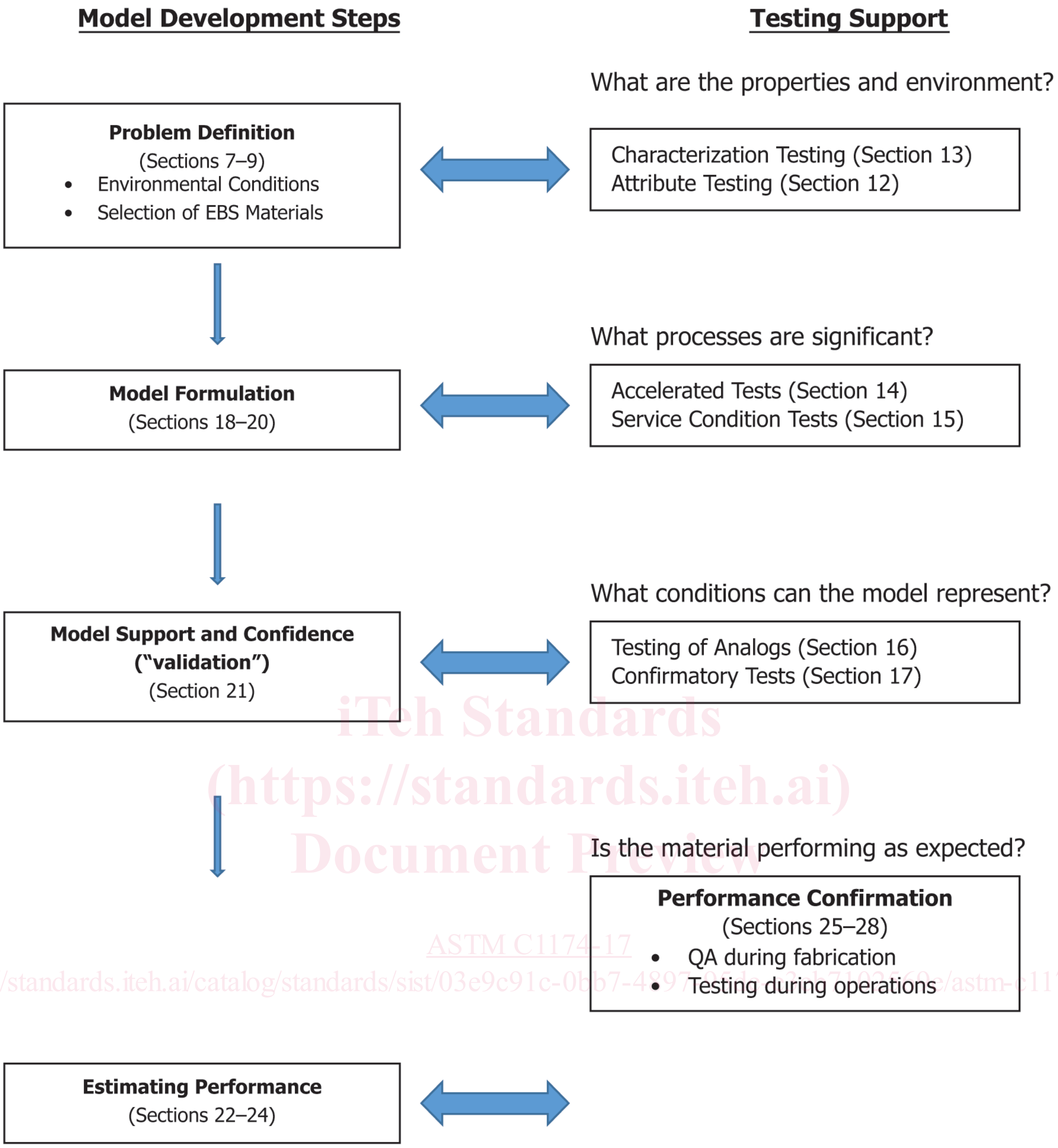

FIG. 1 Model Development Steps and Testing Support

~~5.1.2.2 10 CFR 63.113 provides that the EBS be designedsuch that, working in combination with the natural barriers, the performance assessment of the EBS demonstrates conformance to the annual reasonably expected individual dose protection standard of 10 CFR 63.311 and the reasonably maximally exposed individual standard of 10 CFR 63.312 , and shall not exceed EPA dose limits for protection of groundwater of 10 CFR 63.331 during the NRC-designated regulatory compliance period after permanent closure.~~

5.1.3 The ~~regulations of the U.S. Environmental Protection Agency (EPA) in Part 191 of Title 40 of the CFR provide that cumulative releases of radionuclides from the disposal system—this refers to the total system performance not just the EBS performance—for the regulatory compliance period after disposal shall have a likelihood of less than one chance in ten of exceeding the values stated for each radionuclide in the regulation. These environmental standards relate to the overall system performance of a geologic repository and they are referred to in NRC requirements of 10 CFR 60.112 and 63.111. Analyses of overall repository system performance may include anticipated and unanticipated events.~~Swedish Regulatory Authority has provided general advice to the repository developer that the application of best available technique be followed in connection with disposal, which means that the siting, design, construction, and operation of the repository and appurtenant system components should be carried out so as to prevent, limit, and delay releases from both engineered and geological barriers as far as is reasonably possible.

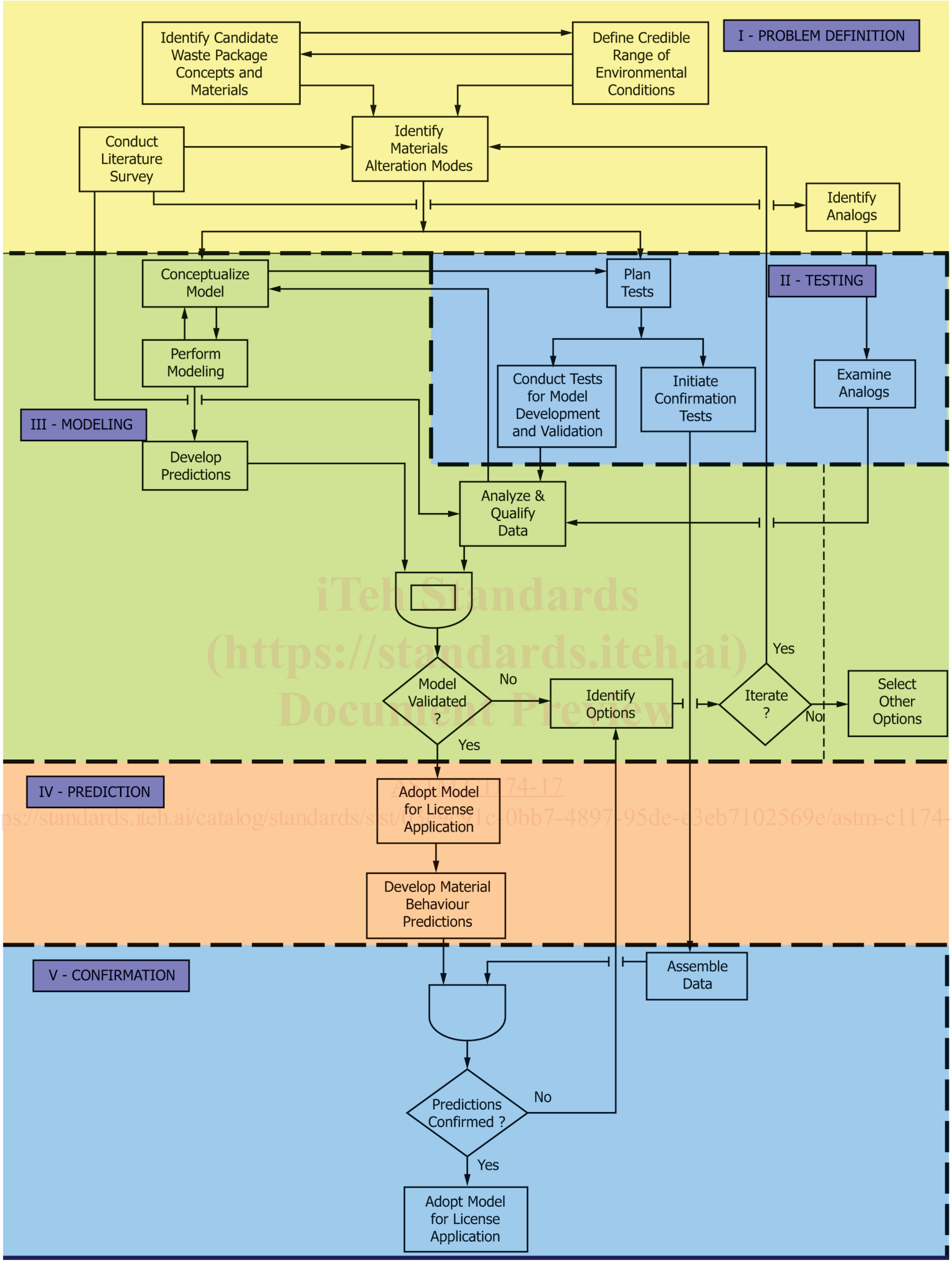

FIG. ~~1~~2 Logic for the Development of ~~Predictive~~ Models for Estimating the ~~Post-Closure~~Alteration Behavior of ~~Waste Package~~ Materials

5.1.4 The Regulatory Authority in Finland identified the need to support the safety assessment stating that the input data and models utilized in the safety case shall be based on high-quality research data and expert judgement. Data and models shall be validated as far as possible and correspond to the conditions likely to prevail at the disposal site during the assessment period.

5.1.5 The Office of Nuclear Regulation in the United Kingdom will regulate an operating geological repository under the Nuclear Installations Act through application of the Safety Assessment Principles developed for all nuclear facilities and the post-closure disposal period will be regulated under the Radioactive Substances Act by the Environmental Agency. The two regulators have a Memorandum of Understanding outlining how the regulators work together (onr.org.uk/wastemanage/position-statement.pdf).

5.2 ~~The current governing regulations are 10 CFR 60 as applicable to generic requirements for a repository in the US and 10 CFR 63 as applicable to the proposed repository site at Yucca Mountain. Other site-specific regulations may be required in the development of any alternative or additional US geologic repository site (per 10 CFR 60).~~ This practice aids in defining acceptable methods for making useful estimations of long-term behavior of materials from such sources as test data, scientific theory, and analogs.

5.3 This practice recognizes that technical information and test data regarding the actual behavior of ~~waste forms and materials that are used in the EBS and exposed to repository conditions for such long periods of time will not be sufficient to develop fully validated models in the classical sense. Rather, the (necessarily) short-term test data acquisition, and use of the data in formulating reliable long-term predictive models, is to be~~ EBS materials will by necessity be based on test durations that are short relative to the time periods required for geologic disposal (for example, thousands of years and longer). In addition to use in formulating acceptable long-term performance models data from short-term tests are used to support the ~~design, performance assessment, and even the selection of waste package/EBS materials (e.g.,~~ EBS design and selection of materials. For example, low confidence in a degradation model for one material may justify the selection of alternative EBS barrier ~~materials).~~ materials that can be modelled with higher confidence. It is expected that the data and model will reflect the intended application of establishing design criteria, comparison of performance assessment results with safety limits, etc. See Section 21 for further discussion on model support and confidence.

~~5.4 This practice aids in defining acceptable methods for making useful predictions of long–term behavior of materials from such sources as test data, scientific theory, and analogs.~~

5.4 The EBS environment of interest is that defined by the natural conditions (for example, minerals, moisture, biota, and mechanical ~~stresses) as modified by effects of time,~~ stresses); changes that occur over time, during repository construction and ~~operations, and the consequences~~ operation, and as a consequence of radionuclide decay, ~~for example radiation radiation damage, heating., and radiolytic effects.~~ namely, radiation, radiation-induced damage, heating, and radiolytic effects on the solution chemistry; and changes that may occur over the post-closure period. Environmental conditions associated with ~~both anticipated and unanticipated scenarios should~~ disruptive events (for example, mechanical stress from seismic events) and processes (for example, changes in water chemistry) should also be considered.

6. General Procedure

6.1 ~~*Development of Modeling Approach:*~~ The major elements in the approach to develop models for estimating the long-term behavior of EBS materials are problem definition, testing, modeling, performance estimate, and confirmation. Fig. 2 is a flow chart showing the logical approach for model development followed in this practice. Although it is not expected that the structure of Fig. 2 will apply exactly to every situation, especially as to the starting point and the number and type of iterations necessary to obtain acceptable alteration models, it is likely that the development of models for most materials will contain these major elements. Details on the individual elements are given in Sections 7 – 26. Development of performance models will likely be conducted under a quality assurance program as discussed in Section 27. An important aspect of performance models is the uncertainty of the model, including uncertainties in the form of the model, the data used to determine model parameters, and the environmental service conditions to which the model is applied. The consequences of these uncertainties with regard to the performance of the disposal system are used to determine the uncertainty in the risk. These are discussed in Section 24.

~~6.1.1 Fig. 1 outlines the logical approach for the development of models for the prediction of the long-term behavior of waste form and EBS materials in a repository. The major elements in the approach are problem definition, testing, modeling, prediction, and confirmation. It is not expected that Fig. 1 will apply exactly to every situation, especially as to the starting point and the number and type of iterations necessary to obtain validated alteration models. However, it is likely that development of models will contain these major elements. Details on these elements are given in Sections 7 – 26. Development of predictive models will likely be conducted under a quality assurance program as discussed in Section 27. An important aspect of predictive models is determination of the uncertainty of the model , including uncertainties in the form of the model (that is, how well the model represents the physical system or process), uncertainties in the data used to determine model parameters, uncertainties in the predicted environmental service conditions to which the model is applied, etc. The consequences of these uncertainties with regard to the performance of the disposal system are used to determine the risk.~~

6.2 *Identification of ~~Risk-Significant Waste Form and EBS Material Behavior Characteristics:~~ Materials:*

6.2.1 ~~Using a~~ The various materials to be evaluated for use in the systems, structures, components, and barriers that are designed and deployed to contain radionuclides within the repository environment must be identified. A risk-informed approach to repository performance ~~assessment, those waste form and engineered barrier materials behavior characteristics~~ assessment can be used to identify the behavior characteristics of those materials that may substantially contribute to risk ~~(by~~by affecting the release of radionuclides from the repository over the ~~regulatory compliance period) are included in the final performance assessment. However, the repository operator must perform initial performance assessments to~~post-closure period. Performance assessments can analyze the sensitivity ~~of~~to specific materials ~~alteration processes to fully identify those barriers that are important to safety and those barriers that are important to waste isolation.~~and alteration processes and disruptive events (for example, seismic activity) to identify the attributes of particular EBS materials that are most important for limiting the release of radionuclides over the long time periods of geologic disposal. It is the long-term behavior of these risk-significant materials that is the subject of this procedure.~~ Criteria for identifying materials that may be risk-significant are the following:~~

~~6.2.1.1 Materials, systems, structures, components, and barriers that are depended on to contain the waste form within the repository environment,~~

~~6.2.1.2 Materials, systems, structures, components, and barriers that are deployed to protect the containment of the waste form, and~~

~~6.2.1.3 Natural barriers that hold up release of waste radionuclides in the event of containment material failure and waste form degradation.~~

6.2.2 ~~EBS and waste form materials whose degradation characteristics~~ Modeling the alteration behaviors of EBS materials having degradation characteristics that are determined to be important to waste isolation needs to be performed with sufficient accuracy and precision to determine the useful lifetimes and expected performance of these materials. All relevant degradation processes need to be understood sufficiently so that the impact of these materials is not under-estimated and modeling outputs can be used to provide reliable input to risk-based decision making / optimization. The alteration behaviors of EBS materials having degradation characteristics that are determined to be unimportant to waste isolation ~~should be evaluated to determine their useful lifetimes and expected performance, but their behavior models may~~ do not need to be ~~as mechanistically based as those~~ modelled with the same accuracy and precision as those materials deemed to be important to waste isolation.

6.3 *Identification of Credible Ranges for Environmental Conditions:*

6.3.1 The alteration behavior of a material will depend on the environment in which it is used. The environment within a disposal system will be affected by both the natural conditions and ~~the effects~~ events, the design and materials used in the EBS, and by the alteration of EBS components. For example, ~~corrosion of EBS materials and radiolysis will significantly alter~~ the chemistry of ~~the~~ groundwater that contacts the waste ~~forms.~~ forms will be significantly affected by reactions with the natural materials, the thermal effects of waste emplacement, corrosion of EBS materials, and radiolysis. The anticipated range of repository environments throughout the post-closure period should be defined and ~~validation of model predictions be done over this range. Tests conducted under conditions outside this range could serve as accelerated tests.~~the model developed using test results representing this range to the extent practical.

PROBLEM DEFINITION

7. Scope

~~7.1 Problem definition includes evaluation of the following issues that are important in the development of models to support predictions of long-term behavior of repository materials:~~

~~7.1.1 Identification of potential environmental conditions to which the materials may be exposed,~~

~~7.1.2 Identification of possible waste-package design concepts,~~

~~7.1.3 Identification of waste package materials, including waste forms,~~

~~7.1.4 The identity, composition, and condition of the waste forms and important radionuclides,~~

~~7.1.5 Identification of potential materials alteration modes,~~

~~7.1.6 Identification of appropriate natural analog materials, and~~

~~7.1.7 Literature surveys and other sources of information helpful in characterizing the alteration of EBS and waste package materials.~~

7.1 The objective of the problem definition ~~approach~~ is to identify the ~~processes and interactions~~ materials and environments to be assessed and the processes, interactions, and alteration modes that should be included in the ~~predictive model and possible alteration modes.~~ models. This information is used to design conceptual models and design tests to develop and evaluate process models. An extensive list of features, events, and processes (FEPs) that should be considered has been compiled and utilized world-wide; however, many of these FEPs lists tend to be more generic than specific to a particular site or material. A generic FEPs list is a reasonable starting point for developing more site and material specific FEPs that would be expected to address the specific materials and site conditions being investigated.

7.2 In this practice, methods are recommended for the development of ~~predictive~~performance models for long-term ~~alterations of EBS and waste package materials, including waste forms,~~ alteration of EBS materials that are proposed for use in the geologic disposal of high-level radioactive wastes. This practice recommends a methodology for assessments of performance of materials proposed for use in systems designed to function either for containment or control of release rates of radionuclides.

7.3 Problem definition includes identifying factors that are important in the development of models to support evaluations of long-term behavior of repository materials during the post-closure period. This can be done using literature surveys and other sources of information helpful in characterizing the alteration of EBS materials. The key factors include the following:

7.3.1 Identification of potential environmental conditions to which the material may be exposed,

7.3.2 Identification of possible EBS design concepts,

7.3.3 Identification of EBS materials,

7.3.4 The identity, composition, and condition of the waste forms,

7.3.5 Identification of potential materials alteration modes, and

7.3.6 Identification of appropriate natural analog materials.

7.4 This practice outlines a logical approach for ~~predicting~~estimating the behavior of materials over times that greatly exceed the time over which direct experimental data can be obtained. It emphasizes accelerated tests ~~and/or~~and the use of models that are based on an appropriate mechanistic understanding of the processes involved in long-term alterations of materials used under repository conditions.

8. General Considerations

8.1 *Site Characterization*—A potential repository site must be investigated with respect to its geologic, hydrologic, seismic, etc. ~~conditions.~~ conditions that could affect the performance of the repository. For purposes of this practice, site characterization includes the identification of likely impacts of the environmental conditions on the ~~behaviors~~behavior of the ~~waste form and~~ EBS materials (see 8.5.1, 9.1, and 10.2).

8.1.1 *Environment*—The geologic environment shall be evaluated by characterization of the initial environment and mechanical condition and consideration of the effects of time and alteration of EBS and waste form materials on the environment. Ranges in the values of such environmental conditions as temperature, groundwater chemistry, ~~and colloid content~~ microbiology, colloid content, and disruptive events (for example, seismic activity) may be needed to account for changes in the environmental conditions that occur over time. A special underground laboratory, called an underground research laboratory (URL), may be built to enhance characterization activities and for in situ testing or tests to be carried out in a representative repository excavation.

8.2 *Conceptual Designs*—A general concept for an EBS design ~~is devised~~ can be initially developed to meet regulatory ~~requirements. Specific designs for the components of the EBS are developed~~ requirements based on current understanding ~~of~~ of: (*1*) the conditions of a particular site, and (*2*~~the waste package design.~~) the performance of EBS materials under the site conditions.

8.3 *Materials Identification*—From the initial concepts and investigations of a repository site, candidate EBS ~~and waste package~~ component materials are proposed based on the geologic environment and the conceptual design. Since these materials serve the function of containment and control of potential radionuclide release rates, their alteration behavior under the set of conditions expected in the repository over long time periods must be reliably determined and the alteration modes understood. This understanding is developed by first reviewing both the available information regarding the environmental conditions and the effects of the environment on the candidate materials.

8.3.1 Information regarding natural analogs might be available to provide early guidance for the selection of EBS component materials ~~and/or~~and the long-term alteration of these ~~and waste form~~ materials in the repository environment.

8.3.2 The selection of ~~WP/EBS~~ materials for ~~waste package and/or EBS application, or the way in which waste forms are configured within a waste package, could also~~ the EBS could be influenced by the ~~level of validation attainable for the~~ support and confidence for degradation rate ~~model.~~models. This approach could lessen the need for hard-to-achieve high confidence levels in a degradation model. For example, a container material that exhibits a moderate but predictable rate of general corrosion, but is not susceptible to localized corrosion, might be selected for use as a corrosion barrier and the thickness of the wall engineered to provide for a 'corrosion allowance.'

8.4 *Ranges of Materials Properties ~~and/or~~and Environmental Conditions*—Preliminary descriptions of the materials to be tested shall be used to determine their physical and mechanical properties. Frequently, a range of values will be needed to specify parameters used to characterize materials.

8.4.1 *Ranges*—A range of parameter values for environmental conditions or material properties may be used to account for ~~uncertainty in~~ uncertainty. For example, environmental conditions may include the anticipated temporal and spatial ~~variability in the environmental condition, etc. The waste forms themselves will likely have to~~ variability, and the waste forms may be described by ranges ~~to~~that take into account differences in properties due to variations in composition production history, product usage, process ~~control, etc.~~control.

8.4.2 *Bounding Conditions*—Bounding conditions represent the anticipated extreme credible values of a range of parameter or variable values. These furnish necessary input for ~~making predictions of~~ estimating performance limits. However, thorough evaluations of the alteration mechanisms, all important material attributes, and the effects of these attributes on the anticipated alteration processes are required to ensure that the calculations ~~with~~representing bounding conditions do indeed provide performance limits. For example, the pH value that gives the lower limit of the glass dissolution rate (for example, pH 7) may not be the extreme value of the range of environmental pH ~~values.~~values considered (for example, pH 3). Additionally, it is important