UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON NUCLEAR WASTE
WASHINGTON, D.C. 20555-0001

August 4, 2005

MEMORANDUM TO: Michael Ryan, ACNW Chairman
Allen Croff, ACNW Vice Chairman

FROM: Ruth Weiner, ACNW Member

SUBJECT: TRANSMITTAL OF THE ACNW TEAM REPORT FROM THE APRIL 13-15, 2005 VISIT TO THE CENTER FOR THE REGULATORY ANALYSIS OF NUCLEAR WASTE

As you know, three members of the Advisory Committee on Nuclear Waste (ACNW) and two ACNW consultants visited the Center for the Regulatory Analysis of Nuclear Waste (CNWRA) in San Antonio, Texas on April 13-15, 2005 and conducted a focused discussion of topics that had been selected by the ACNW. The ACNW team consisted of ACNW members Ruth Weiner, James Clarke, and William Hinze, ACNW Consultants Bruce Marsh and Paul Shewmon, and Richard Savio, Sharon Steele, and Jenny Gallo of the ACNW/ACRS Staff. NRC/NMSS staff present at the CNWRA included Jack Guttmann, John Trapp, and Allen Fetter. Additional NRC/NMSS and ACNW staff at NRC Headquarters participated by video teleconferencing.

The NMSS and the CNWRA staffs were provided with a number of specific questions relating to the topics to be discussed prior to the visit and were provided with opportunities to discuss these questions with the cognizant ACNW members prior to the visit. The questions were discussed with the ACNW prior to the ACNW members' visit to the CNWRA. The information provided to the ACNW in a February 24, 2005 briefing by members of the CNWRA staff was used in developing these questions. The purpose of the ACNW members' and consultants' visit was to gather information which would be later discussed by the ACNW and used to provide advice to the NRC Commission.

The presentations to the ACNW team were helpful, and generally responsive to the ACNW's questions. Although responses to the questions related to igneous activity were a marked improvement in depth and breadth over previous presentations to the Committee, some concerns still remain. The attached report contains a summary of what the ACNW team learned. Appendixes 1 and 2 contain a detailed summary of the CNWRA and NMSS staff responses to the questions provided prior to the April 13-15, 2005 visit (Appendix 1) and a discussion of issues relevant to the interaction of magna with the waste package (Appendix 2).

Attachments: As stated:

cc w/Atts.: W.Hinze
J. Clarke
B.Marsh
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WORKING PAPER ON THE ACNW VISIT TO CNWRA, APRIL 13-15, 2005

Summary

A team from the Advisory Committee on Nuclear Waste (ACNW) comprised of three ACNW members, two ACNW consultants, and an ACNW staff member, visited the Center for Nuclear Waste Regulatory Analysis (CNWRA) April 13-15, 2005. The ACNW team's impressions of the CNWRA investigations and analyses may be summarized as follows:

- CNWRA's investigations of several performance assessment models and codes for use in decommissioning analyses appear to be thorough and are proceeding well.
- CNWRA's experiments and analyses of waste package performance, potential waste package corrosion, radionuclide mobility, and waste form dissolution are providing appropriate input and abstractions to the next version of CNWRA's Total System Performance Assessment Code TSPA 5.0.1.
- Regarding the analysis of a potential igneous event:
  - o The ACNW team differs with the CNWRA analysis of the magma/waste package interaction, in particular with the assumption of complete disruption of the waste package in an igneous event. This assumption is not supported by evidence available to the ANCW team.
  - o The ACNW team and CNWRA differ on the question of assessment of the probability of an igneous event.
  - o CNWRA's analysis and modeling of the health consequences of an igneous event is appropriate but needs better documentation of the supporting evidence.
  - o The ACNW will continue to use this working paper as the source document for a letter on the igneous activity as more information identified below comes forward. At an appropriate point in the future, the ACNW will write a follow up letter on igneous activity discussing closure on points where agreement has been reached and identify and detail points on which the ACNW may hold differing views from the Center or ACNW staff.

These points are discussed in greater detail in the following paragraphs.

Introduction

The Center for Nuclear Waste Regulatory Analysis (CNWRA) of the Southwest Research Institute is performing technical assistance and confirmatory research for the NRC, in preparation for the review of the anticipated License Application (LA) from the DOE for construction of the proposed underground HLW repository at Yucca Mountain, Nevada. Three members of the Advisory Committee on Nuclear Waste (ACNW), responding to its charge to gather information related to the technical/scientific work being performed by the CNWRA, conducted a focused discussion of selected topics on April 13-15, 2005 in San Antonio, Texas. These members were supported by two ACNW consultants. This group will be referred to as the "team" or "the ACNW team" in the remainder of this report.

The ACNW team was provided with an overview of the accomplishments of the Center and future projects by the Technical Director of the CNWRA during its 157th Meeting in February of 2005. Much of the information that had previously been made available to the ACNW was outdated. The ACNW team focused its discussion of the Center's activities on a few topics of importance to the Yucca Mountain repository review program and of particular concern to the Committee. Prior to the ACNW team's visit, the ACNW presented the Center staff with 33 questions relating to specific topics that the members wanted addressed during the April 13-15, 2005 discussions, most of which pertained to the topic of igneous activity and its potential consequences. The Center was advised that these questions were illustrative only and that additional questions could be anticipated in the discussion among the principals. A few days before the visit, the Center provided the ACNW team with some published and unpublished documents related to the topics of the questions.

The ACNW team consisted of ACNW Members Ruth Weiner, James Clarke, and William Hinze, ACNW Consultants Bruce Marsh and Paul Shewmon, and Richard Savio, ACRS/ACNW Staff. In addition Sharon Steele and Jenny Gallo of the ACNW staff were in attendance. NRC/NMSS staff present at the CNWRA included Jack Guttmann, John Trapp, and Allen Fetter. Additional NRC/NMSS and ACNW staff at NRC Headquarters participated by video teleconferencing.

A significant portion of the briefing presented by the Center during the review was of a pre-decisional nature. The ACNW team was sensitized to the importance of not releasing this information until it was made public by members of the NMSS staff that accompanied the group to the Center.

Observations

Container life, source term, and radionuclide mobility:

1) The presentations concerned with container life, the radionuclide source term, the near-field environment, radionuclide retardation, and the published versions of the Department of Energy's Total System Performance Assessment (TSPA), were comprehensive.

The Center has made significant progress in understanding the controls and the processes involved in container corrosion. Laboratory corrosion studies include studies of stress corrosion cracking resistance of Alloy 22, high-level waste glass dissolution processes, mechanical properties of the waste package, and the relationship between in-package chemistry and package corrosion. The laboratory studies show that corrosion by chloride-containing solutions can be inhibited by nitrate, sulfate, carbonate, or bicarbonate, if the ratio of any of these to chloride concentration is 0.1 or greater. Nitrate appears to be the most effective inhibitor; bicarbonate, the least. Studies of Yucca Mountain dust composition indicate that nitrate and sulfate are present in this dust in sufficient concentration to potentially mitigate corrosion. The results of corrosion studies are expressed as distributions that incorporate uncertainty in corrosion rates. The Center's humidity deliquescence studies showed that, although chloride deliquescence could form corrosive brine, other components of this dust can mitigate such corrosion. The Center is abstracting these results for incorporation in ongoing model development activities.

2). Progress continues to be made at the Center on spent fuel dissolution and the mobility of radionuclides in the near-field environment. The Center staff is using parameter values from the technical literature as well as results from laboratory experiments to model the dissolution of radionuclides from various regions of the spent fuel matrix. Studies have shown that gap and grain boundary inventory increases with increasing fuel burnup, but burnup does not influence dissolution of the uranium dioxide matrix significantly.

3) The revised version of the TPA computer code (5.0.1) incorporates several advancements such as tephra remobilization, consequences of drift degradation, drip shield and waste container weld corrosion, and colloid transport. Furthermore, numerous parameter values and their distributions are reflecting recent progress in the understanding of and information on the germane FEPs. Details on revisions are pre-decisional at this time, but modification to the code should lead to improvements in evaluation of the risk associated with the FEPs involved in the performance of the proposed repository.

4) The Center is studying performance assessment models to apply to analysis of potential decommissioning sites. This work appears to be proceeding well.

Igneous activity

The ACNW team and the Committee as a whole believe that there are differing views on various issues related to the igneous activity. The text that follows in the remainder of this trip report is the Committee's documentation of its views on these questions and to suggest paths forward. The Committee recognizes that in some instances its views differ from those of NRC and CNWRA staff. The differing views result from professional judgments, and may or may not be resolved by additional work. The Committee plans to continue to its dialogue with the NRC and CNWRA staffs to resolve issues as additional information becomes available, and to highlight differences in professional judgments without trying to necessarily reach a final consensus. The Committee will work collaboratively to assure that the facts and NRC and CNWRA staff views are clearly and accurately represented in follow up communications. The Committee believes that this process will best inform the Commission on this important topic.

1) The selection of the components of the igneous activity topic that are of high risk significance - probability of a volcanic event, number of waste packages affected by a volcanic eruption, occurrence of secondary volcanic conduits, and human inhalation of resuspended contaminated ash – seem to be the most important items for analysis from a risk viewpoint. The criteria used in ranking of these components of the igneous activity topic appear to be inconsistent and to include some subjective judgments. Subjective judgments should be eliminated as much as possible from the ranking process to avoid the possibility of inconsistencies and improve risk insights, in accord with the concern of the Committee expressed in their letter to the

Commission of May 3, 2004 regarding "Risk Insights Baseline Report" that specific guidance on prioritizing issue resolution is desirable.

2) The increased emphasis on consequences of igneous activity is a step forward in decreasing uncertainties and increasing realism. The investigations of the Center relating to the exposure scenario resulting from igneous activity have improved during the past year. We look forward to publication of the associated documentation in the near future. However, the ACNW team has remaining concerns about the realism of the assumptions that are being used in the dose modeling, which has led to recommendations for improvement. In particular, better documentation is needed for neglect of the effects of the tephra plume immediately on emission and for the contribution of particles larger than 10 microns to the total effective dose equivalent.

3) The NRC estimates that the probability of an igneous intrusion into the proposed Yucca Mountain HLW repository is 10^{-7}/yr over the next 10,000 years. This is neither an average event probability nor a bounding value because published estimates range from the order of magnitude of 10^{-6}/yr to 10^{-10}/yr. Apparently, it is accepted as a reasonably conservative value, and is being used as a surrogate for the mean value in 10 CRF Part 63. The use of this single point value in a probabilistic performance assessment is without compelling support and is in contradiction to the established practice of the NRC to use a risk-informed approach to studies incorporating a range of probability values in such assessments. Accordingly, the NRC is urged to use a range of estimates from 10^{-7}/yr to 10^{-8}/yr as specified in a published journal article of the CNWRA and NMSS/NRC staff until further evidence supports a change in this range of values.

4) The ACNW team believes that important questions remaining regarding the magma/waste interaction that should be addressed by the NRC. The principal concerns relate to the credit given in performance assessment to the waste containers contacted by the magma and the role of solidification of magma upon encountering the open drifts of the repository and the waste containers.

Items for further follow up

1) *Studies of container life, source term, and radionuclide mobility, and development of TPA 5.0.1 appear to be progressing steadily and appropriately, as do investigations into analysis of decommissioning sites.* Therefore, the team's only recommendation related to these analyses is that they continue as presently undertaken.

2) *Criteria used in risk ranking the components of an igneous event should be clarified and consistent, particularly for those phenomena those are of high risk significance* (probability of a volcanic event, number of waste packages affected by a volcanic eruption, occurrence of secondary volcanic conduits, and human inhalation of resuspended contaminated ash).

3) *The NRC is urged to use a range of estimates of the probability of an igneous event:* i.e., from 10^{-7}/yr to 10^{-8}/year, as specified in a published journal article of the CNWRA and NMSS/NRC staff until further evidence supports a change in this range of values.

4) *Alternative tectonic models and processes should be evaluated as part of the ongoing monitoring of the DOE's current Probabilistic Volcanic Hazard Analysis - Update (PVHA-U).* Similarly it is recommended that the possibility of incorporating geologic controls into the estimates of the recurrence interval through Bayesian statistical methods should continue to be considered.

5) *The NRC staff should broaden their view of scenarios involving magma/repository interaction to evaluate in a quantitative manner the effect of magma on the waste containers and the effect of solidification of magma in the repository and surrounding waste containers.* The current position of the NRC is that the waste containers encountered by the intruding magma lose their integrity, so that no credit is taken for the waste container in performance assessment. No quantitative support is provided for this position. By not considering scenarios for the interaction of magma with the waste containers, important processes that may have implications for understanding other processes (e.g., entrainment and eruption of waste) may be missed, and the overall consequences of the magma disruption process may be evaluated erroneously. An example is the lack of consideration of the phenomenon of magma solidification upon eruption into the repository openings and surrounding the waste containers. The ACNW team believes that whether DOE uses a risk informed scenario to describe magma package interactions or not should not be used as the justification to overlook the insights that could be gain regarding a more realistic scenario.

6) *We encourage the staff to revisit the calculation of dose to the RMEI, taking into account magma/waste package interaction scenarios that do not result in complete disruption of the waste package and fragmentation of the spent fuel.* The process of fragmentation of the waste upon interaction with magma and the resulting particle size distribution and the incorporation of the fragments into the ejected magma (tephra) remains a concern. The Center's position that all of the waste in the intercepted package is contacted by the magma, and that fuel rods and package are completely assimilated into the intruding magma, has resulted in an apparently excessively conservative calculation of dose to the RMEI.

7) *We encourage the staff to fully evaluate eruption scenarios involving secondary conduits (boccas), building upon recent studies by their consultants.* Flank eruptions of volcanoes involving secondary conduits (boccas) that may erupt through the repository is a potentially important scenario to consider when evaluating the consequences of igneous activity intersecting the proposed Yucca Mountain repository.

8) *The interaction of magma with waste forms other than spent nuclear fuel should be considered in the full performance assessment, although this is a small minority of the waste.* It appears that current evaluation of magma/waste interaction does not include waste scheduled for the HLW repository other than spent nuclear fuel (SNF).

9) *The staff's contention that the risk from the initial dispersion of the tephra plume can be neglected needs to be documented; the statement was presented without documented evidence.* The staff has concluded that risk to the RMEI is negligible from the waste-contaminated tephra that is aerosolized or deposited immediately when the plume is emitted. However, the tephra remobilized either by fluvial or aeolian processes may reach sufficient concentrations that the risk to the RMEI must be evaluated. As a result, the remobilization model is significant. We look forward to the publication of this model and the assumptions that have been used to establish it. Neglect of the immediate resuspension of the plume obviates the question of differences between the Center's model and Dr. Anspaugh's model as presented at the 153rd meeting, since that particular resuspension model deals with a plume when it is emitted rather than the remobilized ash.

10) *The calculation of inhalation (and aeolian remobilization) dose using a triangular distribution of the logarithm of particle size, and incorporating the contribution of larger particles as a deceasing fraction of the dose due to the one-micron particles requires better documentation than the Center was able to present at the time of the meeting.* The assessment of consequences presented by the Center at this meeting is an improvement over the wholesale acceptance of particles 100 microns or smaller as respirable.

Appendices

The first appendix to this trip report, Appendix 1, is a collection of the questions put to the Center staff and a summary of the ACNW team's understanding of the responses.

Appendix 2 is a discussion, prepared by Professor Bruce Marsh of the magma/waste package interaction. The evidence detailed in the Appendix 2 illustrates the basic nature of the processes involved in the solidification of magma upon interaction with the repository and waste canisters. This leads to a more realistic view, and less conservative one, of the potential consequences from the interaction of the magma with the repository than currently being used by both the NRC and DOE. This has potentially important implications not only to understanding the magma disruption process, but to the understanding of other processes such as the entrainment and eruption of waste into the environment and subsequently into inhalation scenarios.

Appendix 1

QUESTIONS POSED BY THE ACNW TEAM, RESPONSES, AND ACNW TEAM COMMENTS

Prior to the ACNW team's visit, the ACNW presented the Center staff with 33 questions relating to specific topics that the members wanted addressed during the April 13-15, 2005 discussions, most of which pertained to the topic of igneous activity and its potential consequences. The Center was advised that these were important questions to the Committee, but that they were illustrative only and that additional questions could be anticipated in the discussion among the principals. In this report, the questions and responses about which the ACNW team had no further concern are presented first, followed by the questions about which the ACNW team still has concerns, either because the questions were not completely answered, or because the answers communicated an approach that is not risk-informed or technically sound, or, in a few cases, where the answers were predecisional and the questions were not probed further. Statements in the discussion that follows to the effect that the ACNW team had been provided with information should not be interpreted as meaning that the related work has been completed. Following each question is a brief summary of the team's understanding of the response. Each of these two sections is summarized in Tables 1 and 3, respectively, which are placed at the end of the sections.

<u>Questions about which there are no further concerns:</u>

- *What Dose Conversion Factors were used and in particular what solubility class was assumed for an inhaled species? How where these selections justified?*

The Center assumes the solubility of uranium dioxide (Clearance Class Y) for the inhaled species. In accordance with NRC practice, the Center has used the dose conversion factors (DCFs) in FRG 11/12. Other work in which the ICRP72 DCFs were substituted for the FGR 11 values indicates that the differences in doses for many radionuclides were not significant. The final resolution of this question rests, however, with a decision to use of the ICRP doses and compare the results. Use of the ICRP72 DCFs by the DOE would require an exemption request after the transmittal of the license application or a modification of the existing EPA standard. The Center is not however precluded from assessing differences between the DCFs in the FRG11/12 and the ICRP72.

- *What pathways of exposure were included or excluded in the models used by CNWRA and what was the technical basis for these choices?*

Section 1.01 The Center used the GENII code and calculated the total effective dose equivalent (TEDE) for each of 42 radionuclides presumed to be present in the soil. Calculation of the TEDE is consistent with NRC practice. In response to questions, Center staff recognized that the inhalation dose was the dominant dose for the igneous scenario. The "critical group" is identified as farmer/ranchers in the Amargosa Valley. Dose calculations in the performance assessment will be done for the Reasonable Maximally Exposed Individual (RMEI) meeting the criteria defined in 10 CFR 63.312. Some recognition was also given to the realistic situation of crops that can actually be grown in the Amargosa Valley. The Center has not yet done so, but apparently intends to incorporate the ICRP 72 dose conversion factors. Aeolian and fluvial remobilizations are both considered to be the drivers for the exposure pathways.

- *Bayesian statistical methods are useful in incorporating geologic variables into probability studies, but to date the only geologic information used by the NRC has been gravity anomalies. What other geologic and physical attributes of the Yucca Mountain region could be employed to increase the realism of the probability estimates?*

The Center has been a leader in using Bayesian statistical methods incorporating geologic variables into studies of the probability of future volcanic events occurring within the footprint of the repository. The Center has used the spatial variations in gravity anomalies to refine the probability estimates and, although the use of this information has been questioned in this regard, the employment of geologic variables to constrain probability is a potentially powerful technique. The Center staff has not discovered other potential geologic or physical attributes of the Yucca Mountain region to aid in the analysis of probability. Their work of approximately 10 years ago has shown that the use of surface elevation as a controlling parameter does not increase the realism of the probability estimates. However, recent studies as reported at the PVHA-Update Working Group meeting #2 suggest that evidence supports surface elevation as a possible controlling parameter on the propagation of dikes into the footprint of the repository.

- *What tradeoffs have been made in igneous processes parameters involved in both probability and consequence scenarios such that conservative estimates have been made to compensate for absence of significant information? What is the status of research underway to determine the needed information?*

The Center has not deliberately substituted modeling conservatisms in some areas of igneous activity to compensate for a lack of understanding of other features, events, and processes in other areas.

- *What has been the progress in your corrosion and humidity deliquescence studies during CY 2004 and 2005? What conclusions have you been able to draw regarding the stability of the waste package?*

The Center's corrosion studies have progressed to the point where the results are formatted as distributions that incorporate the uncertainty in corrosion rates. These distributions are abstracted as inputs to TPA Version 5.0.1. The Center is using data developed in the Center laboratories, and qualifying the data. The purpose of this work is to provide support for the NRC's review of the corrosion studies submitted by the DOE and is by its nature focused on specific issues and questions. The uncertainties that persist are incorporated as abstractions into the performance assessment codes.

- *Has CNWRA (or DOE) examined meteorite corrosion in desert sites as a source of analogue data on the corrosion of iron based alloys over periods of 100,000 years?*

If meteorites fall into an environment that does not support fast corrosion, e.g. no oxygen and little water, then they will remain in their metallic state for a long time. However, it is difficult to know the terrestrial age of a meteorite, or the corrosive environment it has experienced. The CNWRA examined the use of old metallic meteorites as an analog for the performance of the waste package. The corrosion properties of these iron-nickel alloys differ greatly from that of the engineered materials used in the waste package and the terrestrial age of the meteorites and corrosive environment are not well known. The CNWRA believes that the information obtained from these types of analogs is of limited usefulness. Thus they see little value in the study of meteor corrosion.

- *The probability of a container failure/leaking in the first 10,000 years may be determined by the probability of seal failure. Please describe what is known as to the design of this seal and what would be the relative corrosion rate of the seal relative to the rest of the container? (Residual stresses are the source of the problem here and perhaps bimetal galvanic effects, depending on the weld design.)*

The final design of the seal has not been fixed. A preliminary design has been examined and some work has been done on the degree of corrosion acceleration induced by welding. The seal preliminary design that was described showed that the appropriate parameters had been considered: i.e., (1) multiple welded barriers at the ends are proposed, in case one barrier leaks; (2) the welding process will be machine controlled, thus providing uniform welds that are easier to inspect than hand made welds; (3) the weld procedure used will minimize weld metal volume and composition variation across a weld zone, thus reducing the tendency of the welds to suffer localized corrosion.

- *What has CNWRA accomplished in its work on radionuclide transport modeling in CY 2004 and 2005? Have you incorporated spatial variations in water chemistry into Kd determinations and usage in the TPA and if so how are you doing this?*

The Center has been responsive to the suggestions made during the ACNW's Geosphere Transport Working Group meeting. Potential spatial water chemistry impacts on K_d values have been evaluated and additional sorption studies are underway to evaluate neptunium transport in the alluvium.

K_d values are critical to modeling the movement of radionuclides to the accessible environment and ultimately to radiation exposure of the RMEI.

- *What studies are contemplated on the solubilities and mobilities of spent fuel constituents in the presence of free water? What additional studies will be required if the period of performance assessment were to extend beyond 10,000 years?*

A previous proposal to use unirradiated UO_2 as a surrogate to study release from the matrix – a proposal that the ACNW commented on extensively after the 2004 visit to the Center—is not being pursued by the Center. The NRC and the Center are using published work on irradiated SNF to construct abstractions, for the TPA, of the solubilities and mobilities of radionuclides in the gap and at exposed surfaces of SNF. These abstractions include a full range of uncertainties, and would appear to be appropriate for the TPA. The question of additional studies was not directly addressed. However, experimental results of the Center's the laboratory studies are extrapolated for long periods of time, even for the 10,000 year time of compliance, so the extrapolation method would probably be comparable. Temporal extrapolation is included in the uncertainty band.

- *Please provide a description of the changes being incorporated into Version 5 of the TPA code and, where applicable, the physical phenomena modeling that these changes address.*

Version 5.0 of the TPA code incorporates tephra remobilization, the consequences of drift degradation, updated near-field calculations, drip shield and waste package weld corrosion, and colloid transport. Various parameter values and distributions have been added/ modified to reflect current knowledge and some code testing has been done for time periods longer than 10,000 years (to 100,000 years). This code testing appears to have addressed numerical stability. Code development is still ongoing. Consideration is being given to an ACNW member visit to the CNWRA in the Fall of 2006 to discuss the models incorporated in the TPA Version 5.0. The work on the development of TPA 5.0.1 is not complete and this version of the TPA code has not yet been released.

- *Please describe what processes will be used to provide a scientific validation (peer review, publication in refereed journals, etc) for the TPA code and the basis by which these processes will provide adequate confidence that the TPA code can be used in a regulatory decision-making process.*

The Center does encourage publication in peer-reviewed journals and when this is done the technical work that forms the basis of the TPA code is subject to this level of review. The CNWRA has an internal QA process that is used to assure code quality and technical review of the code models and parameter/data input. The Center directors also wish to encourage review of Center work by the ACNW, which they view as an independent peer-review group.

- *The Center is currently evaluating a set of multimedia environmental models for complex decommissioning sites (GENII, MEPAS, RESRAD-OFFSITE, and GOLDSIM). Recognizing that the Center's work is still ongoing: What model or models best represent physical situations encountered at decommissioning sites? What models should be used and why?*

Information was provided concerning the three (3) main models of interest - RESRAD, GENII and MEPAS. GoldSim was covered by a demonstration. GoldSim is a computer code, developed for commercial distribution by Golder Associates, that provides a simulation language which can be used to construct site models. The code modules (with the exception of GoldSim) were developed for particular applications and reflect this in their ease of application to particular sites. The final report on this code comparison is scheduled to be completed in August 2005 and will provide more information and another opportunity for ACNW interaction with the NMSS staff. Training sessions will be arranged for the NRC staff..

- *Demonstration of the capabilities of the GOLDSIM code*

The CNWRA demonstration was thorough and responsive to ACNW team questions. There was a brief discussion of DOE's use of the GoldSim computer code for the DOE performance assessment model. CNWRA appears to be thoroughly familiar with GoldSim and is apparently able to use it appropriately to review the DOE's performance assessment. The code appears to be adaptable to complex decommissioning site needs and has graphics capabilities that enable transparent displays of the model features and results. The site model being used to evaluate this code (a military site used for the testing of spent uranium projectiles) can be run on an ordinary PC with reasonable run times. DOE's performance assessment model of the proposed Yucca Mountain repository is being run on a number of networked PCs

Table 1. Summary of questions about which there are no further concerns

General Topic	Question briefly summarized
Calculation of RMEI dose	*What Dose Conversion Factors were used...*
	What pathways of exposure were included or excluded...
Igneous activity	*What other geologic and physical attributes of the Yucca Mountain region could be employed to increase the realism of the probability estimates?*
	What tradeoffs have been made in igneous processes parameters
Corrosion and radionuclide mobility	*What has been the progress in your corrosion and humidity deliquescence studies...*
	Has CNWRA (or DOE) examined meteor corrosion in desert sites...
	The probability of a container failure/leaking in the first 10,000 years may be determined by the probability of seal failure...
	What has CNWRA accomplished in its work on radionuclide transport modeling...
	What studies are contemplated on the solubilities and mobilities of spent fuel constituents in the presence of free water?
Performance assessment	*Please provide a description of the changes being incorporated into Version 5 of the TPA code*
	Please describe what processes will be used to provide a scientific validation (peer review, publication in refereed journals, etc) for the TPA code...
Decommissioning	*The Center is currently evaluating a set of multimedia environmental models for complex decommissioning sites*
	Demonstration of the capabilities of the GOLDSIM code

Questions about which the ACNW has remaining concerns:

An igneous event, and the processes related to it, represented the most important area for the ACNW team visit to the Center, for which the Committee had in hand the most outdated information, and about which the Committee the largest number of questions and concerns. The most important questions are related to how the interaction of magma with the repository and the waste is modeled, how consequences of an igneous event are modeled, what assumptions are made regarding particle size, solubility and respirability, how dispersion and resuspension are modeled, and the factors included in calculating the dose to a receptor. Additional questions concerning the interaction of magma with the waste and waste package arose during the ACNW team visit and became one focus of the discussion.

- *Considering the various igneous activity scenarios, list the key physical and chemical processes hierarchically in terms of their impact upon risk along with an assessment of the present state of understanding, including uncertainties of the basic science of these processes? What specific efforts are being carried out to better understand these key processes?*

The first part of this question was answered using the NMSS/NRC staff's "Risk Insights Baseline Report" (April, 2004) [RIBR-04] as a basis. However, the ACNW team questions the Center's "risk ranking" of the various phenomena involved in an igneous disruption. The components of the igneous activity topic that are rated of high risk significance are 1) probability of a volcanic event, 2) human inhalation of resuspended contaminated ash, 3) the number of waste packages affected by eruption, and 4) the occurrence of secondary volcanic conduits that may intersect more waste packages than occur within the diameter of a vertical volcanic conduit that could intersect the repository. The fourth process is appropriately interpreted as being part of item 3, the number of waste packages affected by eruption, in RIBR-04.

The Center's risk ranking, which is based on the significance of the issue to waste isolation, appears to be a semi-quantitative evaluation as described in the RIBR-04 report. However, in some cases the ranking may have been influenced by the approach being taken by the DOE. The introduction of this additional subjective factor departed from the Risk Insights approach taken to other features, events, and processes (FEPs). These additional criteria resulted in the observed inconsistencies. The Center presented in a figure, Conceptual Model for Igneous Disruption, risk ranking of the processes in an igneous disruption as being either of high or medium significance, as shown in Table 2. The figure did not show processes whose risk insights were categorized as of low significance.

Table 2. CNWRA Risk Ranking of Processes in an Igneous Event

High Risk Significance	Medium Risk Significance
Probability of a volcanic event,	Volume of material released to the environment in the eruption
Human inhalation of resuspended contaminated ash	Number of waste packages damaged
Number of waste packages ejected	Surface water reworking of released material
Occurrence of secondary volcanic conduits that may intersect more waste packages than occur within the diameter of a vertical volcanic conduit that could intersect the repository	Wind reworking of released material

- *What investigations have been conducted by the Center's contractors and consultants on igneous activity issues over the past year and what future activities are planned? What have been the goal, rationale, and results to date of these studies? What is the level of the effort by contractors and consultants to the Center?*

For several years the CNWRA has contracted with consultants to perform theoretical analyses and supporting laboratory model studies on the interaction of a volcanic dike with the underground repository and, thus the potential impact of an intersecting dike on the number of waste packages ejected during a volcanic event and on the integrity of the packages. The consultants' initial studies suggested the possibility of the 'dog-leg' scenario in which the magma upon intersecting the repository flowed down the length of the repository and broke through to the surface at a distant point from the original intersection of the dike with the repository, thus leading to the possibility of entraining many waste packages into the erupting volcano.

The dog-leg scenario is subject to question because of the assumptions that were used. More recent investigations by the contractors have attempted to capture more realistic assumptions and processes in modeling the nature and character of the flow of magma into the repository when it is intersected by a volcanic dike. These studies are materially significant to assumptions about the entrainment of waste canisters in the magma and the potential effect of the magma on the canisters and their integrity. The Center consultants' studies assume that the magma remains liquid during its passage through the repository and apparently do not include a sufficiently mechanistic treatment of cooling and solidification of the magma when it intersects the repository and contacts the waste containers.

The questions about the Center's contractors' and consultants' studies of magma-repository interactions were answered to the extent available in published NRC sources. A summary of potential magma-repository interactions is scheduled for release prior to the end of 2005, with subsequent submission of some results for publication. The studies and their conclusions are currently pre-decisional. These studies are being terminated, so that questions concerning follow-on studies are moot.

- *The NRC is not taking performance credit for the waste container once it is entrained in an igneous intrusion. What is the basis for this decision? What evidence is there to assume that waste container's integrity is lost due to thermal effects when the container is engulfed by an intruding magma?*

CNWRA and the NRC take the position that they need take no credit for the waste container. Since the DOE has assumed this position, the Center sees no need to, make a more thorough analysis than what is needed to judge the application. This has major impact on estimates of the consequences of an igneous event, and on the calculation of the RMEI dose, both of which are excessively conservative as a result.

- *What is the progress of studies underway to estimate the effect of eruptions from a bocca on the consequences of a magma intrusion into the potential repository? Why is this important?*

The work on this scenario is incomplete and currently pre-decisional, but it is likely that consideration of this high risk significance item could seriously impact the potential risk from igneous activity. Studies have shown that secondary conduits (boccas) have occurred during volcanism in the Yucca Mountain region including at the Lathrop Wells volcano. Presumably, these secondary breakouts occur as a result of resurgence of volcanic activity after the primary conduit has been choked by solidified magma. Resurgent activity may find the path of least resistance to the surface is via a secondary path that includes the repository, thus leading to eruption of waste canisters. The occurrence of secondary conduits intersecting the proposed repository is specified as of high risk significance.

A summary of the work on the dynamic controls on summit (primary) and flank eruptions (secondary breakout or bocca) is scheduled for release by the NRC in May of 2005. We note the recent release (subsequent to the visit to the CNWRA) of a manuscript by Wood et al. regarding physical models of secondary eruptions and potential controlling factors in secondary eruptions.

- *At the September, 2004 ACNW Working Group meeting Dr. Harper of Sandia reported on studies of creation of aerosols from ceramics and metals by explosions. Are these results applicable to the CNWRA work on consequences? If not, why not?*

Section 1.02 The forces generated in Dr. Harper's experiments were about three orders of magnitude greater than the forces expected in an igneous eruption. With greater force one might expect smaller particles and more dispersion. Dr Harper's results indicated that only 10% of the particles in his more forceful explosions are respirable – much less than the Center's earlier assumption of 100% respirability. Although the Center has modified this assumption, they have not incorporated Dr. Harper's findings in their consequence assessment.

- *Since the predominant movement of any airborne pollutant is downwind (crosswind diffusion is orders of magnitude less) the Center should be able to apply a wind rose and calculate the centerline air concentrations and deposition readily with greater realism. What has the Center done with regard to applying variable wind direction and speed to the analysis of the distribution of contaminated ash around an eruption through the proposed repository? Explain the impact on consequences of assuming a realistic distribution of wind speed and direction.*

The model used has significant effect on the calculated dose to the RMEI, and thus needs thorough justification and documentation. Since much of this work is pre-decisional, the need for thorough justification should be recognized by NMSS and CNWRA. The remobilization model and the new TEPHRA code are an improvement over the model used in current TPA code (Version 4.1j) and the Suzuki dispersion model is itself adequately documented. The Center's remobilization model uses a mass resuspension model much like that presented by Anspaugh, et al in *Health Physics* 2002, pp. 669-769.

In the Center's model, the area over which contaminated tephra is deposited, and the time for resuspension, is at considerable variance with some of the information on resuspension of the initial plume that was presented by Dr. Lynn Anspaugh during the September 2004 ACNW working group. The Center emphasizes remobilized tephra far more than the initial tephra plume dispersion, and stated that significant doses would not result from exposure to the initial ash plume, claiming that local potential receptors would flee that plume.

Apparently a wind rose, based on several decades of daily wind measurements from a nearby location, is being applied to the dispersion calculation. The dispersion is not calculated using a Gaussian dispersion equation. Instead, the tephra plume is stratified by height of the stratum above the ground. The dispersion model used follows the Suzuki model and is appropriately referenced in the supporting documentation. The remobilization model and the details and complementary cumulative distribution functions (CCDFs) resulting from this calculation are predecisional at this time, and will be part of TPA Version 5.0.1.

- *What resuspension model is the CNWRA using in calculating dose? Dr. Anspaugh reported at the September, 2004 ACNW Working Group meeting on Nevada test site weapons test work that showed resuspension of aerosols occurs over time periods of days rather than years? Why is resuspension characterized as occurring over a period of years in the CNWRA's consequence work? If Dr. Anspaugh's assertion is wrong or not applicable to basaltic ash, why is it wrong or not applicable?*

The statement was made that the initial plume (including immediate resuspension of that plume) had minimal effect on the dose to the RMEI. That dose was presumed to be primarily due to remobilization of contaminated ash which does take place over a number of years. Examination of several of Dr. Anspaugh's papers on this subject revealed that his research group has proposed several models, including models of immediate resuspension and models of remobilization (mass movement). The Center's remobilization model does incorporate the ideas in Dr. Anspaugh's remobilization models.

- *What evidence is being used to estimate the size distribution of the waste being incorporated into the tephra? How does this size affect the tephra particle size in which the waste is incorporated? What evidence is being used to determine the particle size distribution (PSD) of the ejecta and how is this validated using the ejecta of nearby volcanic materials? How does the nature of the PSDs change with the nature of the physical fragmentation process (e.g., vesiculation, ash formation, chemical weathering, etc.), the nature of the source material (magma, wall rock types, chemically weakened canister materials including fuel pellets), and the effect of man (e.g., agricultural practices, construction)? What is the evolution of the PSD as a result of geomorphic, chemical, aeolian, and other processes after the ash is deposited? What is the distribution of waste as a function of ash particle size used in the analyses and what is the supporting evidence for this distribution? What is the impact of this distribution on the consequences of a volcanic event?*

The particle size and density are the most significant factors in the dispersion and respirability of any radionuclides released to the accessible environment following an igneous event. Therefore, these assumptions significantly affect the consequences and the dose to the RMEI. The two questions that prompted concerns were: (1) the neglect of the effect of the vitrified waste packaged with the DOE SNF and (2) the assumption that the waste package and cladding are completely destroyed.

The Center's statements (during the meeting) about vitrified waste implied that SNF would be surrounded by vitrified HLW "logs" in all waste packages. Consultation with several independent outside sources confirmed that only the DOE SNF, which constitutes at most 10% of the repository volume, will be surrounded by glass logs in the waste package, and there may be too few glass logs even for that. Thus, since the total amount of DOE spent fuel and HLW would occupy 10% of the repository volume, the vitrified HLW is at most 5% of the emplaced waste, and would have a negligible impact.

The second factor is discussed extensively above.

The CNWRA response to much of this question is contained in an unpublished CNWRA paper by LaPlante and Jarzemba, which is incorporated in the User Guide for the model ASHPLUME Version 1.0 (CNWRA 97-004, 1997). For any waste packages that are in contact with magma, it is assumed that all cladding and packaging are breached and all of the waste comes in contact with magma. An igneous event is assumed to disrupt one waste package. A lognormal size distribution of HLW and SNF particles from 0.01 cm to 1 cm is assumed and modeled as a triangular distribution of the log of the diameters, with the median diameter = 0.1 cm. Particle size of deposited ash is based on the Suzuki model and is also assumed to be distributed log normally. The CNWRA model assumes that only a waste particle one-tenth the size of a tephra particle, or smaller, would be incorporated into the tephra particle. The average density of a contaminated tephra particle was assumed to be 5 gm/cm^3 and a lognormal distribution of waste fractions (in tephra) was used in the calculations. These assumptions about the particle size distribution, incorporation of radioactive particles in the tephra, and the density of contaminated tephra appear to be reasonable and adequately documented. The LaPlante and Jarzemba report states that these assumptions can be revised as new data become available. At the ACNW's working group session on igneous activity, the Electric Power Research Institute (EPRI) pointed out that, using ASHPLUME, 80 percent of the performance assessment realizations had negligible accumulation of ash at the RMEI location, and that the ash that did accumulate was not in the respirable range. Different analysts' results appear to cover a wide uncertainty range.

- *What studies are underway to reduce the uncertainties concerning the respirable fraction of waste-contaminated ash? In what way are the current assumptions conservative and what can be done to decrease their uncertainties?*

The studies leading to the remobilization module and the discussion of particle size distribution indicate that the Center continues to gather data and information to reduce uncertainty, and that this information tends toward realism rather than excessive conservatism. The Center is now using a lognormal particle size distribution and calibrating the contribution of larger particles to the TEDE against the dose delivered by one-micron-sized particles. This method is partly documented, and is discussed further below.

- *What particle size distributions (in the respirable range of 0.01 to 10 micron) are derived from the CNWRA analysis? What fractions of radioactive materials involved in an igneous event are sequestered and what fraction will be available for potential inhalation? How are the radioactive materials assumed to be distributed in the respirable fraction of the aerosols?*

- *What are the specific parameters that the CNWRA scientists are using in the inhalation and exposure scenario for the receptor? Why are particles up to 100 microns assumed to be respirable? What is the justification?*

Airborne concentrations are assumed to be from remobilization, rather than from the initial plume, which passes very quickly. Particles are assumed to be produced by physical crushing. The median diameter that DOE uses is 20 micron; NRC uses 10 micron. According to the oral presentation made by Center staff, ICRP 72 estimates that the range of particles up to100 micron contributes something to the TEDE but the DCF – the contribution to dose – depends on particle size. In particular, the Center considers a distribution of DCFs with a maximum DCF for 3 micron particles and somewhat less for one micron particles. The DCF is assumed to decrease for larger particles, and the DCF for 20 micron particles is assumed to be 1/8 of the DCF for one micron particles, with some small contribution for all airborne particles.

The only justification for considering that particles up to 100 microns contribute to the inhalation dose is the assumption of log-normally distributed dose conversion factors as functions of particle size, an assumption which assigns a very small, non-zero contribution to 100 micron particles. The physical rationale for even having 100 micron particles dispersed is that the dispersal is due to remobilization and is not the initial dispersion. This rationale is questioned elsewhere. The physiological rationale given is that the larger particles provide a naso-pharyngeal dose. Although this statement alone is not an adequate justification, the Center appears to be moving toward a position expressed during biosphere segment of the igneous activity WGS: that sinus-gastrointestinal absorption of radionuclides needs to be better accounted for in dose calculations. Particles larger than 10 microns might well penetrate the paranasal sinuses, but no data has been presented that presents the largest size for which such penetration is possible.

- *What consideration have you given, in light of the comments that were made during the September, 2004 Working Group meeting on igneous activity, to using a less deterministic overall approach to the fate and transport modeling? For example, in addition to wind direction, other model inputs could (and should) be handled through distributions, especially source term estimates (emission rates) and atmospheric stability-related dispersion coefficients (as well as resuspension). Have you incorporated any of this thinking into your models and if not, why not?*

- *With respect to modeling an igneous event, what changes, if any, have you contemplated to your atmospheric dispersion model as a result of discussions at the ANCW November, 2004 meeting? What changes will be made to make the current models more risk-informed?*

A probabilistic, risk-informed approach has been adopted for some parameters. For example, wind direction data for 365 days, integrated over elevation, is being incorporated in a distribution that is sampled. Airborne particle size is also modeled as a distribution. It is the team's understanding, however, that the source term and some other model parameters are still being approached deterministically.

- *A variety of tectonic models have been suggested for the Yucca Mountain region. How are they being evaluated and used in determining the probability of future volcanism at Yucca Mountain?*

The tectonic history and current tectonic processes of the Yucca Mountain region have significant impact on the nature and occurrence of volcanic events and their products. Several new data sets for the Yucca Mountain region, regarding tectonic geodesy derived from GPS studies and seismic velocities of the lithosphere obtained from topographic investigations, have become available. These data sets were recently discussed at the DOE PVHA-Update Working Group meeting #2 attended by the Center and NRC staff. This new information pertains to the tectonic history and processes that could have an impact on the prediction of volcanic event probability, a high risk significance issue. At least two new alternative theories of tectonic evolution (Richard Carlson, Carnegie Institution of Washington Geophysical Laboratory, and Mark Tynan, YMPO/DOE) were presented at this Working Group meeting that could have implications on the volcanic history of the Yucca Mountain region and future volcanic events.

The Center staff recognized the importance of being involved in the April 2005 Penrose Conference of the Geological Society of America dealing with the "Kinematics and Geodynamics of Intraplate Dextral Shear in Eastern California and Western Nevada". This meeting is germane to the recent tectonic geodesy studies of the region of the proposed repository and the information derived from the conference should be useful in improving understanding of the tectonic processes that may bear upon the volcanic event probability.

- *How is the Center using volcanic clustering in probability analyses? Are the short-term high recurrence rates within clusters being used as an extreme upper bound on long-term average probability? If so, is the level of conservatism such that it leads to incorrect conclusions and insights?*

- *How is the Center using the spatial and temporal clustering of volcanic events in estimating the probability of an igneous intrusion into the proposed repository? What assumptions are made? Are they conservative or realistic? Are any Miocene basaltic events incorporated into the present probability determinations? If so, what is the basis of this assumption?*

- *The NRC has stated that their current estimate of the probability of an igneous intrusion into the proposed Yucca Mountain repository is 10^{-7}/yr over the next 10,000 years. This is stated as an average value. What values are used to determine this average and what is the distribution of the values used in determining the average?*

Concerns remain regarding NRC's estimate of 10^{-7}/yr (for 10,000 years) as a single point value for the volcanic event probability at Yucca Mountain by the NRC. The Center staff stated that 10^{-7}/yr is not an average event probability at Yucca Mountain, nor is it a bounding value because published values range from the order of 10^{-6} to 10^{-10}/yr. Apparently, it is accepted at this stage in the preparation for the LA review as a reasonably conservative value for the probability of an igneous event. It is being used as a surrogate for the mean value which is used in 10 CRF Part 63 to judge compliance. Current DOE studies related to the age, distribution, and number of hidden volcanic events evidenced in aeromagnetic anomalies in the Yucca Mountain region could impact probabilities up to an order of magnitude. The use of this single point value is in contradiction to the expressed view of the NRC to use a risk-informed approach to studies incorporating a full range of probability values in probability assessment. A range of estimates from 10^{-7}/yr to 10^{-8}/yr is specified in a published journal article of the CNWRA and NMSS/NRC staff.

- *What insights are currently available as to how these model changes [in TPA version 5.0.1 will alter perceptions of repository performance and the risk significance of the individual components?*

The model changes for TPA 5.0.1, which are pre-decisional, appear to provide a more accurate representation of the repository performance that TPA 4.0j, particularly the proposed remobilization model, the modeling of container life and corrosion, and the modeling of SNF dissolution and subsequent radionuclide mobilization. The CNWRA staff told the ACNW team that parameter and data input had been updated to reflect current knowledge. Consideration is being given to further discussion with the Center regarding the TPA Version 5.0. The suggested changes are likely to affect ACNW's perception of repository performance, since they respond to prior ACNW critiques.

- *What information is available at this time as to the capability (code stability and adequacy of models and input parameters) of the TPA code to model repository performance and to provide a tool for assessing uncertainty for periods substantially longer than 10,000 years? Are there identified conservatisms in the TPA code that will significantly limit its use as a regulatory tool in evaluating repository performance for periods substantially longer than 10,000 years?*

The TPA code is being revised and will be released within several months by the NRC, thus details regarding the code are of a pre-decisional nature. However, as reported at the ACNW meeting on February 24, 2005 the code will likely incorporate an ability to conduct assessments for time periods in excess of the 10,000 yr time of compliance currently defined in 10 CFR 63. Various parameter values and distributions in the TPA code have been added or modified to reflect current knowledge and some code testing has been done for time periods longer than 10,000 years (to 100,000 years). This code testing appears to have addressed numerical stability. Code development is still ongoing.

Table 3. Summary of questions about which serious concerns remain

General Topic	Summary of Question	ACNW Concern (briefly stated)*
Igneous activity and related topics	*...list the key physical and chemical processes hierarchically in terms of their impact upon risk...*	Inconsistencies in risk ranking need to be explained and minimized.
	What investigations have been conducted by the Center's contractors and consultants on igneous activity ...	Excessively conservative assumptions are made about magma-waste package and magma-waste interactions.
	The NRC is not taking performance credit for the waste container ....What is the basis for this decision?	Assumption that the destroyed waste package and waste are completely entrained and emitted.
	What is the progress of studies underway to estimate the effect of eruptions from a bocca...	Work is incomplete (and pre-decisional). This process could have serious impact.
Consequences of an igneous event	*At the September, 2004 ACNW Working Group meeting Dr. Harper of Sandia reported on studies of creation of aerosols....*	Section 1.03 The Center has ... not incorporated this finding of Dr. Harper's in their consequence assessment.
	...the Center should be able to apply a wind rose and calculate the centerline air concentrations and deposition readily with greater realism.	The remobilization model is similar to an Anspaugh remobilization mode. However, the effect of immediate dispersion and resuspension is neglected, in favor of remobilization, without adequate justification.
	What resuspension model is the CNWRA using in calculating dose?	
	What evidence is being used to estimate the size distribution of the waste incorporated into the tephra?	The effect of vitrified high level waste is not considered. The size distribution estimate depends on the waste package being completely destroyed.
	What studies are underway to reduce the uncertainties concerning the respirable fraction of waste-contaminated ash?	The Center continues to gather information to reduce uncertainty, and tend toward realism, but documentation was inadequate.
	What particle size distributions (in the respirable range of 0.01 to 10 micron) are derived from the analysis?	The Center estimates that the range of particles up to 100 u

	What are the specific parameters that the CNWRA scientists are using in the inhalation and exposure scenario for the receptor? Why are particles up to 100 microns assumed to be respirable?	contribute to the TEDE. The contribution to dose depends on particle size, and considers a distribution of DCFs with a maximum for 3 micron particles. Assumptions are not adequately justified...
	What consideration have you given, to using a less deterministic approach to the fate and transport modeling?	The source term and some other model parameters are still being approached deterministically
	What changes... have you contemplated to your atmospheric dispersion model....to make the current models more risk-informed?	
Probability of an igneous event	*How are [new tectonic models] being evaluated and used in determining the probability of future volcanism...*	New tectonic data is becoming available that the Center needs to consider.
	How is the Center using volcanic clustering in probability analyses?	Concerns remain regarding the use of the 10^{-7}/yr value as a single point value for the volcanic event probability at Yucca Mountain by the NRC.
	How is the Center using the spatial and temporal clustering of volcanic events in estimating the probability of an igneous intrusion into the proposed repository?	
	The NRC has stated that their current estimate of the probability of an igneous intrusion into the proposed Yucca Mountain repository is 10^{-7}/yr...	
Performance assessment	*What insights are currently available as to how these model changes will alter perceptions of repository performance*	Model changes are being made and are pre-decisional. This is the <u>only</u> reason these responses are not considered to be satisfactory.
	What information is available at this time as to the capability...of the TPA code to model repository performance ...for periods substantially longer than 10,000 years?	The TPA code is being revised; any revision is pre-decisional This is the <u>only</u> reason these responses are not considered to be satisfactory.

* These brief statements are not intended to reflect the ACNW team's entire concern. They are only intended to identify the concern, and the related question and topic.

Appendix 2

By not considering scenarios for the interaction of magma with the canisters, there is a real possibility of missing important processes that may not only have implications for understanding other processes (e.g., entrainment and eruption of waste) but also in correctly sensing the overall seriousness of the magma disruption process itself. A prime example is the un-appreciation of the exceedingly common phenomenon of magma solidification. This is a serious omission. Some explanation for this view is given below.

Magma Crystallinity: The magma-type that has historically inhabited this region is called alkali basalt. Under surface pressures, it begins to melt at about 1000°C (*solidus* temperature) and with continued melting maintains a rigid structure until the amount of melt exceeds about 50% (vol.) whereupon it becomes a highly viscous, gooey mush of crystals and melt. Continued melting produces a pure, crystal-free, melt at about 1150°C, which is the *liquidus* temperature. The lesson here is that once any magma reaches, in the strictest sense, a crystal content of about 50% it is no longer mobile, but becomes rigid immobile rock. This general characteristic of magma is shown in Figure 1for some common magma types along with the alkali basalt from Lathrop Wells; this is the same Lathrop Wells composition used in the experimental study by Nicholls and Rutherford (2004). In a more practical sense, the viscosity increases so strongly with approach to this 50% crystallinity barrier that magma becomes immobile at crystallinities nearer 40%. A local loss in temperature of about 100°C will thus solidify the magma.

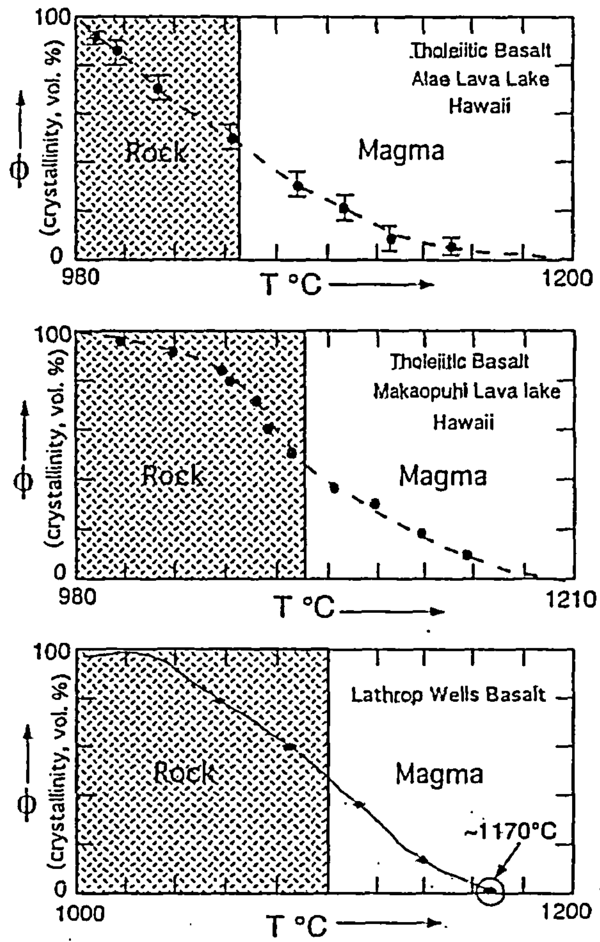

Figure 1. The variation of crystallinity with temperature for some common rock types (after Marsh, 1981).

All magmas erupting on Earth have temperatures below their liquidus and thus always contain some crystals. And during the later stages of ascent, prior to imminent eruption, adiabatic expansion promotes cooling, regardless of heat loss to the surroundings, which increases crystallization. Moreover, if the magma contains volatiles, like H_2O and CO_2, which are common constituents of alkali basalts, the dramatic loss of these volatiles with approach to the surface (i.e., drop in pressure) causes the governing phase diagram to shift to higher temperatures (see below). This thus causes even more crystallization and quenching, which most often takes the form of swarms of needle-like crystals of feldspar (plagioclase) in glass, In this state, magma quenches against virtually anything it touches. In Hawaii, for example, magma even quenches against and around trees. The heated sap bursts the tree and the trees often catch fire and burn away leaving a hollow vertical pillar in the lava. All magmas moving as dikes through fissures near Earth's surface show strongly quenched edges in all contacts with the host rock. These are called 'chilled margins' and are ubiquitous. The basic physics of this process is very straightforward. In attempting to heat up the material in which it is in contact, the magma loses the critical amount of heat that brings it to a solid or glassy state. The overall process is very much akin to the behavior of molten paraffin, which when spilled quenches against all that it touches, even cooler blocks of paraffin. The perception that magma will continue to 'run' past and bathe the container in a well-mixed bath of magma is a gross misperception. Only if the canister were dropped into a vertical column of magma and was allowed to settle hundreds of meters would such a situation be approximated.

Quenched Magma on Canisters: The melting point of Alloy 22 is in the range of 1350-1380 °C; the container itself, although significantly above the temperature of the ambient drift wall rock, will be much cooler than any invading magma. The magma will immediately quench against the canisters, forming a glassy rind of a thickness that can be easily calculated from knowledge of the canister thermal inertia or enthalpy and its size. The volume of quenched magma is given by

$$V_{quench} = \frac{(\rho C_p \Delta T V)_{cannister}}{(\rho C_p \Delta T)_{magma}}, \qquad (1)$$

where V is volume, □ is density, Cp is specific heat, and □T is the temperature contrast; because the magma will quench to mainly glass the role of latent heat has been ignored. Quenching will be especially effective against the canisters because of the large thermal conductivity of metal, which greatly facilitates heat transfer, making the principal thermal resistance in the magma. The thickness (d) of the quenched rind assuming a cylindrical canister of surface area A_c will be, $d = (V_{quench}/A_c)$, and (1) now becomes

$$d_{quench} = \frac{(\rho C_p \Delta T V)_{cannister}}{A_c(\rho C_p \Delta T)_{magma}} \qquad (2)$$

Since the canister is not a solid mass of metal, some allowance must be made for the effective mass of the canister, for the rate of internal heat transfer, and the possibility of a higher heat capacity due to the presence of a silicate glass. It is also important to realize that the values of □T for magma and canister will be different; the magma need only cool by about 100 °C to quench, but the canister can heat up to near 1000°C and still be effective in the quenching process.

Using general properties for magma and metal and an internal packing of 50% for the canister (assuming a canister size of 1.8m by 5m), the quench thickness is on the order of 10 meters. The time (t_q) to grow this quenched rind will not be instantaneous and will be given by (approximately)

$$t_q = 0.5\, d_q^2\, \kappa^{-1} \qquad (3)$$

where □ is the thermal diffusivity of the magma (~10^{-2} cm^2/sec). The time to grow a 5 m thickness of quenched rind is about 5 months, which is consistent with the rates of solidification of Hawaiian lava flows.

A relevant example of this process of quenching is well demonstrated in a series of massive experiments conducted by Sandia Laboratories in the late 1970's in an attempt to understand the extraction of thermal energy from molten magma using an inserted heat exchanger (e.g., Hardee, H.C., 1975, Convective heat extraction from molten magma, Jour. Volcanology and Geothermal Research, 10, p. 175-193; Fewell, M.E., Hardee, H.C., & Montoya, C, 1975,Design of a molten-lava, single tube boiler expoeriment. SAND75-0080; Hardee, H.C. & Fewell, M.E., 1975, Molten lava/single tube boiler experiment. SAND75-0069).

The basic setup was a barrel-like cylindrical vat holding 0.2 m^3 of Hawaiian basalt maintained by induction heating in a superheated state of 1450 to 1650 °C. (This is 250 to 450 °C above the basalt liquidus.) A heat exchanger (cylindrical finger or probe (~15 cm diam.) made of Type 310 stainless steel) was inserted into the vat of magma and the efficiency of heat transfer to steam within the probe was monitored. Even though the basalt was maintained at an extreme temperature through constant heating, which forced the melt to vigorously convect, a quenched rind of glass always formed on the probe. Because of the extreme and unrealistic external heating, it is not possible to compare the rind thickness (~2 cm) to that predicted above in equation (2). It does suffice to show, however, that quenching will clearly occur even under the most extreme conditions.

Magma Solidification During Final Ascent: During ascent, magma free of dissolved water (i.e., Dry Magma) cools and solidifies only by adiabatic expansion and conductive heat losses to the wall rock (see Figure 2). The geometry of the phase diagram of Dry Magma relative to adiabatic cooling, which is ~0.5 °C/km, shows that any crystals in the magma will begin to melt; without conductive losses, solidification stalls and is reversed. For magma containing dissolved water (Wet Magma), the geometry of the associated phase diagram for the same basalt is much different (Figure 2), and, although adiabatic cooling will cause further solidification, there is a much stronger effect. Because the solubility of water in magma is essentially zero at surface pressures (1 bar), ascending Wet Magma will undergo strong exsolution of water (the magma essentially gets the bends) and, in essence, undergoes dehydration. The loss of water causes the phase diagram to suddenly and progressively shift to higher temperatures, which promotes rapid crystallization. This is the process that fragments the suddenly quenching magma into popcorn-like tephra.

The pre-eruptive water content of typical Lathrop Wells basalt has been inferred by Nicholls and Rutherford (2004) by matching the observed phase assemblage of the lava to that found experimentally under varying water contents in the melt. They conclude that the magma was at or near water saturation at a pressure of about 200 MPa (2 kb = ~6 km depth), which is also shown on Figure 2. The phase diagrams for the same Lathrop Wells melt composition are shown by Figure 2; the Dry Magma phase equilibria was calculated using the well-known MELTS numerical code of M. Ghiorso, and the Wet phase diagram is from Nicholls and Rutherford. The pre-eruptive conditions determined by Nicholls and Rutherford are shown and the most likely eruption path is also indicated. The slight heating with approach to the surface is due to the heat of volatile exsolution. The net result is that the magma will undergo strong quenching and fragmentation with approach to the surface. This is a well-known phenomenon.

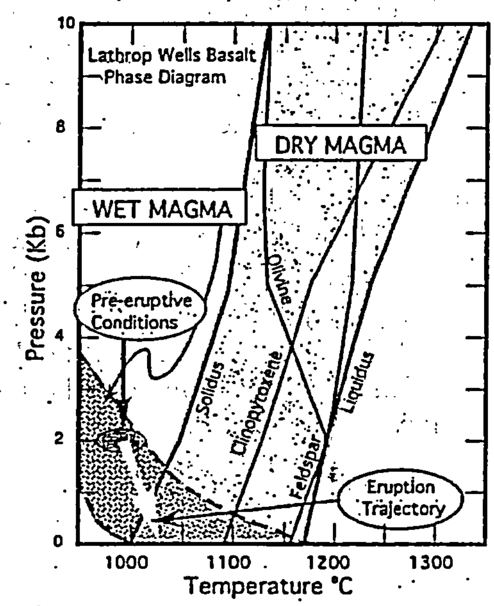

Figure 2. Phase diagram for Lathrop Wells basalt under Dry and Wet conditions.

The basic conclusion is that should this magma encounter the repository during ascent, the already rapidly quenching magma will undergo even more strong exsolution-induced quenching. Instead of fluid magma entering the drift and flowing along to eventually fill it (like filling a bathtub), a cinder cone will begin developing at the point of intersection. The cinders will avalanche into the drift, rapidly pile up, and plug the drift; the fragmental material will not flow far. The insulating effect of the close wall rock will minimize radiant heat loss, allowing the pile of cinders and tephra to tack or partially anneal together to form a mass of some strength. This will form a plug in the drift, sealing the point of intersection, which will either force the magma to continue upward to erupt on the surface or simply seal off the dike locally, redirecting the flow to other portions of the dike that have already reached the surface. The net effect is that the area of the drift affected by the invading magma may be minimal and the number of canisters affected may be very limited.

If the magma has already degassed before reaching the drift, which could conceivably happen if the magma interaction took place late in the episode of local volcanism, lava itself could enter the drift. The viscous nature and rapid cooling of the lava would form either a volcanic dome or a true lava flow. The advancing lava would solidify at the rate of about 1 m/4 days and could envelope some canisters forming a thick quenched rind. Based on the nature of the flows at Crater Flat, the lava would be blocky and sluggish and advancement might be difficult in a cylindrical drift. It certainly would not be a simple case of a viscous, non-solidifying fluid flowing along a pipe. There is not the slightest chance that the lava would undergo any form of wholesale thermal convection whatsoever (Marsh, 1989, Jour Petrology, 30,479-530; Brandies & Marsh, 1989, Nature, 339, 613-616; Brandeis & Marsh, 1990, Geophysical Research Letters, 17,1125-1128; Hort, Marsh, Resmini & Smith, 1999, Jour. Petrology, 40, 1271-1300).

Radiative heat transfer from the tephra pile or lava pile outward along the drift may heat exposed canisters to the point of softening and canisters may undergo serious sagging and deformation under their own weight. Some consideration should thus be given to the structural integrity and form of the cradles holding the canisters.

Summary: These considerations are intended to illustrate the basic nature of the processes that present themselves when a more accurate and integrated system of magma solidification and interaction with the canisters is considered. The calculations serve to point how these processes work and how they force us to visualize the overall nature of the process with more realism. More detailed and straightforward calculations are called for that will further flesh out and establish the nature of these and other processes involving solidification and magma flow.