CONF-770625--5

BNWL-SA-6068

MASTER

Safety Assessment of Geologic Repositories for Nuclear Waste

by
J.W. Bartlett
H.C. Burkholder
W.K. Winegardner

Presented at the International Conference on Nuclear Systems Reliability Engineering and Risk Assessment

Gatlinburg, Tennessee
June 20-24 1977

Battelle
Pacific Northwest Laboratories

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

BNWL-SA-6068

SAFETY ASSESSMENT OF GEOLOGIC REPOSITORIES FOR NUCLEAR WASTE

by
J.W. Bartlett
H.C. Burkholder
W.K. Winegardner

Presented at the International Conference on Nuclear Systems Reliability Engineering and Risk Assessment

Gatlinburg, Tennessee
June 20-24, 1977

BATTELLE
Pacific Northwest Laboratories
Richland, WA 99352

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Safety Assessment of Geologic Repositories for Nuclear Waste

J. W. Bartlett, H. C. Burkholder and W. K. Winegardner*

Abstract. Consideration of geologic isolation for final disposition of radioactive wastes has led to the need for evaluation of the safety of the concept. Such evaluations require consideration of factors not encountered in conventional risk analysis: consequences at times and places far removed from the repository site; indirect, complex, and alternative pathways between the waste and the point of potential consequences; a highly limited data base; and limited opportunity for experimental verification of results.

R&D programs to provide technical safety evaluations are under way. Three methods are being considered for the probabilistic aspects of the evaluations: fault tree analysis, repository simulation analysis, and system stability analysis. Nuclide transport models, currently in a relatively advanced state of development, are used to evaluate consequences of postulated loss of geologic isolation.

This paper outlines the safety assessment methods, unique features of the assessment problem that affect selection of methods and reliability of results, and available results. It also discusses potential directions for future work.

1. Introduction. Western nations with significant commitments to nuclear power currently anticipate that long-lived radioactive wastes will be managed by isolation in geologic formations. This management method acknowledges current lack of practical methods to eliminate the wastes from existence on earth. It aims at eliminating

*Battelle Pacific Northwest Laboratories, Richland, WA 99352. This research was supported by the U.S. Energy Research and Development Administration under Contract EY-76-C-06-1830.

or minimizing potential for adverse consequences in the biosphere by separating the wastes from man and his environment until that potential is negligible.

All waste management operations preceding final commitment of wastes to geologic isolation can be accomplished with known technology. The safety of these operations can be estimated using techniques such as those used to estimate risk for reactor operations. Engineered designs to satisfy safety requirements can be developed, although perhaps at high cost.

In comparison with safety evaluations for design and operation of conventional engineered systems, evaluations for geologic isolation must incorporate some unusual considerations. They include: an analysis time frame related to half-lives of long-lived ($T_{1/2} \simeq 30$, 25,000, and 400,000 yr) nuclides; potential for radiological consequences at locations remote from the repository and at times long after emplacement of wastes; and reliance on geologic rather than engineered structures for containment. In addition, the scope and content of the evaluations are potentially influenced by nontechnical issues such as temporal and geographic export of risk; longevity of human institutions; and the choice between concentration and dispersion of nuclide inventories. These issues are related to what may be conveniently summarized as "perceived risk." Much has been and will be written on these issues. They are beyond the scope of this paper but cannot be neglected.

2. <u>Technical Basis for Safety Estimates for Geologic Isolation</u>. Radioactive wastes are produced in a variety of forms in the nuclear fuel cycle. Actual quantities and types will depend on the way the fuel cycle is operated (e.g., once-through or U + Pu recycle). Wastes requiring isolation can be subjected to treatment, interim storage, and transportation operations prior to isolation. Conventional inductive and deductive safety analyses and safety assurance actions apply to these operations.

Criteria for geologic isolation are not yet firmly established, but lack of firm criteria is relatively unimportant to this discussion. What is important is the intent to isolate those nuclides which have long half-lives and high toxicity. The usual focus of public attention is plutonium. Other radioactive materials, including plutonium decay products such as ^{226}Ra, the fission products ^{129}I and ^{99}Tc, and the activation product ^{14}C may also be important.

To date, attention has been directed primarily at so-called "high-level" waste, the fission product waste resulting from Purex reprocessing of spent fuel to recover uranium and plutonium. This waste contains more than 99% of the radioactivity in fuel cycle wastes as measured a year or so after fuel discharge from the reactor.

It is expected to contain about 0.5% of the uranium and plutonium in spent fuel. In the long term, after decay of fission products cesium and strontium (ca 800 yr), radioactivity levels in the high-level waste are greatly reduced and associated primarily with the long-lived transuranics.

The high-level waste will contain on the order of 50% of all transuranic nuclides expected to be consigned to repositories for a fuel cycle operated to recover uranium and plutonium. Other waste forms such as cladding hulls and consolidated trash from MOX and reprocessing plants would contain the remainder of the transuranics. In a once-through fuel cycle, the uranium and plutonium levels in the spent fuel, which would be the waste form, would be about 200 times higher than that in high-level waste.

High-level and other transuranic wastes can be expected to be placed into repositories as solids. Specific final form requirements have not yet been established. They may depend somewhat on results of safety analyses such as those discussed here.

In broadest terms, technical safety assessment for geologic repositories of nuclear wastes requires analysis of two factors: loss of isolation, and its consequences in the biosphere. Loss of isolation is dependent on disruptive events (natural phenomena and human intrusion). Consequences in the biosphere can depend on several factors: the mode of loss of isolation, transport in the geologic medium, and transport and interactions in the biosphere. For some potential loss-of-isolation scenarios such as extreme faulting and meteorite impact, the repository can be postulated to be directly exposed to the biosphere. For most, however, nuclides must move from the repository through the geosphere and subsequently the biosphere.

Excepting scenarios based on human intrusion of the repository, the most likely scheme for transporting wastes to the biosphere with adverse consequences is expected to be leaching of the waste by groundwater in convective motion. Under this scenario, potential consequences in the biosphere will depend on leach rates of the waste form, age of the waste when release occurs, transport in the geosphere, and pathways in the biosphere.

In this paper, past and anticipated analyses based on the various scenarios are reviewed and discussed. Risk concepts, probability estimation, and consequence estimation are emphasized.

3. <u>Concepts of Risk for Geologic Repositories</u>. The basic, conventional concepts of technical risk estimation (i.e., evaluation of likelihoods and consequences) apply to long-term safety assessments for geologic repositories. Modified use of the concepts is necessary, however, because consequences of disruptions potentially

producing adverse consequences may not be immediate or occur at the location of the risk-producing event. Furthermore, the "event" potentially producing risk may be a slow, extended process rather than a discrete occurrence.

The technical estimations of potential long-term radiological risk from geologic repositories must include consideration of:

- delays between risk-initiating "events" and occurrence of consequences (e.g., as a result of slow nuclide transport in the geosphere)
- geographic translocation (consequences can occur at locations distant from the repository because of nuclide migration)
- risk dispersion (atmospheric resuspension, surface water transport, etc., can produce biosphere transport of the radioactive nuclides)
- nuclide accumulation in the biosphere (quantities of nuclides at a given location may increase with time because of continued input from the repository, slow decay, and lack of biosphere dispersion phenomena)
- populations and lifestyles (total human risk will depend on how many people are present and how they interact with radioactivity in the biosphere).

R&D programs aimed at developing risk estimation methods that account for these considerations are under way in the U.S. and other countries.

4. Probability Estimation Methods. Identified phenomena that have been postulated to potentially have an effect on the stability of a geologic repository are of four types:

1. rapid man-caused events (e.g., resource exploration or acts of war)

2. rapid natural events uninfluenced by humans (e.g., meteorite impact or seismically induced fracturing)

3. slow natural processes independent of the existence of the repository (e.g., tectonic activity or erosion)

4. slow processes caused by the existence of the repository (e.g., faulting caused by radiation, thermal and/or mechanical force gradients).

Three methods have been proposed to assist in identifying and evaluating potential loss-of-isolation scenarios involving the above phenomena:

1. fault tree analysis[1]
2. repository simulation analysis[2]
3. system stability analysis.[2]

Fault tree analysis is a technique by which the component failures leading to system failure can be logically deduced. Application of the technique yields combinations of basic events whose occurrence causes the undesired failure events. These event combinations can then be evaluated by various screening techniques to determine the high risk scenarios and their probability of occurrence. A risk-based fault tree analysis method for the identification, preliminary evaluation, and screening of potential accidental release sequences is presented in Reference 3. For its application the fault tree method requires probability information about all of the individual component failures. The fault tree technique is well suited to analyzing the rapid events (which have discrete probabilities). It is not well-suited to analyzing the slow processes for which event ordering, interdependencies, and time-phasing are important.

Repository simulation analysis begins by listing all phenomena in the four types, estimates probabilities for the rapid events and rates for the slow processes, and defines the generic failures which are possible.[2] The analysis then steps through time assuming random occurrence of the rapid events at the estimated probabilities and continuous occurrence of the slow processes at the estimated rates. This procedure simulates repository behavior and if applied until one of the postulated failures occurs produces an estimate of the time and conditions of repository failure. Performance of this repository simulation a large number of times produces a distribution of times and conditions of repository failure. From this distribution the probabilities of failure in any given year can be calculated.

System stability analysis begins by mathematically modeling the natural geologic processes and the processes induced by the presence of the waste (i.e., processes caused by introducing radiation, thermal, and/or mechanical force gradients into the previously undisturbed geology).[2] This modeling activity produces a set of coupled differential equations (along with mathematical expressions for the appropriate boundary conditions) which describe not only the individual processes but also their interaction. Linear and nonlinear stability analyses are then performed on the model system. The linear analyses determine the systems response to small arbitrary disturbances which are ever present in all systems. The nonlinear analyses determine the systems response to large arbitrary disturbances caused by the occurrences of rapid events (e.g., earthquakes). If the modeled system damps the disturbances, it is said to be stable; if the system allows the disturbances to grow in amplitude, it is said to be unstable and the analysis proceeds to determining the rate of approach to nuclide release. The results of such instability could be manifest in occurrences such as local fracturing, metamorphosis of the local geology with subsequent repository collapse, movement of the respository as a whole, or movement of individual canisters with subsequent meltdown. The output of the analysis is either a conclusion that the system is stable or a conclusion that the system is unstable with release expected at some given time. The analysis is performed repetitively over the expected range of the important input parameters and produces a distribution of predicted failure times (an ever-stable system will have a null distribution) from which failure probabilities can be estimated. The system stability analysis technique may be adequate for analyzing the slow processes and their interactions, but it is not well suited for analyzing the rapid events whose processes are difficult to model by continuum mathematics.

None of the three analysis techniques taken alone seems ideal for analyzing the failure of geologic repositories, but together they provide a reasonably comprehensive analysis method. Thus a prudent plan for this portion of the repository safety analysis problem might include investigation of all three techniques simultaneously. The multiple technique approach is particularly justified because the repository simulation and system stability analysis techniques have not advanced beyond the conceptual stage and may not be ultimately successful. All techniques (but especially stability analysis) may require a detail of knowledge about the natural geologic processes which does not presently exist.

5. Probability Estimations for Geologic Repositories. All four types of loss-of-isolation phenomena have been investigated. Schneider

and Platt (1974) report a detailed fault tree approach to the problem.[1] These fault trees were not evaluated because of time constraints and a lack of probability information about the component events. A simplified fault tree approach with enough detail to permit interaction of all four types of phenomena but not so much detail that the trees are too sophisticated for the quality of the data has not been documented. Claiborne and Gera (1974) estimated the individual probabilities of some Type 1, 2, and 3 phenomena for the proposed Carlsbad Repository in southeastern New Mexico.[4] The probability of a catastrophic meteorite impact was estimated to be 1.6×10^{-13}/yr, and the probability of faulting (which would not necessarily lead to containment failure) was estimated to be 4×10^{-11}/yr. The interaction of these various events was not investigated, and hence the significance of such interaction is not clear at this time. Additional work on the first three types of phenomena can be found in References 1 and 5. A number of investigations of some Type 4 processes have been completed.[1,6-10]

6. Consequence Estimation Methods. Estimation of radiological consequences requires modeling of radionuclide transport from the point where the nuclides become mobile to the point(s) of interaction with humans. Radiation doses are then calculated. Radionuclide transport modeling requires an understanding of the important physicochemical, biophysical, and biochemical processes which govern the

concentration and rate of nuclide movement and their interaction with humans. These processes must be known with sufficient accuracy to be described by abstract mathematical relationships and to be characterized by experimentally measurable parameters. Humans are affected by radionuclides either by external exposure from nuclides in the environment or by internal exposure from nuclides which have been ingested or inhaled. Thus water and atmospheric transport models as well as radiation dose models are needed. Models of both types exist, and comprehensive compilations of each type are under way at the present time. Examples of integrated water-dose and air-dose models can be found in References 11 and 12. These integrated consequence estimation models require input information concerning the time and conditions of nuclide release and produce output information about projected doses to individuals and populations at various times after failure. The models also require such input data as: radionuclide inventories; waste form volatilities and leach rates; groundwater and surface water directions, velocities, and volumetric flow rates; wind directions, durations, and velocities; sorption properties of geologic media; biosphere transfer and dose conversion factors; demography; and population living habits.

These requirements are addressed by geosphere transport models which have been specially developed for geologic isolation studies. Lester, Jansen, and Burkholder (1975) developed an analytical model to describe the transport of radionuclides by flowing groundwater following a leach incident at an underground nuclear waste disposal site.[13] This model is applicable to particulate and faulted monolithic media and can be applied to heterogeneous media if a weighted averaging technique can be applied to the relevant input parameters.[14] A computer code named GETOUT has been developed to implement this model.

Burkholder and DeFigh-Price (1977) developed a companion model to describe the diffusion of radionuclides in either the liquid or gas phase from a geologic or seabed nuclear waste disposal site.[15] All of the assumptions of the previous model were made except that convective transport was neglected and diffusion was modeled instead of dispersion. The generalizations of the migration model to faulted monolithic and/or heterogeneous media applied to the diffusion model as well. A computer code named DIFFUS has been developed.

A model to describe geosphere transport from a salt formation is under development.[16,17] This model describes both the transport of radionuclides and dissolved salt following groundwater intrusion into a geologic isolation site in a salt formation.

Together these models provide the framework for modeling the important geosphere transport situations of geologic isolation. When combined with already existing models for surface water transport, atmospheric transport, and dose calculation, they provide a complete set of models needed to estimate the consequences of disruptive events at geologic repositories.

7. Estimation of Radiological Consequences. A number of investigations have described methods for making consequence estimations for geologic isolation[1,4,12,18,19] but only three have thus far produced specific dose estimates.[4,12,19] Claiborne and Gera (1974) estimated the local contamination consequences of meteorite impact on a hypothetical nuclear waste repository located in a bedded salt formation in southeastern New Mexico. The meteor was assumed to be of sufficient size to exhume the entire repository, and impacts were assumed to occur 1,000 yr and 100,000 yr after disposal. Doses were calculated using a generalized model to predict quantitative radionuclide movement through terrestrial food pathways (TERMOD) and dose codes EXREM and INREM.[20,21,22] The radionuclide source inventory was not specified. Fifty-yr bone (the critical organ) doses of 2.3×10^6 (event at 1,000 yr) and 9.8×10^6 (event at 100,000 yr) mrem were predicted for individuals who moved into the local area after the meteorite impact and reestablished a human society similar to our present society. The dose controlling nuclide was ^{241}Am for the 1000-yr event and ^{226}Ra for the 100,000-yr event. Claiborne and Gera noted that a cataclysmic meteorite impact would cause great devastation, regardless of the simultaneous presence of radioactive wastes.

Carrying this line of reasoning further, it seems logical that any disruptive event for geologic isolation can be neglected if the consequences of the initiating event itself are much larger than the long-term integrated consequences of the released radionuclides. Claiborne and Gera also estimated the local consequences from groundwater intrusion into the repository at 1,000 and 100,000 yr after disposal. They assumed that the waste consisted of 2-mm-dia particles of borosilicate glass with a leach-rate of 10^{-7} g/cm^2 day and that 1% of the waste was contacted by groundwater. The resulting saturated salt brine with its contained radioactivity was assumed to be pumped directly to the surface and used to irrigate crops with no subsequent dilution. The crops were assumed to grow with the salt saturated water, and the surrounding populace was assumed to eat only contaminated crops. Fifty-yr bone doses of 5×10^5 (event at 1,000 yr) and 6×10^5 mrem (event at 100,000 yr) were predicted for these local individuals.

Burkholder, Cloninger, Baker, and Jansen (1975, 1976) used the geosphere transport code GETOUT and a currently unnamed biosphere transport-dose code containing the programs ARRRG and FOOD to predict the consequences of groundwater intrusion into a geologic isolation repository.[12,23-26] The radionuclide inventory in the repository was assumed to be accumulated high-level waste from the U.S. nuclear power economy through the Year 2000 including all tritium, carbon, and iodine from the spent fuel and all activation products from the cladding. The surrounding geology was assumed to have the nuclide retention properties of western U.S. desert subsoils as estimated in Reference 1 and discussed in Reference 14. Following the intrusion event, the groundwater and its dissolved nuclides were assumed to flow at a velocity of 1 ft/day (10 times the velocity of "typical" desert aquifers) back to the biosphere.

A "typical" biosphere scenario was assumed with nuclides entering the biosphere where a surface river and underground aquifer intersect. The nuclides were assumed to be diluted by a 10,000-cfs river (∿1/10 the flowrate of the Columbia River) before exposure to humans occurred. The nuclides were assumed to affect humans by external exposure from shoreline activities and recreation on and in the river and internal exposure from drinking the water and eating aquatic foods or foods grown or raised using the river water for irrigation. Doses were calculated to "maximum" individuals who were assumed to live within the region of influence of the isolation site at various times after disposal. In calculation of these doses, the nuclide inflow rates to the biosphere at any time of interest were assumed to have accumulated on the irrigated land at those rates for 50 yr. The "maximum" individual was then assumed to be exposed to the results of that 50-yr accumulation for another 50 yr. At the end of this 100-yr period the nuclides were assumed to disperse throughout the regional, national and international biosphere with no subsequent dose.

Thus the dynamic biosphere accumulation and dispersion phenomena were approximated by a steady-state accumulation. The 50-yr accumulation assumption seems conservative, but investigation is needed to provide supporting information.

In the Burkholder et al. studies, release consequences were calculated for combinations of three parameters. These parameters (called waste-management-control variables) are measurement scales for the effectiveness of the radioactivity release barriers (containment, leach resistance, and nuclide retention) provided by geologic isolation systems. The time that water first contacts the waste (the time of initial release) is a measure of canister integrity and site stability from water penetration. The time for complete dissolution of the waste (the leach time) is a measure of the resistance of the waste form to leaching. The distance that the dissolved nuclides move through the geologic medium in migrating from the isolation site to the biosphere (the path length) is a measure of geosphere isolation.

Burkholder (1976) extended the consequence estimations for high-level wastes to other nuclear fuel cycle waste such as spent fuel, TRU-contaminated cladding hulls, tritium solids, carbon solids, iodine solids, miscellaneous α, β, γ solids, miscellaneous β,γ solids, and ore tailings.[19] The results showed that for the situation investigated:

1. Spent fuel disposal requires greater assurance of nuclide isolation than high-level waste disposal because of the larger amounts of uranium and plutonium in the spent fuel.

2. Poor selection of isolation conditions can sometimes increase and good selection can greatly decrease the projected maximum dose consequences to humans compared to leaving the waste in the biosphere. The former effect is a result of the reconcentration phenomenon of radionuclide chain migration (discussed in Reference 27).

3. A strongly nonlinear relationship exists between the amount of radioactivity at a given site and the waste form leach resistance requirements necessary to meet specific site acceptability criteria. Thus multisite isolation of nuclear wastes can greatly reduce waste form leach resistance requirements for some wastes.

8. Constraints on This Use of Risk Analysis. Assessment of geologic isolation safety is unique relative to assessments for other engineered systems because some elements of the analysis are not amenable to uncertainty reduction by additional R&D. The limitations result from the long time periods of interest to the assessments, the hypothetical nature of the nuclide release scenarios, and limits on the ability to characterize the system without destroying its function. Examples are listed below for the groundwater intrusion scenario:[18]

1. The circumstances surrounding the release initiation will be purely hypothetical because disposal sites will not be located where flowing water is initially present. Thus the origin, direction, and velocity of future groundwater flow cannot be accurately predicted.

2. The future dissolution or leach rate of the waste form will depend on the long-term stability of the waste form and the chemistry of interaction with intruding ground water.

3. Nuclide retention data for the geology in the immediate vicinity of the site will be constrained by need to avoid destroying the integrity of the site.

4. Capability for laboratory simulation of actual nuclide transport conditions will be limited.

5. Accumulation and dispersion processes for radionuclides in the biosphere over long time periods will always be uncertain.

6. The demography and living habits of future civilizations will always be conjecture.

Because of these limitations on input information, there will always be limitations on the accuracy and precision of the results of consequence estimations for geologic isolation. Consequently, appropriate sophistication levels for the models should be determined. Highly sophisticated models should be used with caution or perhaps not be used at all. They could create unwarranted "illusions of certainty."

Results of these safety assessments will be subjected to judgment in accordance with two types of acceptability criteria: 1) validity of the technical safety evaluations, and 2) social perceptions of what levels and types of risks are acceptable.

The above factors provide guidance on the direction and depth of development of safety assessments of this type. Experience to date suggests the following guidelines for future development:

- Sufficiency of scope of scenarios considered is more important than detail.
- Levels (i.e., magnitudes) of projected risks are more important than the precision of the estimates.
- Probabilities and consequences are important independently in addition to their multiplicative role as components of risk. Perceived risk tends to be highest at the extremes of the spectrum, i.e., for high P, low C scenarios and for low P, high C scenarios. These inequalities in perceived risk are the reason for interest in, and a role for, assessment methods such as consequence estimation.

- A primary target for the analyses should be estimation of the upper boundary of projected risks.

- Scenarios should include consideration of corrective action as a factor mitigating risk. For example, consequences of accidental intrusion of a repository during drilling can be minimized by stopping the activity. Consequences of broad dispersion in the environment can be reduced by control procedures and regulations. In general, time constants associated with repository releases are so large that there is ample time for corrective action.

- Potential consequences of loss of isolation should be placed in perspective. In a drilling intrusion, which presumably could result from searching for resources, accompanying analytic procedures should reveal the presence of transuranics; adverse consequences could then be limited by direct action. If released radioactivity is broadly dispersed in the environment, a release or its much-delayed entry to biosphere would be significant only if a significant perturbation in background resulted, could be detected, and produced adverse effects that could not be mitigated.

- A role should be anticipated for perceived risk in the acceptance of risk assessment results and, if possible, the performance of the assessments. At present, the level of perceived risk associated with geologic isolation is unknown. The issue is clouded by concerns associated with the fact that isolation has not been put into practice.

In summary, present risk assessment methods provide a basis for evaluation of geologic repositories, and there are guidelines for future development of methods. The evaluations are essential as an aid to system design and site selection because of the insights they provide concerning factors that influence or control safety. The evaluations also provide a framework from which to communicate those insights to decision makers and the general public.

REFERENCES

[1] K. J. SCHNEIDER and A. M. PLATT, eds. High-Level Radioactive Waste Management Alternatives, BNWL-1900, Battelle Pacific Northwest Laboratories, Richland, WA, 1974.

[2] H. C. BURKHOLDER, J. A. STOTTLEMYRE, and J. R. RAYMOND, Safety Assessment and Geosphere Transport Methodology for the Isolation of Nuclear Waste Materials, BNWL-SA-6310, Battelle Pacific Northwest Laboratories, Richland, WA, 1977.

[3] T. H. SMITH, P. J. PELTO, D. L. STEVENS, G. D. SEYBOLD, W. L. PERCELL, and L. V. KIMMEL, A Risk Based Fault Tree Analysis Method for Identification, Preliminary Evaluation, and Screening of Potential Release Sequences in Nuclear Fuel Cycle Operations, BNWL-1959, Battelle Pacific Northwest Laboratories, Richland, WA, 1976.

[4] H. C. CLAIBORNE and F. GERA, Potential Containment Failure Mechanisms and Their Consequences at a Radioactive Waste Repository in Bedded Salt in New Mexico, ORNL-TM-4639, Oak Ridge National Laboratory, Oak Ridge, TN, 1974.

[5] F. GERA and D. G. JACOBS, Considerations in the Long-Term Management of High-Level Radioactive Wastes, ORNL-4762, Oak Ridge National Laboratory, Oak Ridge, TN, 1972.

[6] G. H. JENKS, Radiolysis and Hydrolysis in Salt-Mine Brines, ORNL-TM-3717, Oak Ridge National Laboratory, Oak Ridge, TN, 1972.

[7] T. R. ANTHONY and H. E. CLINE, "Thermomigration of Liquid Droplets in Salt," in Northern Ohio Geological Society, Case Western Reserve University, Fourth Symposium on Salt, 1: 313, 1974.

[8] K. A. HOLDOWAY, "Behavior of Fluid Inclusions in Salt During Heating and Irradiation," in Northern Ohio Geological Society, Case Western Reserve University, Fourth Symposium on Salt, 1: 303, 1974.

[9] G. H. JENKS, Gamma-Radiation Effects in Geologic Formations of Interest in Waste Disposal: A Review and Analysis of Available Information and Suggestions for Additional Experimentation, ORNL-TM-4827, Oak Ridge National Laboratory, Oak Ridge, TN, 1975.

[10] F. M. EMPSON, R. L. BRADSHAW, W. C. MCCLAIN, and B. L. HOUSER, "Results of the Operation of Project Salt Vault: A Demonstration of Disposal of High Level Radioactive Solids in Salt" in Northern Ohio Geologic Society, Case Western Reserve University, Third Symposium on Salt, 1:455 1969.

[11] J. R. HOUSTON, D. L. STRENGE, and E. C. WATSON, DACRIN - A Computer Program for Calculating Organ Dose from Acute or Chronic Radionuclide Inhalation, BNWL-B-389, Battelle, Pacific Northwest Laboratories, Richland, WA, 1974.

[12] H. C. BURKHOLDER, M. O. CLONINGER, D. A. BAKER, and G. JANSEN, Incentives for Partitioning High-Level Waste, BNWL-1927, Battelle Pacific Northwest Laboratories, Richland, WA, 1974.

[13] D. H. LESTER, G. JANSEN, and H. C. BURKHOLDER, "Migration of radionuclide chains through an adsorbing medium," AIChE Symposium Series No. 152, Adsorption and Ion Exchange, 71:202, 1975.

[14] H. C. BURKHOLDER, "Methods and Data for Predicting Nuclide Migration in Geologic Media," Proceedings of the International Symposium on the Management of Wastes from the

LWR Fuel Cycle, CONF-76-0701, U.S. Energy Research and Development Administration, p.658, 1976.

[15] H. C. BURKHOLDER and C. DEFIGH-PRICE, "Diffusion of Radionuclide Chains Through an Adsorbing Medium," BNWL-SA-5787, Battelle Pacific Northwest Laboratories, Richland, WA, 1977.

[16] H. C. BURKHOLDER and G. E. KOESTER, "Radionuclide Migration from Salt Formations," in Nuclear Waste Management and Transportation Quarterly Progress Report January through March 1975, BNWL-1913, Battelle Pacific Northwest Laboratories, Richland, WA, 1975.

[17] A. G. GIBBS and H. C. BURKHOLDER, "Radionuclide Migration from Salt Formations," in Nuclear Waste Management and Transportation Quarterly Progress Report April through June 1975, BNWL-1936, Battelle Pacific Northwest Laboratories, Richland, WA, 1975.

[18] S. F. LOGAN, A Technology Assessment Methodology Applied to High-Level Radioactive Waste Management, PhD Dissertation, University of New Mexico, Albuquerque, NM, 1974.

[19] H. C. BURKHOLDER, "Management Perspectives for Nuclear Fuel Cycle Wastes," in Nuclear Waste Management and Transportation Quarterly Progress Report January through March 1976, BNWL-2029, Battelle Pacific Northwest Laboratories, Richland, WA, 1976.

[20] W. D. TURNER, S. V. KAYE, and P. S. ROHWER, EXREM and INREM Computer Codes for Estimating Radiation Doses to Populations from Construction of a Sea-Level Canal with Nuclear Explosives, K-1752, Oak Ridge National Laboratory, Oak Ridge, TN, 1968.

[21] S. K. TRUBEY and S. V. KAYE, The EXREM III Computer Code for Estimating External Radiation Doses to Populations from Environmental Releases, ORNL-TM-4322, Oak Ridge National Laboratory, Oak Ridge, TN, 1973.

[22] R. S. BOOTH, S. V. KAYE, and P. S. ROHWER, "A Systems Analysis Methodology for Predicting Dose to Man from a Radioactively Contaminated Terrestrial Environment," in Proceedings of the Third National Symposium on Radioecology, CONF-710501, U.S. Atomic Energy Commission, 1:877, 1973.

[23] H. C. BURKHOLDER, M. O. CLONINGER, D. A. BAKER, and G. JANSEN, Incentives for partitioning high-level Waste, Nuclear Technology, 31:202, 1976.

[24] D. H. DENHAM, D. A. BAKER, J. K. SOLDAT, and J. P. CORLEY, Radiological Evaluations for Advanced Waste Management Studies, BNWL-1764, Battelle Pacific Northwest Laboratories, Richland, WA, 1973.

[25] J. K. SOLDAT, N. M. ROBINSON, and D. A. BAKER, Models and Computer Codes for Evaluating Environmental Radiation Doses, BNWL-1754, Battelle Pacific Northwest Laboratories, Richland, WA, 1974.

[26] D. A. BAKER, G. R. HOENES, and J. K. SOLDAT, FOOD - An Interactive Code to Calculate Internal Radiation Doses from Contaminated Food Products, BNWL-SA-5523, Battelle Pacific Northwest Laboratories, Richland, WA, 1975.

[27] H. C. BURKHOLDER and M. O. CLONINGER, The Reconcentration Phenomenon of Radionuclide Chain Migration, BNWL-SA-5786, Battelle Pacific Northwest Laboratories, Richland, WA, 1976.