OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
ERRATA

QA: QA

Page 1 of 1

1. TER No. TER-02-0010

DC Tracking No. 31672

2. Product DI:	Title:	Revision:
ANL-WIS-MD-000015	Dike Propagation Near Drifts	Rev00, ICN01

3. Location	4. Clarification/Restriction
Section 7, Conclusions	Change the third paragraph of the Conclusions section to read: Data and assumptions used in these analyses are derived from the published literature as indicated in Table 1. No corresponding "qualified" data (data acquired under the controls of current QA procedures) have been developed specifically for Yucca Mountain and vicinity. Data developed during the analysis reported herein have been submitted to the Technical Data Management system, identified by Data Tracking Number SN0111T0511101.001. The data file also includes information on uncertainties in the data and restrictions on its use.

5. QER Review: (Print Name)	Initials:	Date:
James Graff	JG	03/04/02
6. Responsible Manager: (Print Name)	**Initials:**	**Date:**
Kathy Gaither	KG	3.04.02

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT ANALYSIS/MODEL COVER SHEET

Complete Only Applicable Items

1. QA: QA

2. ☒ Analysis — Check all that apply

Type of Analysis	☐	Engineering
	☒	Performance Assessment
	☐	Scientific
Intended Use of Analysis	☐	Input to Calculation
	☒	Input to another Analysis or Model
	☐	Input to Technical Document
	☐	Input to other Technical Products

Describe use:

Provide preliminary analyses to support evaluation of the interactions of a hypothetical dike with a repository drift.

3. ☐ Model — Check all that apply

Type of Model	☐ Conceptual Model	☐ Abstraction Model
	☐ Mathematical Model	☐ System Model
	☐ Process Model	
Intended Use of Model	☐ Input to Calculation	
	☐ Input to another Model or Analysis	
	☐ Input to Technical Document	
	☐ Input to other Technical Products	

Describe use:

4. Title:

Dike Propagation Near Drifts

5. Document Identifier (including Rev. No. and Change No., if applicable):

ANL-WIS-MD-000015, REV 00 ICN1

6. Total Attachments:

1

7. Attachment Numbers - No. of Pages in Each:

I - 3

		Printed Name	Signature	Date
8.	Originator	G.E. Barr	SIGNATURE ON FILE	11/13/00
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OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
ANALYSIS/MODEL REVISION RECORD
Complete Only Applicable Items

2. Analysis or Model Title:

Dike Propagation Near Drifts

3. Document Identifier (including Rev. No. and Change No., if applicable):

ANL-WIS-MD-000015 REV00, ICN1

4. Revision/Change No.	5. Description of Revision/Change
REV00	Initial issue.
REV00, ICN1	This ICN was developed to address a design option - "Open" drifts (no backfill), associated with Technical Change Request T2000-0133 (CRWMS M&O 2000d) – developed after the initial issue of this report. New information in this report addresses the interactions of a hypothetical dike with a repository drift (i.e., tunnel) and with the drift contents for the case in which there is no backfill in the drifts. Marginal bars indicate changes.

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ACRONYMS

ANL	Analysis
AMR	Analysis and Model Report
CRWMS M&O	Civilian Radioactive Waste Management System Management and Operations Contractor
DIRS	Document Input Reference System
DOE	U. S. Department of Energy
DP	Development Plan
DTN	Data Tracking Number
EBS	Engineered Barrier System
ICN	Interim Change Notice
IRSR	Issue Resolution Status Report
LA	License Application
MD	Model Development
NRC	U.S. Nuclear Regulatory Commission
PA	Performance Assessment
PMR	Process Model Report
PWR	Pressurized Water Reactor
QA	Quality Assurance
SR	Site Recommendation
TBD	To Be Determined
TBV	To Be Verified
TDP	Technical Development Plan
TSPA	Total System Performance Assessment
WIS	Waste Isolation System

1. PURPOSE

The purpose of this Analysis and Model Report (AMR) supporting the Site Recommendation/License Application (SR/LA) for the Yucca Mountain Project is the development of elementary analyses of the interactions of a hypothetical dike with a repository drift (i.e., tunnel) and with the drift contents at the potential Yucca Mountain repository. This effort is intended to support the analysis of disruptive events for Total System Performance Assessment (TSPA). This AMR supports the Process Model Report (PMR) on disruptive events (CRWMS M&O 2000a). This purpose is documented in the development plan (DP) *Coordinate Modeling of Dike Propagation Near Drifts Consequences for TSPA-SR/LA* (CRWMS M&O 2000b). Evaluation of that Development Plan and the work to be conducted to prepare Interim Change Notice (ICN) 1 of this report, which now includes the design option of "Open" drifts, indicated that no revision to that DP was needed.

These analyses are intended to provide reasonable bounds for a number of expected effects

1. Temperature changes to the waste package from exposure to magma

2. The gas flow available to degrade waste containers during the intrusion

3. Movement of the waste package as it is displaced by the gas, pyroclasts and magma from the intruding dike (the number of packages damaged)

4. Movement of the backfill (Backfill is treated here as a design option)

5. The nature of the mechanics of the dike/drift interaction.

These analyses serve two objectives: to provide preliminary analyses needed to support evaluation of the consequences of an intrusive event and to provide a basis for addressing some of the concerns of the Nuclear Regulatory Commission (NRC) expressed in the Igneous Activity Issue Resolution Status Report (IRSR) (Reamer 1999).

The estimates of the number of waste packages at risk and the circumstances of that risk are functional inputs for two technical products: *Igneous Consequence Modeling for TSPA-SR* (CRWMS M&O 2000c) and *Number of Waste Packages Hit by Igneous Intrusion* (CRWMS M&O 2000d).

2. QUALITY ASSURANCE

This document was prepared in accordance with AP-3.10Q, *Analyses and Models,* and the development plan *Coordinate Modeling of Dike Propagation Near Drifts Consequences for TSPA-SR/LA* (CRWMS M&O 2000b), which was, in turn, prepared in accordance with AP-2.13Q, *Technical Product Development Planning*. Although AP-2.21Q, *Quality Determinations and Planning for Scientific, Engineering, and Regulatory Compliance Activities*, has since replaced AP-2.13Q, it has been determined that this development plan remains in effect for this AMR. For Revision 00, a Technical Change Request (T2000-0040) for the DP was approved in accordance with AP-3.4Q, *Level 3 Change Control*. The development of this technical document was evaluated (CRWMS M&O 1999a) in accordance with QAP-2-0, *Conduct of Activities*, and has been determined to be subject to the requirements of the *Quality Assurance Requirements and Description* (DOE (U.S. Department of Energy) 2000). An additional Technical Change Request (T2000-0133, CRWMS M&O 2000e) was initiated and approved for ICN 1 to Rev 00.

The methods used to control the electronic management of data as required by AP-SV.1Q, *Control of the Electronic Management of Information*, were not specified in the Development Plan, Coordinate Modeling of Dike Propagation Near Drifts Consequences for TSPA-SR/LA (CRWMS M&O 2000b). With regard to the development of this AMR, the control of electronic management of data was evaluated in accordance with YAP-SV.1Q*, Control of the Electronic Management of Data*. The evaluation (CRWMS M&O 2000f) determined that current work processes and procedures are adequate for the control of electronic management of data for this activity. Though YAP-SV.1Q has been replaced by AP-SV.1Q, this evaluation remains in effect.

All inputs to this document are listed in the Document Input Reference System (DIRS) for this report, in accordance with AP-3.15Q, *Managing Technical Product Inputs*. Accepted data as identified in the DIRS sheets are identified in accordance with AP-SIII.2Q, *Qualification of Unqualified Data and the Documentation of Rationale for Accepted Data*. The conclusions presented in this AMR do not affect the repository design permanent items as discussed in QAP-2-3, *Classification of Permanent Items*.

In addition to the procedures cited above, the following procedures are applicable to this document: AP-2.14Q, *Review of Technical Products*, AP-3.14Q, *Transmittal of Input*, AP-6.1Q, *Controlled Documents*, and AP-17.1Q, *Record Source Responsibilities for Inclusionary Records*.

3. COMPUTER SOFTWARE AND MODEL USAGE

No software subject to the requirements of the AP-SI.1Q*, Software Management* was used in the preparation of this document. The commercial application software Microsoft Word (Office 97) and PowerPoint (Office 97) were used to generate text and to construct figures and flow charts. The software was appropriate for the applications.

4. INPUTS

The inputs to this document were analyses and ranges of data published in the technical literature.

4.1 PARAMETERS

Specific parameters used are listed here in Table 1, Table 2, Table 3, and in Section 6.3.1 under Current Stress State, Section 6.3.2 under Design Description and Section 6.3.3 under Gas Flow.

Table 1. Input Parameters and Current QA Status

Definition	Symbol	Value	References	Input Status
Thermal conductivity of Tuff	λ	1.2 J/s m K	DTN: LB997141233129.001	Technical Product Output
Thermal conductivity of solid basalt	K	21.76 J/(kg sec °C) 0.0052 cal/(g sec °C)	Hodgman et al. 1955, p. 2251, Table Heat Conductivity	Accepted
Fusion temperature of magma	T_f	1046-1169 ^{0}C	CRWMS M&O 2000g, Sec. 6.2.3	Technical Product Output
Viscosity of liquid magma	μ	~19.2Pa s	CRWMS M&O 2000g	Technical Product Output
Density of magma	ρ	2484–2663 kg/m^3	CRWMS M&O 2000g, Sec. 6.2.4	Technical Product Output
Mass of Waste Package	M	42.3 metric tons	CRWMS M&O 2000h, p. I-2	Technical Product Output
Container-lid diameter	a (Att.- I only)	1.866 m	CRWMS M&O 2000, Att.- I	Technical Product Output
ontainer-lid thickness	t (Att.- I only)	0.08 m	CRWMS M&O 2000, Att.- I	Technical Product Output

Notes: Data tracking number (DTN)
Quality assurance (QA)

Table 2. List of Exsolved Gases

Species	Mole Fraction	References	Input Status
H_2O	73.16	CRWMS M&O 2000g ANL-MGR-GS-000002	Technical Product Output
H_2	1.17	CRWMS M&O 2000g ANL-MGR-GS-000002	Technical Product Output
CO_2	14.28	CRWMS M&O 2000g ANL-MGR-GS-000002	Technical Product Output
CO	0.57	CRWMS M&O 2000g ANL-MGR-GS-000002	Technical Product Output
SO_2	9.45	CRWMS M&O 2000g ANL-MGR-GS-000002	Technical Product Output
S_2	0.37	CRWMS M&O 2000g ANL-MGR-GS-000002	Technical Product Output
HCl	0.49	CRWMS M&O 2000g ANL-MGR-GS-000002	Technical Product Output
HF	0.06	CRWMS M&O 2000g ANL-MGR-GS-000002	Technical Product Output
H_2S	0.74	CRWMS M&O 2000g ANL-MGR-GS-000002	Technical Product Output

Table 3. Properties of Exsolved Gases

Species	Critical Temperature K	Critical Pressure Atm	Molecular Wt.	References	Input Status
H_2O	647.14	217.7	18.01	Lide and Frederikse 1997 p. 4-37f, p. 6-50f	Accepted
H_2	32.97	12.76	2	Lide and Frederikse 1997 p. 4-37f, p. 6-50f	Accepted
CO_2	304.14	72.78	44.01	Lide and Frederikse 1997 p. 4-37f, p. 6-50f	Accepted
CO	132.91	34.53	28.01	Lide and Frederikse 1997 p. 4-37f, p. 6-50f	Accepted
SO_2	430.8	77.8	64.06	Lide and Frederikse 1997 p. 4-37f, p. 6-50f	Accepted
S_2	1314	204.28	64.12	Lide and Frederikse 1997 p. 4-37f, p. 6-50f	Accepted
HCl	324.7	82	36.46	Lide and Frederikse 1997 p. 4-37f, p. 6-50f	Accepted
HF	461	63.95	20.01	Lide and Frederikse 1997 p. 4-37f, p. 6-50f	Accepted
H_2S	373.2	88.23	34.08	Lide and Frederikse 1997 p. 4-37f, p. 6-50f	Accepted

Reference information was obtained from the Technical Information Center and the Technical Data Management System, which are controlled sources. Sources are cited in the text where applicable and in Section 8, Inputs and References.

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4.2 CRITERIA

These analyses are investigatory and intended to provide estimates of the sizes of the effects of dike propagation. No criteria applicable to these analyses have been identified.

4.3 CODES AND STANDARDS

No codes or standards were used in these analyses.

5. ASSUMPTIONS

Assumptions are described here in general terms and are discussed in more detail in the sections in which they are used.

5.1 GAS FLOW

As real gas is supplied to the drift by the dike or vent:

- There is isothermal flow down the drift (no axial temperature gradient).

- Adiabatic expansion is ignored.
- Heat carried into the rock (the porous media) by the gas is ignored.
- There are no chemical interactions of the gases with the rock.
- The components of the engineered barrier system (EBS), including backfill, are irrelevant to the flow.

Basis–Gases exsolved from magma are real gases that obey the real gas law and satisfy the theorem of corresponding states as discussed (Pirson 1977).

Confirmation Status–These assumptions are shown to be conservative as a result of the analysis and do not need to be confirmed.

Use in the Analysis–These assumptions are used in Section 6.3.3 in the computation of gas flow.

5.2 SOLIDIFICATION OF MAGMA

Estimates and calculations of the phase change behavior occur as discussed in Jaeger (1964), Kreith and Romie (1955), Soward (1980), Stewartson and Waechter (1976), Riley et al. (1974), and Pedroso and Domoto (1973). Drift wall temperature is assumed to be ~ 600°C. Latent heat of fusion (L) is assumed to be 100 cal/gm (upper limit) and the specific heat (C) ~ 0.3, and ~ 0.25 for liquid magma and solidified magma, respectively (from Jaeger 1964).

Basis–The literature provides a reasonable basis for magmatic properties for this analysis and data specific to Yucca Mountain has been provided (CRWMS M&O 2000g).

Confirmation Status–The assumptions are taken from the literature and represent typical or best available information and do not need to be confirmed.

Use in the Analysis–The cited analyses and estimates are used in Section 6.3.4 and referenced in Section 8.1.

5.3 CONTAINER

A container of ~ 42.3 metric tons (CRWMS M&O 2000h, p. II-2) will be a representative package moved by the pressure pulse. The ultimate tensile strength of 316 Stainless Steel (a component of the container) as a function of temperature is assumed to be as provided by the fabricator (Allegheny Ludlum 2000). The basic design of the containers includes a skirt (~ 0.25 m) as specified in CRWMS M&O 1999b.

Basis–Design information is taken from the pertinent design as indicated by the citations. This information is used in semi-quantitative analyses of consequences of an intrusion and not to affect container design.

Confirmation Status–The description of the waste package is obtained from design data and is confirmed in those citations. The material properties, taken from the fabricator's specifications (Allegheny Ludlum 2000) and the current design parameters (CRWMS M&O 1999b) are adequate for the intended purpose of the analyses in this AMR.

Use in the Analysis–The design information is used in Section 6.3.3, and Attachment 1.

5.4 DRIFT DESIGN - DIMENSIONS AND SPACING

The following design assumptions related to the design of the drift were used as assumed values to support the analysis in Section 6.3, and as shown in Figures 6 and 7, based on design information presented in DTN SN9908T0872799.004:

- Radius of the drift – approximately 2.75 m,
- Container separation – approximately .10 m,
- Drip shield perimeter – approximately 5.5 meters

Basis: Controlled design documents are not available to provide these parameter values. The assumptions are based on current uncontrolled design concepts contained in SN9908T0872799.004. The value assumed for the radius of the drift and drip shield perimeter are adopted from the figure "Sketch (not to scale) corresponding to In-Drift Data for Drift-Scale Models For TSPA- SR (rev 01)" shown in the DTN. This figure is recreated as Figure 6 in this document. The container separation value is adopted from the DTN entry "Waste package spacing," and is that specified by Enhanced Design Alternatives (EDA) II, Design B (CRWMS M&O 1999f).

Confirmation Status: No additional work is planned to verify this assumption. Final, controlled designs could specify values different from those assumed here. If such changes occur, the impact of the changes on the results of this calculation will be assessed.

Use within the Calculation: Used to support analyses in Section 6.3.

6. ANALYSIS

6.1 INTRODUCTION

A long-standing problem in understanding the nature of possible volcanic disruption of a repository has been the physical details of how a dike interacts with a repository drift (and with a set of drifts) (Barr et al. 1993, p. 141). This problem of a dike interacting with a repository drift is not amenable to direct simulation—direct calculation of the interactions. Simulation would have allowed systematic examination of the most important processes. Rather, the problem is attacked piecemeal by examining end members or limiting cases of processes which can be modeled, and by interpretation, in terms of the Yucca Mountain site, of geologic observations of relic cinder cones and active volcanic systems believed to be analogous. End members (or bounding cases) are chosen by analysts because they provide an expeditious way to identify and explore physically possible dike/drift interactions for the consequences of the interactions. Some interactions can be rejected on the basis of negligible consequence and those needing more careful examination can be identified.

The results are often simplified because the fundamental driving processes producing the intrusion, extrusion and the volcano are not well-formulated at present. The interpretations are used to produce plausibility arguments about the interaction of the intrusive dike with a repository; and, however well argued, are the matters of contention between the Project and the NRC (Reamer 1999).

This AMR is intended to provide a better focus on identifying the detailed problems, why they might be important, and how they are related. The AMR is also intended to provide simple estimates for some of the effects, based only on analyses and interpretations already provided in the literature.

6.2 BASIC ISSUES

This AMR addresses and attempts to provide context for several end member cases of the dike propagation problem, and to provide a framework for the dike/repository interaction problem as a whole. Because, in the absence of simulation, modeling decisions are made based on plausibility arguments constructed around their interpretations of analogue data and reasoned speculations, part of that context is presented in the form of a "decision tree."

The decision tree, Figure 1 (p. 49), presents where those decisions of what is plausible (represented by "yes" or "no" choices) are made, and how they are interrelated. A simple decision tree allows identification of the modeling choices made to reach surface release. The tree entries which receive the most interest are the final components, namely the formation of the ash plume, and its distribution and deposition. However, getting to the releases requires an assembly of components describing the details of the interactions. Some of those details are indicated on the tree as ovals, referred to as "conditionals." These represent some of the supporting work which is required in order to make decisions about how the dike might reasonably be expected to interact with a drift. The topics of this AMR are analyses that feed these decisions. For a general discussion of dike development and properties refer to *Characterize Eruptive Processes at Yucca Mountain, Nevada* ANL-MGR-GS-000002 (CRWMS M&O 2000g).

Interaction of a dike with a drift, based on velocity of propagation of the dike, is first a mechanical interaction and later, when connecting pathways are established, a thermal and fluid flow interaction. In order to provide an overall perspective of the interaction of a dike and a drift, it is necessary to discuss when and how current interpretations fit together.

6.3 ANALYSES

There are two basic conceptual models of how a dike and drift might interact. The first presumes that a drift is a relatively insignificant heterogeneity in the rock, which is intersected and otherwise provides no interaction with the dike as it propagates to the surface. Essentially, the forces driving propagation of the dike are so large that the drift is only a minor perturbation. The result is a planar (slab-like) intersection of the dike and drift—the idealized interpretation. The dike-repository interactions are then (1) direct physical entrainment of waste in the dike and (2) flow of gas and magma, or gas and fragments, down the drift to interact with waste containers and waste. These two kinds of interactions involving an idealized intersection of drift and dike, are pursued in Sections 6.3.2 Interaction with the Drift, 6.3.3 Gas Flow, and 6.3.4 Thermal Environment. Since energy dissipation has been ignored, the idealization would be expected to produce stronger effects in the drift than would really occur.

The second conceptual model presumes that the dike, which propagates by means of a self-generated crack, (Spence and Turcotte 1985; Turcotte et al. 1987) interacts strongly with the stress-altered region (which forms around the drift) and with the void space in a drift. It is currently thought that dikes are emplaced normal to least principal stress as measured regionally in the near-surface (Tsunakawa 1983; Delaney et al. 1986). For this conceptual model, the thermo-mechanical state of the mountain (and repository) is important. This is the case because the dike is interacting with a stress field which is evolving and therefore the stress-state is not fixed in time. That is, when the drift is driven, the surrounding rock first tries to relax into the drift. When waste is added, the waste heat causes thermal expansion which puts the rock around the drift into compression. This compression relaxes as the repository cools. These stress alterations are large enough so that the least principal stress (currently horizontal, NNW-SSE) is rotated to vertical (Hardy and Bauer 1992); a circumstance which could alter how a propagating dike behaves as it encounters the stress-altered zone (perhaps producing a sill rather than a dike). After several thousand years, as the mountain cools, the least principal stress rotates back to its original direction.

Of these conceptual models, the more complete description from current literature is the second (Watanabe 1999), which will be pursued in this analysis in Sections 6.3.1 Thermal-mechanical Evolution of the Repository and Mountain and 6.3.2 Interaction with the Drift. This second, physically more complete conceptual model, functions to establish the constraints and qualitatively estimate the bounds that apply to the detailed interactions analyzed for the simple idealized model. Performance Assessment (PA) uses the first conceptual model as stated in *Igneous Consequence Modeling for the TSPA-SR,* ANL-WIS-MD-000017 (CRWMS M&O 2000c). PA also uses the second complex model to provide constraints on the first model.

The expected dike-repository interactions are (1) propagation of the dike into and across the drifts as described by the intersection of the dike crack with the drift in an evolving stress field, (2) flow of gas and magma, or gas and fragments, down the drift to interact with waste containers and waste, and (3) direct physical entrainment of waste in the dike.

The specific problem of waste entrainment has been treated in detail elsewhere (Wilson et al. 1994; CRWMS M&O 2000c (ANL-WIS-MD-000017)); CRWMS M&O 2000i (ANL-WIS-MD-000005) and will not be further examined.

The analyses are laid out as indicated in the decision tree in Figure 1, where (1) rhombuses enclose questions, (2) rectangles enclose the analyses implied by the answers, and (3) ovals are conditionals referring to supporting information.

6.3.1 Thermal-Mechanical Evolution of the Repository and Mountain

Analysis of the interaction of a dike with the repository requires identification of the time of occurrence and specification of the design of the repository. The initial interaction of a propagating dike with the repository is a mechanical process involving the interception of the crack propagating ahead of the dike with the void space of the drifts and the stress-relieved zone around the drifts (Brady and Brown 1985, p. 192f). After the initial interaction, the interaction becomes a fluid flow and thermal process. The expected direction of dike emplacement is controlled by the stress state and is generally normal to the least principal stress (Pollard 1987). Because the mechanical stress state of the mountain is changing as an effect of repository heat, the time dependence of the changes needs to be recognized explicitly. Accordingly, future time is separated into the thermal period, when the mountain is heated enough for the least principal stress to have rotated to vertical at the repository horizon, and the post-thermal period when the stress has returned approximately to its present orientation. This separation is honored in Figure 1, the decision tree, with the first branching.

Current Stress State–According to hydraulic fracturing stress measurements at and around Yucca Mountain, it appears that the least principal stress direction is horizontal about N60W as derived from the following references:

- N60W–N65W (Stock et al. 1985)
- N51W–N52W (Warren and Smith 1985)
- N68W (Warren and Smith 1985)
- N55W–N60W (Frizzell and Zoback 1987).

The minimum horizontal stresses measured were 2.6 to 3.1 MPa (Warren and Smith 1985) at 330 m and 4.2 to 5.4 MPa (Stock et al. 1985; Stock and Healy 1988) at 295, 418, and 646 m. Vertical stresses were 6.1, 8.4, and 12.9 MPa, respectively. The experimental determinations included measurements at Yucca Mountain wells (Stock et al. 1985), at G-Tunnel (Warren and Smith 1985; Smith et al. 1981), and at Hampel Wash (Frizzell and Zoback 1987) nearby on the Nevada Test Site.

Expected Changes to the Stress State–Calculations of the stress state at the drifts (Hardy and Bauer 1992) were performed for design considerations, to address drift stability. Their calculations were based on the thermal loading of 57 kW/acre and an earlier layout design (Hardy and Bauer 1991, p. 5-15, p. 5-16). The analysis indicates that the three principal stresses increase, with the horizontal components exceeding the vertical component within a few decades of closure. The details of the time-dependent change of stresses around emplacement drifts and the main access drift differ somewhat, but both drift analyses lead to the conclusion that the least principal stress quickly becomes vertical. Analyses performed for the NRC (Mack et al. 1989) show similar results. Horizontal stresses at the drift alter from 3–6 MPa to 15–20 MPa. Based on this work (Hardy and Bauer 1992) it appears that, at the repository level, the vertical least principal stress will persist for the order of 2000 years (Figures 2 and 3, (p. 50)). The largest principal stress (the vertical component) is initially at about 7 MPa and the least principal stress is about 3.5 MPa (Note that the ordinate scales of the figures differ by about a factor of two.). Because of the drift alignment used, the axial stress indicated in the figures is along the maximum principal horizontal stress. Figures 2 and 3 show that the least principal stress (horizontal at ~N60W) increases to exceed the vertical stress component and does so for about 2000 years. The increases of the stress components at the main access drift are due to thermal expansion of the rock around the emplacement drifts.

Although the calculations cited (Hardy and Bauer 1992) are directed at the level of the emplacement drifts, much more rock will be involved. This rotation of least principal stress can be expected to extend several hundred meters below and out from the repository horizon (the region affected by repository heat)(Mack et al. 1989). Figure 4 (p. 51) presents a diagram that shows the extent of influence. The region of alteration in which the least principal stress has been rotated is time dependent and eventually returns to its approximate horizontal orientation.

Possible Effects of Stress Rotation–Rotation of least principal stress from horizontal to vertical changes the stress field through which the dike and its leading crack must penetrate. If, as the literature indicates (Spence and Turcotte 1985; Turcotte et al. 1987, Stock et al. 1985), the dike will deflect to be normal to least principal stress, then the direction of dike propagation would be expected to be deviated. Figure 5 (p. 52) illustrates the changing stress state and the possibility of deviating the path of the dike from vertical, including possible sill formation. In Figure 5, V_o is the initial vertical principal stress, H_0 is the larger horizontal principal stress and h_0 is the least principal stress. These stresses are altered by the addition of thermally derived stresses from repository heat, (TS). For simplicity, Figure 5 (as modified from Anderson 1951) shows the addition to be linear with multiplying factors of a and b compared to the effect on h_0 (see Figures 2 and 3 for a better estimate of growth and relaxation). At some point the line for h_0 crosses that for V_0 and the least principal stress is then vertical. Accordingly, it is then possible for the direction of dike to deviate from the vertical and for a sill to develop (see the analysis of Anderson 1951, pp. 50–53). This circumstance persists until cooling of the mountain allows rotation of the least principal stress back to horizontal.

Since the Yucca Mountain block has bounding faults (e.g., Solitario Canyon, Bow Ridge), in addition to sill formation, a possible consequence is deflection or redirection of the dike propagation to these fault zones (Wilson et al. 1994, v. 1, pp. 2–24). These faults, which strike mostly north-south, have a strike that is only about 30 degrees from the direction of regional least principal stress. Because the way in which the thermal stress from the repository will affect these near-by fault zones is unknown, deviation of the magma flow up the fault zones to the surface is a possible alternative consequence to sill formation.

As a result of these arguments on the changing stress state of Yucca Mountain, the decision tree of Figure 1 distinguishes the thermal period from the post-thermal period. There are additional, more detailed, effects on the drifts during the thermal period (Mack et al. 1989) which affect the actual dike/drift interaction, but which are not discussed because they are germane to other issues (e.g., closure of water-bearing fractures leading to the drift).

Alternative Interpretations–The Igneous Activity Issue Resolution Status Report (IRSR) (Reamer 1999, p. 52f) considers the details of stress around and at Yucca Mountain on two scales, the regional scale involving the tectonic setting and extension (Reamer 1999, p. 43f), and the local scale (Reamer 1999, p. 52). These issues arise in Probability Criterion 5, the probability of occurrence of igneous activity. The discussions under that Criterion are related to structural control of an intrusion and the ability of an existing fault to influence the propagation of a dike. An argument is presented for dike emplacement perpendicular to the least principal stress and parallel to the principal horizontal stress (Reamer 1999, p. 52).

The time-dependent alteration of the local stress-state around Yucca Mountain (and possible effects on dike injection), due to repository heat, does not appear in the models discussed in the IRSR.

6.3.2 Interaction with the Drift

It appears that dikes propagate by fluid-induced fracturing of the confining rock (Lister and Kerr 1991; Lister 1990a, 1990b; Spence and Turcotte 1985). A dike is preceded by a crack generated by the magma fluid pressure (Figure 4). The driving mechanism for the crack leading the dike is the buoyancy of the magma column relative to the adjacent rock column (due to the density difference) (Lister and Kerr 1991; Lister 1990a, 1990b; Pollard 1987; Spence et al. 1987; Spence and Turcotte 1985; Watanabe et al. 1999). Advance of the dike depends on the local differences between the buoyancy and the viscous pressure loss and the elastic stress in the rock. The total effective buoyancy, P, in the crack drives the fluid flow up the crack and propagates the crack in a manner which can be represented by equation 1.

$$P = (\rho_f - \rho_r)gh + p_e + p_v \qquad \text{(Eq. 1)}$$

where

ρ_f = fluid density
ρ_r = rock density
g = acceleration of gravity
h = height of the dike
p_e = elastic (non-hydrostatic) pressure exerted by crack walls
p_v = viscous pressure loss

(Lister 1990b, p. 265).

With insightful analyses of the fluid mechanics of viscous fluids, interpretations of emplacement of many dikes and sills, and a few data on dike injection velocities (Lister and Kerr 1991; Aoki et al. 1999), various authors have established the general behavior of dike propagation and sill formation (Lister and Kerr 1991; Lister 1990a, 1990b; Pollard 1987; Spence et al. 1987; Spence and Turcotte 1985, 1990; Watanabe et al. 1999). (Equation 1 is a simple representation for these more complicated analyses.) These analyses derive (and depend on) the interpretations that dikes propagate by means such that the rate is in the range of a few meters per second to 1×10^{-7} m/sec (Lister 1990a; Aoki et al. 1999). Once a dike has reached the surface, flow velocities, now less impeded, can be larger.

Two of these interpretations will affect the analyses of the following sections: there is a fluid-filled leading crack, and the plane of the dike tends to be normal to least principal stress.

Design Description of a Drift–Current design of an emplacement drift includes the following components: ground support, invert, rails, waste packages, emplacement pallet, and drip shield, (a drain is a possibility but is not part of current design). The dimensions are shown in Figure 6 (p. 53) (DTN: SN9908T0872799.004), and Figure 7 (p.54) is a sketch of the general configuration of the drift with backfill (CRWMS M&O 1999b). Waste containers have a skirt about 25 cm long at each end, and adjacent containers are separated by about 10 cm along the drift (CRWMS M&O 1999b for skirt length, and DTN:SN9908T0872799.004 for container separation).

This AMR originally considered a design with backfill, and has now been updated to address the design option of an open drift. Figure 8 (p. 55) shows the corresponding layout for an open drift – no backfill). This design change is described in Technical Change Request T2000-0133, dated January 26, 2000 (CRWMS M&O 2000e). This design option also appears as a possible decision in Figure 1.

Local Stress State–The discussion of the thermo-mechanical evolution of the mountain (Section 6.3.1) argues for a long delay (~2000 years) (Hardy and Bauer 1992) for thermo-mechanical stress relief to occur around repository openings. Stress-relief, when it occurs, is expressed in generation of fractures and rockfall and possibly as creep into the drift. In classical rock mechanics (Brady and Brown 1985, p. 192f; Jaeger and Cook 1979), an opening (drift) develops radial and concentric fractures as strain relieves the stress, to some extent, for a distance of up to 3 drift diameters. In Figure 1, this is illustrated in the right branches of the decision tree.

The propagating crack, from the intruding dike, encounters the stress relieved zone and the associated fractures some distance away from the original location of the drift. Effectively, the propagating crack sees a fractured rock before it reaches the drift.

There are two possible end members for the dike-drift interaction. In the first, the propagating crack encounters discontinuous concentric and radial fractures. From the work of Tsunakawa (1983), propagation of magma-filled cracks becomes impeded as the angle of intersection of the dike crack and the local fractures increases. Further, Tsunakawa establishes a requirement for minimum magmatic pressures (depending on angle) for assured propagation.

For the second end member, the propagating crack intersects a radial fracture that persists to the drift. Such stress-relief radial fractures, while approximately parallel to the drift axis, are short and discontinuous and would not be expected to significantly rotate the injection direction of the dike.

Fragmentation History–Fragmentation is the complex process of exsolution of gas, formation of bubbles in the magma and solidification and disruption of the bubbles to form pyroclasts. For flow up an existing dike or up a conduit through the repository, fragmentation may occur below the repository depth. Figure 1, the organizing decision tree, has a pair of right-hand branches dependent on when in the course of propagating the dike that the fragmentation occurred below the repository. The issue is whether, in the course of formation, the magma propagating the dike fragmented below the repository level, or whether it propagated to the surface first and then a pressure relief wave moved back down the intrusion to allow fragmentation at the fragmentation depth. (For a technical discussion of fragmentation, see Dingwell 1998, pp.1-23.)

The first case is one of the three circumstances in which magma, as a liquid, is available to flow into the drift (the second is late stage degassed flow and the third is pressurized flow). In addition, the pressure at the drift level for the flow of ash and shards (with a density of perhaps 1000 kg/m^3) can be less than that for a magma flow (with a density of 2556 kg/m^3). [The value for magma density is taken from CRWMS M&O 2000g, ANL-MGR-GS-000002, for 2 wt% water content.] There are two reasons for concern about whether fragmentation occurs during driving of the dike. The first is that magma has to be available at the drift in order to flow into the drift. The second is exsolution of gas and fragmentation into the drift. The drift is at ~0.1 MPa (atmospheric pressure) compared to ~7.5 MPa (~1100psi) in a liquid magma flow and perhaps ~3.1 MPa in a fragmented flow. The fragmented flow, with a high gas content, is more likely to be susceptible to loss of pressure through fractures around the drift that are intercepted by the dike, with a reduction of flow of pyroclastics down the drift. The pressure, p, at the drift is calculated from $p = \rho gh$, where ρ = density of contents of the dike (magma or fragments), g = acceleration of gravity, and h is the distance to the surface. P is then the minimum pressure at the drift necessary to support the dike (the actual pressure may be larger).

Fracture/Fracture Interaction–The buoyancy-driven magma fracture eventually interacts with the drift. The drift consists of a void space—the original opening with waste packages, drip shield and backfill—and the stress-relieved region around the opening. This stress-relieved region develops as country rock relaxes into the openings. Classically, the stress-relieved region extends out to about 3 drift diameters (Brady and Brown 1985, p. 192f; Jaeger and Cook 1979). Because the thermal output of the repository has significantly altered the local stress conditions (Hardy and Bauer 1991; Mack et al. 1989), the extent of stress-relief depends on when, in repository history, the dike intrusion is presumed to occur. During the thermal period (Figure 1, left branch), there is no stress-relief, rather the drift is experiencing compression (Mack et al. 1989). Stress relief appears as strain adjustment, that is, concentric and radial fractures develop around the drift, accompanied by stoping (chimneying) in the drift. This fracture/fracture interaction is intended to provide input for each of two decisions on parallel branches on the right hand side of the tree.

The stress-relief fractures around the drift, which may be important controls for pressure relief, are ignored here. No calculational tools are available to include them and they are likely to mitigate some of the effects of the intersection.

Physical alterations of the drift, by the many small earthquakes which accompany dike injection (and continue for the period of dike movement), are also ignored. Such quakes are likely to alter ground support and rockfall. Drift damage is expected to choke the shock interactions and flow moving down a drift. The actual physical changes to the drift may be estimated based on limited mine experience, but are not predictable.

The crack leading the dike segment below the drift will be taken to intersect the floor of the drift. Since the ambient pressure in the drift is nominally at 1 atmosphere (0.1MPa) and the dike is at 7.5MPa, break through into the drift is accompanied by an explosive decompression of 7.4 MPa of the magma into the drift. (If the dike would otherwise reach the surface, the pressure at the drift must be sufficient to support the liquid magma to the surface, $p = \rho g h$, where ρ = density of contents of the dike, g = acceleration of gravity, and h is the distance to the surface).

The crack leading the dike can not propagate across the drift as long as the driving pressure in the dike segment is below the minimum pressure to cause hydraulic fracturing of the formation. Propagation of this part of the dike segment (drift intersection) is delayed until the drift can be pressurized.

Since drifts are 81m apart (CRWMS M&O 2000j) and 5.5 m in diameter (DTN: SN9908T0872799.004), for analysis and specific arguments a unit cell is taken as the drift and an 81m segment of dike centered on the drift. The drift occupies about 6% of the unit cell. This would suggest that well-spaced drifts do not halt dike propagation between the drifts. Rather, that propagation might reasonably be expected to continue during the flow of magma, pyroclasts and gases into the drift. Because a drift does not fill instantaneously, the dike between the drifts may advance past the elevation of the drifts.

To continue dike propagation across a drift, a mechanism is required for loading the drift so it can fail along a structural zone of weakness, by restart of a crack. It can be shown that a penny-shaped crack requires a higher loading than a linear crack (Daneshy 1978, p. 33), so only a linear crack will be considered. A possible mechanism is loading of the drift, by filling the drift with sufficient magma to initiate hydraulic fracturing. Loading of the drift sufficient to initiate fracturing is discussed in the IRSR (Reamer 1999, p. 78f). As a result, if the drift is subsequently loaded, the linear crack resumes along a line of weakness, probably at a rib (drift wall). While the section of the drift is filling to reinitiate hydraulic fracturing, the crack leading the dike is advancing vertically in the pillars between adjacent drifts. Local delay at the drift could mean that the flow of magma is diverted preferentially to the region between drifts. This suggests the possibility that a dike may tend to divert around a drift, leaving it locally filled with magma or with pyroclasts. The time to fill a section of drift can be estimated from the void space assumed for a length of the drift to be filled, the dimensions of the dike and the flow velocity in the dike (greater than the dike propagation velocity). The dike propagation velocity then allows an estimate of how far the dike has advanced before a linear fracture resumes advancement from the drift.

A rough assessment of where along the drift that a dike might be reasonably expected to resume propagation, depends on the specific mode of flow of magma (liquid or pyroclasts) down the drift.

Four different modes are apparent:

1. Pyroclastic flow which seals the drift (or drift segment) and allows pressurization of the drift
2. Pyroclastic flow which evolves back to liquid magma as pressurization of the drift exceeds the fragmentation pressure
3. Liquid magma flow down the drift for degassed magma
4. Effusive liquid magma flow down-drift, which partially fills the drift.

Development of each mode depends on the specific gas content of the magma delivered by the dike and the then current permeability of the surrounding rock.

In the instance of mode 1, the pyroclastic flow, driven by the continuing pressurization from the dike, seals the drift sufficiently to allow pressurization to initiate gas-induced fracture of the formation, (to repropagate the dike). Repropagation could be initiated anywhere along the pressurized section; the location is dependent on any local weakness in the country rock. This circumstance is unlikely because the pressurization would be below the fragmentation pressure and thus below the driving pressure necessary to originally advance the dike.

In mode 2, the pyroclastic flow seals the formation and the developing pressure exceeds the fragmentation pressure. Under this circumstance, liquid magma flows into the drift to fill voids and to pressurize the formation. As long as there is flow and adequate pressurization, an argument can be made on the basis of pressure drop along the drift, that the preferred region for initiation of the dike propagation is at or close to the dike-drift intersection (see below). The exception is a preferential flow path, such as a fault with a favorable stress orientation, which directs the flow to an outlet (the surface).

For mode 3, only degassed liquid magma flows down the drift. This could represent either an intermittent stage in the intrusive event or the late stage of such an event. In both cases, the flow, which fills the drift segment (or possibly the entire repository), is driven by the dike pressure. As long as there is flow, the argument applicable to mode 2 can also be used.

For the case of mode 4., effusive flow of liquid magma which partially fills the drift, the drift is effectively a lava tube and the pressure is inadequate to initiate a fracture for dike propagation. Flow continues because the flow pressure in the dike is sufficient to provide a small pressure head in the magma and ceases when the magma flow chills and solidifies to fill the accessible void space.

Calculation of Flow Losses for Mode 2 (or 3) - For the case of a flowing system, a drift filled with magma, the pressure drop along the drift can be estimated under certain simplifying (and bounding) assumptions. If the flow is taken to be isothermal and non-solidifying, then from the Reynolds number and a suitable reference (Bird et al 1960, p. 186), the friction factor can be estimated. From the friction factor, the dimension of the drift, the density and the mean velocity of the flow, the pressure gradient along the drift can be calculated. Since the friction factor will be much larger for a real drift (because of waste containers, ground support, etc., the pressure gradient – the drop in pressure as a function of distance from the location of the dike-drift intersection – will be larger. If the dike pressure is representative of the minimum pressure necessary to propagate a crack (as it was for the initial propagation), then rapid decrease of pressure along the drift would imply that pressure is likely to be sufficient to reinitiate dike propagation only near the dike-drift intersection (if pressurization of the drift is possible at all). From Bird et al, p. 188, Example 6.2.1, the Reynolds number (Re) is given by:

$$Re = 2Q\rho/(\pi R\mu),$$

where

- Q = volumetric down-drift flow rate (m^3/s)
- R = drift radius (2.75 m, from DTN: SN9908T0872799.004)
- ρ = fluid density (2553 kg/m^3, from CRWMS 2000g)
- π = pi
- μ = fluid viscosity (~ 0. 95 Pa s, - given as log μ = 1.978 poise, CRWMS 2000g)

The friction factor, f, for a smooth tube $f = 0.0791/Re^{1/4}$, (from Bird et al 1960, p. 186); for the real drift with impediments to flow the Reynolds number will be larger and the friction factor smaller.

From the referenced example, $f = R (P_0 - P_L)/(4L \rho\langle v\rangle^2)$, and

$$(P_0 - P_L)/L = (4f \rho/R)(Q/(\pi R^2))^2$$

where

- R = drift radius
- P_0 = pressure at the mouth of the tube
- P_L = pressure a distance L down the tube
- $\langle v\rangle$ = average flow velocity = $Q/(\pi R^2)$
- Q = volumetric flow (m^3/s) into the drift
- ρ = density of the flow

The volumetric flow rate, q, for a fissure eruption, has been given as a range of values for eruptive mass discharge per fissure length, relating water content and eruption velocity (CRWMS M&O 2000g, Sec. 6.3). The range, 1000 to 1 x 10^6 kg s^{-1} m^{-1}, translates to 2.15 to 2.15 x 10^3 m^3 s^{-1} under the assumption that one drift diameter (5.5 m) is the length of the fissure supplying magma of density 2553 kg m^{-3} to the drift. If q describes the fissure flow rate, then if the flow evolves to be a magma driven by the same pressure, the magma flow into the drift is given by Q = ½ q (if the dike intersection is away from a drift end) or Q = q (if the dike intersection is at a drift end). For the case of Q = ½ q (intersection away from the end), the pressure drop along the drift for a liquid magma of density 2553 kg/m^3 varies as a function of flow rate from ~7. Pa m^{-1} to ~2.1 x 10^4 Pa m^{-1}, depending on flow rate. At the highest flow rate (q = 2.15 x 10^3 m^3 s^{-1}) the pressure loss is about 2.1 x 10^4 Pa/m (~3% per 10 meters along the drift). For the lowest value (2.154 m^3 s^{-1}) the loss is negligible. For high flow rates, because of this pressure loss along the drift, initiation of hydraulic fracture to repropagate the dike is biased toward the vicinity of the dike-drift intersection.

Alternative Interpretations–The Igneous Activity Issue Resolution Status Report, in Section 4.2.3.3.2 (Reamer 1999, p. 78f), develops requirements for hydraulic fracturing which is initiated from a loaded drift. That is, the drift is filled with magma and two orientations for reinitiation of hydraulic fracturing are considered. These directions are normal to the drift axis and along the drift axis (in present design, normal to least principal stress and normal to maximum horizontal principal stress, respectively). The details of the mechanical interaction of the crack leading the dike with the drift have not been considered. The analyses address how a dike may be propagated by hydraulic fracturing of the rock around a drift pressurized by magma.

In present repository design the drifts are oriented roughly along the current least principal horizontal stress. Since the most likely orientation of a dike is normal to the least principal stress (Reamer 1999, p. 52), an intersection of a dike with a drift along the axis of the drift is unlikely. Therefore, this possibility has not been considered in this AMR.

Interaction of Flows with the Drift – Since some of the physical effects of interaction of the dike with a drift with backfill will differ from those with an open drift (no backfill), the two options will be discussed in parallel sections. The backfilled drift will be examined first because it was the first design option (see for example, Figures 6 and 7). How the two design options (backfilled drifts and open drifts) are connected with other physical effects appears in Figure 1.

Backfilled Drift - Intersection of dike and drift will result in a pressure pulse generated by the rapid exposure of the drift to the ~7.5 MPa (1100psi) pressure of the dike (the minimum pressure to support a dike to the surface). This pressure pulse, an oblique shock wave, moves rapidly down the drift, interacting with the packages, drip shield and backfill. The backfill is displaced and compressed by the moving drip shield to close the openings above and around the waste packages and drip shield. The pressure pulse is followed by a flow of pyroclastics down the drift. This flow of pyroclastics reaches and reinforces (and may move) the blockage of jammed drip shield and backfill which was generated by the pressure pulse. A flow of pyroclastics, which develops from fragmentation of the liquid magma, depends on the gas and water content of the magma as well as on the pressure drop that occurs as the magma flow enters the drift.

Air in the drift is at ~0.1 MPa (atmospheric pressure) while the dike volatiles are about 7.5 MPa (~1100 psi) for a liquid magma dike and ~3.1 MPa for a fragmented flow producing the dike (pressures derived are the minimum for a dike which reaches the surface, with densities of the magma and pyroclastic flow are 2556 kg/m^3 and 1000 kg/m^3, respectively). A sudden connection means that leakage of gas and magma to relieve pressure through any fractures around the drift is precluded. The decision tree in Figure 1 shows two choices: either liquid magma reaches the drift with rapid exsolution and decompression or fragmented flow reaches the drift with a smaller decompression. The topic of this section is intended to allow a decision about the scope of the disruption. Figures 6 and 7 show a number of drift components for the pressure pulse to interact with. It is expected that waste packages will be displaced and the drip shield, backfill and invert will be moved. Waste packages falling directly in the dike path are not considered here; they are considered in *Igneous Consequence Modeling for the TSPA-SR,* ANL-WIS-MD-000017 (CRWMS M&O 2000c).

Interaction with Waste Packages - To estimate waste package movement, the pressure pulse is applied uniformly across the head (end cap) of the first waste container. Figure 7 is a sketch of the pre-intrusion layout in the drift. The waste package slides along the emplacement pallet until the center of gravity of the waste package passes the emplacement pallet end (or the emplacement pallet otherwise collapses). Containers have an attached skirt about 25 cm long and are separated by 10 cm. When the first waste package moves down the drift more than 10 cm skirts are in contact and crushed thereby moving the adjacent waste package.

To estimate the velocity of a waste package it is necessary to have a mass for the waste package and a coefficient of friction. A representative container is taken to be a 21 assembly PWR waste package. The waste package mass is calculated to be ~ 42.3 metric tons (CRWMS M&O 2000h, p. II-2). The waste package rests on an emplacement pallet with its motion resisted by a coefficient of friction of 0.3 (The specific value will turn out to be unimportant because the driving pressure is so large.). The interaction is idealized in that the pressure pulse provides a constant acceleration until the shock wave reaches the end of the waste package.

From Glasstone (1962, p. 121f) the shock wave velocity v in air is given by $U = C_o(1 + 6P/(7P_o))^{1/2}$, with C_o = ambient speed of sound, P = overpressure, and P_o = ambient pressure. For p = 7.5 MPa, the dike pressure, $U \sim 8C_o$. The dynamic pressure q ($= 5/2 \bullet p^2/(7P_o + P)$) is ~17 MPa (Glasstone 1962, p. 122). Since the incident shock wave is reflected from the waste package end cap, the overpressure may be approximately twice the incident overpressure and the total driving pressure, P = P (overpressure) + q (dynamic pressure), is ~32 MPa.

In this idealized case the force F**,** on the head of the waste package, is given as

$$F = (A\,P - \mu_f M\,g) = M\,a \qquad \text{(Eq.2)}$$

where

A = the cross-sectional area of the container (~2.19 m^2)

P = the total pressure

μ_f = the coefficient of friction (nominally 0.3)

M = the mass of the waste package (represented by a 21 assembly PWR waste package of 42.3 metric tons (CRWMS M&O 2000h, p. II-2)

g = the acceleration of gravity (9.8 m/sec^2)

a = the acceleration of the waste package

Integration gives the velocity v as

$$v = t\,(A\,P - \mu_f M\,g)/M \qquad \text{(Eq. 3)}$$

where t is the length of time the force is applied as the waste package slides down the emplacement pallet. The driving pressure accelerates the waste package until pressure has built up on the back end cap. The time for buildup (Glasstone 1962, p. 184), t = L/U + 4R/U (L = container length, R = container radius), is $t \sim 3.27 \times 10^{-3}$. Substitution of this value of t into equation 3 yields a velocity v ~ 5.4 m/sec. Details of shock buildup and decay (Glasstone 1962, p. 182f), which would reduce the driving pressure (perhaps by more than a factor of 2) and the velocity, have been ignored.

For small velocities, the waste package would be expected to stop moving almost immediately on contacting the invert. (Based on a train derailment analogy, rail cars of 50–100 tons each, stop fairly quickly in the track ballast even though derailment occurs typically at much higher speeds).

On this basis, it appears that the first waste package will move until it drops off the emplacement pallet, presumably <2 m, when the center of gravity of the waste package passes the end. Collapse of the emplacement pallet, which would further reduce motion, is undetermined and is conservatively neglected. Since the waste package then stops quickly, its translation affects adjacent waste packages with much of the movement accommodated in crush of the skirts. The approximately 2 m of movement is accommodated by movement of 3 to possibly 4 waste packages. If the pulse is produced by a fragmented flow then the pressure and the velocity scale according to the equation for velocity, **v**, with the density of the flow (magma ~2556 kg/m^3, fragmented flow <1000 kg/m^3). (A possible final orientation of the disrupted waste packages appears in Figure 9 (p. 56)).

The pressure pulse interacts with the other components of the drift as well. The interactions are not amenable to an idealized calculation and are treated qualitatively. As shown in Figure 7, the waste package sits on a emplacement pallet above a ballast invert and is covered by a drip shield loaded with backfill. If the drip shield functions as designed, diverting water from the packages, there are some few locations along a drift where the backfill is wetted by the drip. From Figure 6, the load on top of the drip shield is <10 Pa. Accordingly, it is to be expected that the pressure pulse will displace the drip shield and both the backfill and invert material as well. The drip shield (Figure 6) has a circumference of about 6.5 m (DTN: SN9908T0872799.004) and it will be made in short lengths for emplacement. The pressure pulse can be expected to displace the drip shield upward and down the drift and to jam it into the void space above the backfill ("snowplowing" the backfill). From Figure 8, the drip shield and backfill associated with one waste package appear adequate to block the opening (~13 m^2 per segment); however, since three waste packages (and possibly 4) are likely to be displaced by the pressure pulse, Figure 8 shows drip shields from three waste packages involved. Figure 9 portrays displacement of the ballast, its accumulation along the damaged waste packages, and upon close inspection, tries to include mechanical damage to the waste packages (everted heads and crumpled sidewalls). The extent of damage depends on both dike flow characteristics and the age, that is to say the strength of the affected waste packages. Splitting of welds and waste package blowout are possibilities that are not addressed. The first waste package has been treated as a rigid, non-deformable body (except for the skirt), a conservative assessment since damage to the first waste package would reduce damage to waste packages further down the drift. Note that since failure of ground support and rockfall have not been considered, progression of the plug of magma down the drift may be substantially overestimated.

Open Drift (No Backfill) - The intersection of the dike with the drift generates an oblique shock wave which reflects off the drift walls and propagates down the drift (See Figure 1 for how this design option may be connected to other physical effects.). The shock wave interacts with the drip shield, displacing it and driving it down the drift to interact with waste containers and ground support. There is no load of backfill on the drip shield to dampen and spread out the shock front and any obstruction of the drift by jamming of drip shield and ground support is likely to occur much further down the drift than for the backfilled drift. The initial propagation velocity of the shock wave is ~ 8 times the local speed of sound (as estimated in the preceding section) and would reflect from the end of the drift in less than a second (if not blocked by the drip shield-ground support jam). The pressure pulse generated in one drift propagates, with some decay and degradation in amplitude, to any connected drifts. The shock wave (pressure pulse) is followed by a pyroclastic flow into and down the drift. The dynamic pressure of this flow is estimated in a preceding section (~17MPa). Figure 10 (p. 57) illustrates the propagating oblique shock wave and initial flow, and Figure 11 (p. 58) shows this pyroclastic flow following the shock wave past the containers and down the drift. As suggested in Figure 11, the pyroclastic flow can be visualized rather like that of a fire hose; first eroding the back of the drift and then interacting with particles reflected off the back of the drift to form a turbulent cloud of pyroclastic material which flows down the drift. Pyroclastic materials stick to containers, ground support and drip shield, and chill to form a crust and loci for further accumulation. The pyroclastic flow continues until the drift and dike repressurize at least to the fragmentation pressure. (A drift 5.5 m in diameter, w/20% occupied by containers and drip shield, intersected by a dike 2m thick w/ flow velocity of ~ 200m/s through a 5.5m long opening – a drift diameter – would fill with pyroclastic materials about 100 m of length per second.) Above the fragmentation pressure, liquid magma flows into the voids available in the drift. At that time, the dike is able to resume propagation by hydraulically fracturing the rocks surrounding the drift.

Shock Interaction with Waste Packages – The calculation discussed earlier for waste package movement did not consider the effects of backfill and its compression in order to estimate the waste package velocity. Because backfill was not considered in that calculation, the calculation there applies here as well. Three, or possibly four, waste containers are physically moved and damaged on either side of the intrusion as a result of interaction with the shock wave and dynamic pressure. Actual damage to those containers and to containers further down the drift will likely include damage from flying pieces of drip shield and ground support. It is likely that damaged waste packages will also be embedded in the accompanying pyroclastic flow.

Alternative Interpretations–The Igneous Activity Issue Resolution Status Report (IRSR) (Reamer 1999, Section 4.2.3.3.1 Flow Conditions, p. 77f) discusses response to the pressure pulse and possible shock wave and is based on scoping calculations done for the NRC. The study presumes that backfill is absent from the drifts and on intersection, the pressure in the dike will fall to atmospheric pressure. The dike will then decompress and magma will have a tendency to flow into the drifts. The IRSR argues that the capacity of a drift is so large compared to the expected dike width (0.5–2m, in their case) that, locally much of the flow is diverted to the drift. Because of the large pressure drop the IRSR authors anticipate an acceleration of magma into the drift at a much larger flow rate than is anticipated. The IRSR authors expect flow speeds for magma down the drift of the order of 100 m/s. The IRSR authors also believe that a shock wave will proceed down the drift, reaching the end in about 10 s (1000 m in 10 s).

The interaction of dike and drift starts with a pressure pulse generated by the rapid exposure of the drift to the ~7.5 MPa (1100 psi) pressure of the dike. For the case of backfilled drifts, a pressure pulse moves rapidly down the drift, interacting with the waste packages, drip shield and backfill. The backfill is displaced and compressed by the moving drip shield to close the openings above and around the waste packages and drip shield. The pressure pulse is followed by a flow of pyroclastics down the drift. This flow of pyroclastics reaches and reinforces the blockage generated by the pressure pulse. An estimate is made of the number of waste packages experiencing physical damage.

For the case of an open drift (no backfill), a shock wave and pressure pulse moves rapidly down the drift, interacting with the waste packages, drip shield and ground support. The ground support is stripped and displaced by a shock wave and the moving drip shield segments to close the openings above and around the waste packages. The shock wave is followed by a flow of pyroclastics (dynamic pressure) down the drift. This flow of pyroclastics reaches and reinforces the blockage generated by the shock wave. Because of the decompression which has occurred in the intrusion, liquid magma flow can not reoccur until the drift has pressurized at least to the fragmentation pressure for the magma (unless the magma is effectively gas-free). It is recognized that repressurization of the drift to allow the flow from the dike as liquid may not be possible unless the pyroclastic flow seals the drift, because otherwise, the permeability of the formation is expected to be high.

Repository Response

Because of the rapid blockage of the drift expected for backfilled drifts, the following discussion is of more importance to the case of open drifts (no backfill). Three distinct regions can be recognized for the dike-drift interaction (CRWMS M&O 2000k). The first region (labeled Zone 1 in Figures 12, 13) (pp. 59, 60; Note that these figures, developed from CRWMS M&O 2000k, have obliterated some design information which has no technical impact to this document, see the citation for a complete figure.) is the region immediately around the dike and represents the 3 or 4 containers, on each side of the dike, damaged as a result of the intrusion as estimated in Section 6.3.2. The container in the path of the dike is presumed to have been ruptured and its contents distributed down the drift in the pyroclastic flow. Zone 1 is the region of concern for backfilled drifts.

The second region (labeled Zone 2) is the collection of drifts containing waste packages, which has been crossed by the dike. These drifts are directly exposed to the shock wave and pyroclastic flow and can be presumed to have been compromised by having end caps damaged and possibly to be embedded in solidifying pyroclastic materials. Some indeterminate part of the drift, between plugs, must be pressurized in order to reestablish dike propagation by hydraulic fracturing of the surrounding rock (Reamer 1999, p. 78f). ("Plugs" refers to blockages of the drift due to jams of drip shield and ground support or possibly to the end of the drifts where pyroclastic materials have accumulated.) Increase of pressure required in order to repropagate the dike means that the part of the drift that is plugged also is pressurized to the propagation pressure, presumably ~7.5MPa. Containers embedded in the cooling pyroclastics or solidifying magmatic flow will also become pressurized as the pressure on the drift filling increases to the dike pressure (or otherwise reaches lithostatic pressure) and may fail as a consequence (see Attachment 1 for discussion of the static loading of waste containers). The temperature of the containers can be approximated by cooling of a cylindrical mass (the filled drift) embedded in an infinite medium (Section 6.3.4 Thermal Environment).

The dike may also cross the "mains", which are the service drifts. If the mains are not backfilled or otherwise stemmed, then shock waves and pyroclastic flow would be expected to travel along (or down) them just as for the emplacement drifts. Such flow is ignored here because the mains do not contain waste and are expected to be backfilled.

The third region (labeled Zone 3) consists of the rest of the repository. The mains, if unfilled, connect emplacement drifts, exposing all of them to the effects of the pressure pulse and to some pyroclastic flow. The shock wave associated with the dike-drift intersection produces a pressure pulse. The pressure pulse in one drift propagates, with some decay and degradation in amplitude, to any connected drifts. Any containers in drifts, which are connected to drifts crossed by the dike, have seen a pressure pulse of a magnitude which varies with distance from the dike. Since the dike crosses a number of drifts, whose distance from cross-connecting tunnels varies, the pressure pulse may be iterated (each drift crossed by the dike acts as a source). For this region, Zone 3, if the mains are not backfilled, some containers may see a pressure pulse sufficiently larger than the capacity of the end caps and welds, and failures may result (internal gas accumulation may, however, pressurize some containers and reduce failure) (See Attachment I for discussion of the static response of waste containers to pressurization). The amplitude and shape of the pressure pulse depends on dissipation of the shock wave as it propagates and on the integrated response of the assembled drifts. Figures 12 and 13 show interception of the drifts in plan view by a single, continuous dike and by a dike emplacement in echelon (here, two segments).

Alternative Interpretations–The Igneous Activity Issue Resolution Status Report (IRSR) (Reamer 1999, Section 4.2.3.3.1 Flow Conditions, p. 77f) discusses response to the pressure pulse and possible shock wave and is based on scoping calculations done for the NRC. The study presumes that backfill is absent from the drifts and on intersection, the pressure in the dike will fall to atmospheric pressure. The dike will then decompress and magma will have a tendency to flow into the drifts. The IRSR argues that the capacity of a drift is so large compared to the expected dike width (0.5–2m, in their case) that, locally much of the flow is diverted to the drift. Because of the large pressure drop the IRSR authors anticipate an acceleration of magma into the drift at a much larger flow rate than is anticipated. The IRSR authors expect flow speeds for magma down the drift of the order of 100 m/s. The IRSR authors also believe that a shock wave will proceed down the drift, reaching the end in about 10 s (1000 m in 10 s).

For this AMR, the interaction of dike and drift starts with a shock wave and pressure pulse generated by the rapid exposure of the drift to the ~7.5 MPa (1100 psi) pressure of the dike. A shock wave, pressure pulse and pyroclastic flow move rapidly down the drift, interacting with the waste packages, drip shield, and ground support. The flow of pyroclastics reaches and reinforces the blockage generated by the pressure pulse. Repressurization of the drift to allow the flow from the dike as magma is not considered possible unless and until the pyroclastic flow has sealed the drift, and this may be unlikely because the permeability of the formation appears to be too high. An estimate is made of the number of waste packages experiencing physical damage from the shock wave and dynamic pressure. Two additional regions of the repository with different levels of damage to waste packages are identified and the temperature history for one of them is developed.

6.3.3 Gas Flow

An issue, which appears in the branches of Figure 1, is that of failure of the waste container. One possible cause of failure is corrosion of the container by the aggressive gases exsolving from the magma intrusion or flowing in the dike or in the vent. This section attempts to estimate the gas flow down the drift under idealized circumstances, in order to estimate the size of a source term to allow a decision about whether corrosion is a possible problem (whether sufficient gas for corrosion is available).

The idealization is that the gas flow is a steady-state flow of a real gas, as controlled by leakage through the drift wall, which persists for the duration of the eruption. More specifically (as listed in Section 5.1), it is assumed that

1. Gas is supplied to the drift by the dike or vent.
2. There is isothermal flow down the drift (no axial temperature gradient).
3. Adiabatic expansion is ignored.

4. Heat carried into the rock (the porous media) by the gas is ignored.
5. There is no chemical interaction of the gases with the rock.
6. The components of the EBS are irrelevant to the flow.

Assumptions 2–6 are those made explicitly for this calculation. They ignore dissipation of energy to the drift wall and the EBS and are intended to be conservative because more energy is retained in the flow. The analysis based on these assumptions overestimates the gas flow.

These assumptions mean that the calculation is for steady-state flow down an empty drift. The volumetric flow rate is controlled only by how fast the gas can escape by leaking through the drift wall into the country rock, and real gas properties are assumed to be more important than heat transfer into the porous medium.

The flow of a real gas through a porous medium is described by the Equations 4, 5, and 6

$$\nabla^2 \mathrm{m(p)} = \phi\mu(p)c(p)k^{-1}\, \partial m(p)/\partial t$$

(Eq. 4)

where m(p) is the pseudo-pressure defined as

$\mathrm{m(p)} = 2\int_{pm}^{p} \frac{pdp}{\mu(p)z(p)}$, with

$\mu(p)$ the pressure dependent viscosity and z(p) the correction to the ideal gas law,

($\rho = \frac{M}{RT}\left[\frac{p}{z(p)}\right]$, where ρ = density, M = molecular wt, R = gas constant, T = temperature, p = pressure, and z(p) = correction for real gases).

In the referenced paper, a steady-state solution is presented for flow through concentric cylinders, which can be adapted for the purpose here. The equation derived there for q_{sc}, the radial mass flux (m^3/sec) is given by

$$\mathrm{q} = \frac{\pi k h T_{sc}[m(p_o) - m(p_w)]}{T p_{sc} \ln \frac{r_o}{r_w}}$$

(Eq. 5)

where

k = permeability (~1–100 Darcys, LeCain 1997, p. 11f)

h = length of drift presumed involved

T = temperature (K)

T_{sc} = reference temperature at standard conditions (300 K)

p_x = pressure at the: outer boundary (x = 0), drift boundary (x = w), standard conditions (x = sc)

r_x = radius at the: outer boundary (x = 0), drift wall (x = w)

For this problem the outer radius is allowed to become infinite and m(p_o) becomes zero, so the equation for q reduces to

$$q = \frac{\pi k h T_{sc} m(p_w)}{T p_{sc} \ln r_w}$$

(Eq. 6)

(Al-Hussainy et al. 1966).

To utilize this work requires values for the pseudocritical temperature and pseudocritical pressure for the volcanic gases. Those values are developed from Table 4.

Table 4. Characteristics of Exsolved Gases and Their Pseudocritical Properties

Species	Mole Fraction	Critical Temperature K	Pseudo- Critical Temp K	Critical Pressure atm	Pseudo-Critical Pressure atm	Molecular Wt.	Average Molecular Wt.
H_2O	73.16	647.14	473.45	217.7	159.269	18.01	13.18
H_2	1.17	32.97	0. 3857	12.76	0.14929	2	0.0234
CO_2	14.28	304.14	43.43	72.78	10.39	44.01	6.2846
CO	0.57	132.91	0.7576	34.53	0.19682	28.01	0.1597
SO_2	9.45	430.8	40.71	77.8	7. 3521	64.06	6.0537
S_2	0. 37	1314	4. 8618	204.28	0.7558	64.12	0.2372
HCl	0.49	324.7	1.5910	82	0.4018	36.46	0.17865
HF	0.06	461	0.2766	63.95	0.03837	20.01	0.0120
H_2S	0.74	373.2	2.76168	88.23	0.652876	34.08	0.2522
			T_{pc} = 568.22		P_{pc} = 179.21		

NOTE: Critical temperatures and critical pressures, p. 6-50f, and Molecular weights, p. 4-37f, Handbook of Chemistry and Physics—Lide and Frederikse 1997; Mole fractions from CRWMS M&O 2000b)

In order to utilize the tables provided by Al-Hussainy and co-workers (their Table 1) for m(p) in terms of measured properties of real gases, a pseudo reduced pressure and a pseudo reduced temperature are extracted from Table 4, above. For $P = P_{pr}P_{pc}$, with P = 75 atm (7.5 MPa) at the drift and, P_{pr} = 0.38, P_{pc} = 179.2 atm, and $T = T_{pr}T_{pc}$, with T = 1100 ^{0}C (1373 K, magma temperature (CRWMS M&O 2000g), T_{pc} = 568.22 K, T_{pr} = 2.42.

For a viscosity of 0.47 cp (linear extrapolation of table values for H_20: Lide and Frederikse 1997, p. F43f), a pressure at the drift wall of 1100 psi (7.5MPa), m(p) is found to be 7.97 x 10^3 $(atm)^2$/cp. With these numbers, the values for q are presented in Table 5.

Table 5. Volumetric Flow Rates for Two Different Wall Lengths and Two Different Permeabilities of the Drift Wall

h (length of drift involved)	Air Permeability k = 1 Darcy	Air Permeability k = 10 Darcy
5. 5 m (1 container)	~2 m^3/sec	~20 m^3/sec
1 km (~1 drift length)	~3.5 $\times 10^2$ m^3/sec	~3.5 $\times$ 10^3 m^3/sec

The volumetric flow rate for the entire drift at k = 10 Darcy implies an unreasonably high velocity for the gas at the effective dike face (location of intersection of dike and drift). The unreasonably high velocity suggests that in this approximation, gas flow is over estimated and that the model should include cooling of gas and heating of the country rock through which the gas is leaking. It appears that the volume of gas arriving at a container is not directly a limiting factor in corrosion. (For a discussion, definition of, and use of pseudo properties see Pirson 1977, p. 341f).

Alternative Interpretations–The Igneous Activity Issue Resolution Status Report (IRSR) (Reamer 1999), in Section 4.2.3.3.1, discusses flow conditions and the possibility that decompression of the magma produces a shock wave and a vesicular flow. It may be inferred from the discussion in the cited section that the drift is expected to pressurize.

For this AMR, Section 6.3.3 discusses the constraints on gas flow down the drift for flow controlled by leakage through the surrounding rock. While the intent is to establish whether sufficient gas is available for container corrosion, as a result it appears that pressurization sufficient to prevent fragmentation is expected to be unlikely.

6.3.4 Thermal Environment

Pyroclastic Flow – Magma entering a zone of reduced pressure exsolves gases to form bubbles in the magma, which fragment to produce shards and drops (pyroclasts). The condition of bubble formation and fragmentation occurs over a small range of depth – the fragmentation pressure is relatively sharply defined. As the dike intersects the drift, the magma is exposed to a drift pressure which is below the fragmentation pressure and the magma exsolves gases and fragments. A pressure gradient develops in the dike, toward the drift. The fragmented flow blows into the drift, interacts with fragments in the drift and the drift back (ceiling), and is projected down-drift. The drift back above the dike may erode (Figure 11) and turbulent flow occurs down the drift.

Down-drift, pyroclastic materials hit and chill on the waste containers, ground support, and the crumpled remains of the drip shield. The pyroclastic flow is roughly isothermal at approximately the temperature of the dike. This flow of shards and droplets gradually fills and seals the drift, allowing some level of pressurization. It is assumed that pyroclastic materials accumulate to fill the drift. The accumulation is possibly from the drift ends, if not closer to the dike at plugs caused by jamming of the drip shield and ground support. Drifts which are not intercepted by the dike are assumed to have not been filled. Clearly, flow can also proceed down the mains and possibly affect the ends of additional drifts, however these flows are ignored here.

When a drift is pressurized to a pressure greater than the fragmentation pressure, magma flow can occur into the residual, connected openings. Chilling of magma is considered in the next section. If the drift has filled with pyroclastic material, the embedded waste packages are exposed to ~ 1100 ^{0}C. The temperature history of these containers can be approximated by the temperature history of a solid composite cylindrical region having the properties of the now-solid pyroclasts and the country rock around the drifts. Carslaw and Jaeger, p. 346, develop an example similar to the case of interest. Their example treats an infinitely long circular cylinder with an initial temperature, $V_{1,}$ embedded in a second material of infinite extent, with initial temperature set to zero. In the case of interest, the pyroclast and magma-filled drift, at an initial temperature equal to or less than the solidification temperature, is embedded in the country rock, with an initial, non-zero ambient temperature distribution. For the purposes here, estimation of the temperature of the embedded waste packages, it suffices to ignore the temperature history of the repository and the geothermal gradient and to set the initial temperature distribution in the country rock as a constant. To proceed as per Carslaw and Jaeger (p. 346), the analysis uses Laplace Transforms, so that the two transformed equations being solved are:

$$d^2\mathbf{v}_1/dr^2 + 1/r\, d\mathbf{v}_1/dr - q_1^2\mathbf{v}_1 = -V_1/k_1, \text{ for } 0 <= r < a \text{ (a = drift radius)}, \qquad \text{(Eq. 7)}$$

$$d^2\mathbf{v}_2/dr^2 + 1/r\, d\mathbf{v}_2/dr - q_2^2\mathbf{v}_2 = -V_2/k_2, \text{ for } r < a, \qquad \text{(Eq. 8)}$$

where $q_1 = (p/\ k_1)^{1/2}$, $q_2 = (p/\ k_2)^{1/2}$ and V_1, V_2 are the initial temperatures of the two regions, respectively (p is the transform variable).

The boundary conditions at the boundary r = a are:

$\mathbf{v}_1 = \mathbf{v}_2$, and $8_1 d\mathbf{v}_1/dr = 8_2 d\mathbf{v}_2/dr$,

(Note: 8_i is used rather than K_i used in Carslaw and Jaeger to avoid confusion with the customary use of $K_i(z)$ for the modified Bessel function of the second kind. $I_i(z)$ is the modified Bessel function of the first kind.).

Further, it is required that the solution for $\mathbf{v}_1$ be finite as r-> 0, and the solution for $\mathbf{v}_2$ be bounded as r-> infinity.

The solutions are

$$\mathbf{v}_1 = V_1/p - (U\ 8_2\ k_1^{1/2}/p)\ (K_1(q_2\ a)\ I_0(q_1\ r)/\ \Delta), \qquad \text{(Eq. 9)}$$

$$\mathbf{v}_2 = V_2/p + (U\ 8_1 k_2^{1/2}\ /p)\ (I_1(q_1\ a)\ K_0(q_2\ r)/\ \Delta), \qquad \text{(Eq. 10)}$$

where $U = V_1 - V_2$, and $\Delta = 8_2\ k_1^{1/2}\ K_1(q_2\ a)\ I_0(q_1\ a) + 8_1\ k_2^{1/2}\ I_1(q_1\ a)\ K_0(q_2\ a)$.

The solutions, $\mathbf{v}_1$ and $\mathbf{v}_2$, may be easily inverted, using Carslaw and Jaeger's inversion formulae (p. 346), to give solutions in terms of integrals of products and quotients of Bessel functions. In order to avoid these extensive calculations and to simplify the analysis, the problem is specialized. The thermal properties of the pyroclasts and magma filling the drift are taken to be identical to those of the surrounding country rock and the temperature is calculated only at the center of the drift. The equivalence of properties presumes that solidified pyroclasts and magma behaves like tuff and simplifies Δ to become $8\ k^{1/2}/(q\ a)$ ($\Delta = 8\ k^{1/2}/(q\ a)$). Since the orientation of waste containers is unknown, only stylized locations can be selected. The obvious locations are the drift wall and the center of the drift. The temperature history at the center of the drift (r = 0) will be chosen because it simplifies the calculation and because it then provides a location consistent with the "magma solidification" calculation which follows in the next section.

For r = 0, $I_0(q\ r) = 1$, so the equation for $\mathbf{v}_1(0,p)$ becomes:

$$\mathbf{v}_1(0,p) = V_1/p - (U\ q\ a/p)\ K_1(q\ a). \qquad \text{(Eq. 11)}$$

The Laplace inverse of $\mathbf{v}_1(0,p)$, $v_1(0,t)$ is available in tables of Laplace transforms (e.g. Abramowitz and Stegun 1964, p. 1021, entry 29.3.1; p. 1028, entry 29.3.107).

$$v_1(0,t) = V_1(1-\exp(-a^2/4kt)) + V_2\ \exp(-a^2/4kt). \qquad \text{(Eq. 12)}$$

Based on a specific heat, c, of 0.25 (Jaeger 1964, p. 453), a density, D, of 2.6 g/cm^3, and a thermal conductivity, 8, of 1.2 J/s m K (DTN: LB997141233129.001), the thermal diffusivity, k, is approximately 0.00044 cm^2/s ($k = 8/(c\ D)$). With these values, the temperature at the drift centerline at 21 days, $v_1(0,21\ da) \sim 1005\ ^0C$, and at 35 days, $v_1(0,35\ da) \sim 860\ ^0C$. After 2500 days the centerline temperature is ~ 120 ^0C.

Magma Flow - If the fragmentation depth is below the repository, then liquid magma can enter a drift during the initial intersection of dike and drift, as an intermittent stage, as a late stage, degassed flow or if the drift is pressurized above the fragmentation pressure. The first, initial intersection, is associated with the entire dike, and as the dike-flow fragments below the repository, the unchilled portion can flow back to the dike from the drift because the dike pressure is reduced, leaving covered (or possibly partially covered) waste packages. The second, the intermittent stage, is related to formation of a vent and conduit, which reduces the population of exposed drifts, and can allow accumulation of fragments (ash) in the drift. The late stage is flow of degassed liquid magma into the drift. Pressurization of the drift to reestablish magma flow permits flow into the connected void spaces in the drift among the accumulated and solidified pyroclastic materials. Magma flow is the presumption of one of the right hand branches of Figure 1, and is intended to support decisions about waste package failure and entrainment of contaminants.

If magma flow follows the decompression and gas flow into the drift, the state of the drift and waste packages is that suggested in Figure 9. The first, and possibly second, waste packages should have experienced considerable damage to their heads (endcaps), with eversion and cracking as strong possibilities, and may be collapsed and fractured along the sides; waste packages further down the drift are damaged to a lesser extent.

Rapid flow of magma (presumed to be approximately at its liquidus) into the drift, as suggested by flow velocities in the dike, would fill the drift more rapidly than it, the magma, could chill, forming a plug in the void space around the waste packages as indicated in Figure 14 (p. 61). The plug space drawn in Figure 9, and in Figure 14 is about 5.5 m (dia.) × 11m (to ~22 m) (length) and if the cross-section of the drift and dike represents the source, would be expected to fill in minutes. The case of a continuing flow of magma, as considered in Reamer (1999), requires an exit to the surface from the drift, a circumstance that is not considered here. An exit would be possible only through paths occurring as a result of reestablishment of dike propagation or opening of existing bounding faults. Further, flow of magma, down an open drift to its end, would be expected to be rapid compared to the chilling (solidification) time for the magma.

There are certain peculiarities of the waste package, which affect the magma–container interaction. The waste package, as a large, cool (relative to the magma) mass with high thermal conductivity and heat capacity, will rapidly chill the magma making initial contact, and as is observed for some objects in lava flows, will tend to form an insulating crust about the waste package. This crust is unstable (not necessarily well-bonded to the waste package). Correspondingly, cracks in the waste package will admit limited volumes of magma that will tend to chill and plug. Large cracks and tears might allow the void spaces in a waste package to fill with magma that chills.

The interaction of waste package and magma is too non-specific and variable to be amenable to a direct calculation without a more detailed description of the part of the interaction to be modeled.

As an approximation, the magma fills a cylindrical chamber (the drift) and solidifies to form a plug. Because, waste can only be dissolved or mobilized while the magma is liquid, what is of interest is how long liquid magma could be in contact with a waste package and its contents.

Magma, which is presumed to be approximately at the liquidus temperature, as it solidifies (chills), releases the latent heat of fusion (e.g., Jaeger 1964, p. 451f) of the order of 3.348-4.185

$\times 10^5$ J/kg (80–100 cal/g). For the cylindrical plug in contact with the drift wall and ground support, the solidification surface gradually moves inward.

This problem is a "Stefan" problem, a so-called moving boundary problem. There is substantial literature describing solidification of a spherical and a cylindrical molten mass (e.g., Soward 1980; Stewartson and Waechter 1976; Riley et al. 1974; Pedroso and Domoto 1973; Kreith and Romie 1955), which has provided series solutions for the temperature history and for the time of final solidification. The particular problem of a magma plug of finite length is not among the solutions mentioned or among the problems tried.

The problem for magma flow solidifying in an infinitely long cylindrical drift is described in Soward (1980), and the general approach to such problems is given in Carslaw and Jaeger (1959, p. 295f). The problem of actual interest, a finite plug imbedded in a medium, at a constant temperature at one end and cooling at the other and cooling along a cylindrical surface, has not been addressed. However, enough can be gleaned from the existing solutions to make preliminary assessments about the waste package environment. Several of the analyses (Kreith and Romie 1955; Riley et al. 1974) provide simple expressions for the time for solidification of a cylinder filled with chilling magma, in terms of the diameter of the drift, the drift wall temperature, and the physical properties of the magma. Riley et al. (1974, p. 1514) estimate a time to chill, t_f, as

$$t_f = a^2(\beta + 1)/(4k) \qquad \text{(Eq. 13)}$$

where

$\beta = L/(C(T_f - T_w))$

a = radius of the drift (~2.75m)

k = thermal conductivity of solid—basalt at 21.76 J/(kg sec ^{0}C) (0.0052 cal/(gm sec ^{0}C) (Hodgman et al. 1955, p. 2251, Table Heat Conductivity)

L = Latent heat of fusion (3.348-4.185 x 10^5 J/kg (80–100 cal/gm))(Jaeger 1964)

C = Specific heat (~0.3) (Jaeger 1964)

T_f = Fusion temperature of magma (~1100 ^{0}C, selected as a representative value from the range reported in CRWMS M&O 2000g, also see Table 1)

T_w = Drift wall temperature (~600 ^{0}C)

With these numbers, the time for solidification to reach the center of the magma filled drift is approximately 70 days. Estimates using other reference calculations suggest that to the order of accuracy of the expansions that the time is $70 < t_f < 82$ days. These estimates depend on the drift wall temperature, which is a function of the thermal properties of the surrounding rock; increasing the drift wall temperature increases the length of time to chill.

As an upper estimate of temperature, part of the waste package has seen T_f for most of the time for solidification. The actual temperature distribution for the chilling magma cylinder is given by Soward in series form (1980, p. 143f).

Alternative Interpretations–The Igneous Activity Issue Resolution Status Report, in Section 4.2.4.3.1 (Reamer 1999, p. 83f), develops a heat transfer model in order to establish a temperature history for waste packages being enveloped in magma. They assume that the waste packages are located centrally in a convecting magma cylinder, the temperature is only a function of radius, the magma represents an infinite heat source, and the drift wall is approximately at the magma temperature for 20 days. Magma displaced by the waste package and waste package thermal properties are accounted for by treating the magma intrusion as a cylinder the diameter of the drift. The calculation allows for the possibility of a chilled rind of basalt forming on the drift wall and reducing the heat transfer coefficient. These assumptions lead to the conclusion that there is ample time to heat the waste packages to failure during a typical basaltic eruption.

This AMR analyzes a pyroclastic plug as an infinite cylinder of solidified, cooling material and a magma plug as an infinite cylinder of solidifying magma, either (or both) of which has entered a drift from the intersecting dike. The flow has filled the drift rapidly and there is no further flow along the drift axis (there is no exit for flow to continue). Details of the heat transfer, such as orientation and location of the waste package relative to the center of the drift, and the fact that a waste package is a large metal object with good thermal conductivity relative to the rock, are treated by replacing the waste package with the flow (pyroclastic or magmatic). While these details are important to the actual temperature distribution in the waste package, they are relatively unimportant to the issue of waste package failure because the length of time the waste package is subject to heat soak is so long. The cooling history is calculated analytically for the solid, hot pyroclastic material in which containers are embedded, and an approximation is provided. The calculation for the magma is for the length of time it takes for the magma-filled-drift to solidify. This time represents the length of time that a typical waste package will be exposed to a temperature near the magma liquidus temperature (1100 ^{0}C). The time calculated for solidification for the magma around the embedded waste packages is long compared to the time estimated in the IRSR.

The case of a continuing flow of magma, as considered in Reamer (1999) requires an exit to the surface from the drift, a circumstance that is not considered here. An exit would be possible only through paths occurring as a result of reestablishment of dike propagation or perhaps opening of existing bounding faults. Further, flow of magma, down an open drift to its end, would be expected to be rapid compared to the chilling (solidification) time for the magma.

7. CONCLUSIONS

The topics (end members) examined in this AMR are: (1) waste package temperature due to flow of magma and pyroclasts down a drift, (2) steady-state gas flow down-drift to interact with containers, (3) physical interaction of pressure pulse from the dike to displace waste packages and drift contents, and (4) qualitatively, the interaction of the self-generated crack leading the dike with the stress-altered region around the drift.

Based on these analyses the following conclusions are physically possible and not excluded by data relevant to the mountain or to a repository.

1. The thermally altered stress state of the mountain may cause propagating dikes to deviate for the order of 2000 years (addresses the nature of the mechanics of the dike drift interaction).

2. Disruption of waste packages caused by flow from the dike extends down the drift from the dike edge to 3 or possibly 4 waste packages (addresses movement of the waste packages as they are pushed down the drift).

3. Pyroclastic flow down the drift may envelop waste containers in each drift intercepted by the dike. Waste package temperatures are given approximately by results from Carslaw and Jaeger 1959 (addresses the temperature and pressure history of containers at risk).

4. Magma flow down the drift is limited to voids still available after drift pressurization to the fragmentation pressure (addresses magma contact with the waste containers).

5. The temperatures inside a magma plug (and approximately in embedded waste packages) are given by Soward (1980) with a solidification time of 70 to 82 days (addresses temperature changes to the waste package from exposure to magma).

6. Gas flow down an idealized drift is about 3.5×10^2—3.5×10^3 m^3/sec, and suggests an isothermal model is inadequate and overestimates the flow rate (addresses the amount of gas available to degrade waste containers).

7. Waste containers away from the drifts intersected by the dike will experience a pressure pulse, with indeterminate consequences, including possible failure (addresses effects distributed throughout the entire repository for the case that the mains are also open drifts).

Data and assumptions used in these analyses are derived from the published literature as indicated in Table 1. No corresponding “qualified” data (data acquired under the controls of current QA procedures) have been developed specifically for Yucca Mountain and vicinity.

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7.1 ALTERNATIVE INTERPRETATIONS

In order to provide the basis for the PMR (CRWMS M&O 2000a) addressing the IRSR criteria on igneous events (Reamer 1999) this section develops observations about the relevance of the analyses done in this AMR to the NRC – IRSR criteria, by comparison to the intent of the NRC – IRSR criteria and the analyses presented in the IRSR. The summary observation is that a more complete level of detail than is included in the IRSR is required to address the NRC – IRSR criteria.

The NRC has developed the following acceptance criteria related to the Igneous Activity Key Technical Issue and the subissues of consequences (Reamer 1999, pp. 76 and 82). The first acceptance criterion related to the subissue of consequences is (Reamer 1999), Section 4.2.3.1.

> Acceptance Criterion: "Estimate of the dose consequences of igneous activity on the proposed Yucca Mountain high-level radioactive waste repository will be acceptable provided that: The models adequately account for changes in magma ascent characteristics and magma/rock interactions brought about by repository construction."

The IRSR analysis assumes that an idealized interception of the drift by the dike has occurred. The analysis is qualitatively concerned about propagation of shock waves and pyroclastic flow down the drift. It explores quantitatively pressurization of the drift by magma and the conditions for re-establishment of dike propagation by hydraulic fracturing.

This criterion contains several implicit questions which are only partly addressed by the IRSR interpretation of the physical processes. These questions are discussed in somewhat more detail by the following analyses (developed in Section 6.3):

1. Stress state evolution around the repository
2. Interaction of a linear crack with a cylindrical drift.
3. Consequences of shock wave movement (pressure pulse) down a drift.

These implicit questions concern how the stress state affects the assent of magma, both in direction and in the detailed interaction with the drifts, and the consequences of the intersection, including pressure pulse propagation down the drift.

The questions are mixed, in the sense that they actually involve both conceptual models introduced in Section 6.3, the simple idealized intersection model, and the stress-field dependent model.

Analyses 1 and 2 involve the second conceptual model—a model in which the stress state of the mountain and its evolution are important. Analysis 3 involves the idealized, first model, in which the stress state of the repository itself is ignored. The results of this AMR differ from those of the IRSR in part because of alternative interpretations of how much physical detail is required.

The second acceptance criterion related to the subissue of consequences is Reamer 1999, Section 4.2.4.1.

> Acceptance Criterion: "Estimate of the dose consequences of igneous activity on the proposed Yucca Mountain high-level radioactive waste repository will be acceptable provided that: The models account for the interactions of basaltic magma with engineered barriers and waste forms."

This IRSR analysis assumes that the waste packages are enveloped by a convecting magma flow which fills the drift. On this basis, the present analysis tries to establish whether waste packages will see temperatures sufficiently high and persistent to compromise package integrity.

This criterion contains several implicit questions which are addressed in part by the following analyses (developed in Section 6.3):

1. Interaction of a linear crack with a cylindrical drift
2. Steady-state flow of a real gas down a drift
3. Chilling of a magma plug enveloped within waste packages.
4. Embedding of waste packages in an indurating pyroclastic flow.

These implicit questions relate to the details of dike propagation in a space with an already existing circular opening, the flow of corrosive gas down a drift (amount available), and the temperature and pressure history of waste packages that are enveloped by magma or embedded in pyroclasts.

As for the previous Criterion, the questions involve both conceptual models (Section 6.3), the simple idealized intersection model, and the stress-field dependent model. In this case, analysis 1 depends on the second stress-dependent conceptual model and analyses 2 and 3 on the first, simple idealized, conceptual model. The results of these analyses differ from the IRSR because of differences (alternative interpretation) of the amount of physical detail required.

The topics (end members) examined in this AMR are: (1) waste package temperature due to flow of magma down a blind drift, (2) steady-state gas flow down-drift to interact with containers, (3) physical interaction of pressure pulse from the dike to displace waste packages and drift contents, and (4) qualitatively, the interaction of the self-generated crack leading the dike with the stress-altered region around the drift.

8. INPUTS AND REFERENCES

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8.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES

AP-2.13Q, Rev. 0, ICN 4. *Technical Product Development Planning*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20000620.0067.

AP-2.14Q, Rev. 0, ICN 1. *Review of Technical Products*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20000405.0477.

AP-2.21Q, Rev. 0. *Quality Determinations and Planning for Scientific, Engineering, and Regulatory Compliance Activities.* Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL. 20000802.0003.

AP-3.4Q, Rev. 1, ICN 3. *Level 3 Change Control*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20000525.0376.

AP-3.10Q, Rev. 2, ICN 3. *Analyses and Models*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20000918.0282.

AP-3.14Q, Rev. 0, ICN 1. *Transmittal of Input*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20000427.0419.

AP-3.15Q, Rev. 2, ICN 0. *Managing Technical Data Inputs*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20001109.0051.

AP-6.1Q, Rev 5, ICN 0. *Controlled Documents*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20000608.0009.

AP-17.1Q, Rev. 1, ICN 2. *Record Source Responsibilities for Inclusionary Records*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.19991217.0505.

AP-SI.1Q, Rev 2, ICN 4, ECN 1. *Software Management*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL. 20001019.0023

AP-SIII.2Q, Rev. 0, ICN 2. *Qualification of Unqualified Data and the Documentation of Rationale for Accepted Data*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.19991214.0625.

AP-SV.1Q, Rev. 0, ICN 2. *Control of the Electronic Management of Information.* Washington, DC.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20000831.0065.

QAP-2-0, Rev. 5, ICN 0. *Conduct of Activities*. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980826.0209.

QAP-2.3, Rev 10. *Classification of Permanent Items*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.19990316.0006.

YAP-SV.1Q, Rev. 0 ICN 1. *Control of the Electronic Management of Data.* Washington, DC.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.19991008.0209.

8.3 SOURCE DATA, IDENTIFIED BY DATA TRACKING NUMBER

DTN: LB997141233129.001. Calibrated Basecase Infiltration 1-D Parameter Set for the UZ Flow and Transport Model, FY99. Submittal date: 07/21/99.

DTN: SN9908T0872799.004. Tabulated In-Drift Geometric and Thermal Properties used in Drift-Scale Models for TSPA-SR (Total System Performance Assessment—Site Recommendation). Submittal date: 08/30/1999.

Additional References contained in Attachment I.

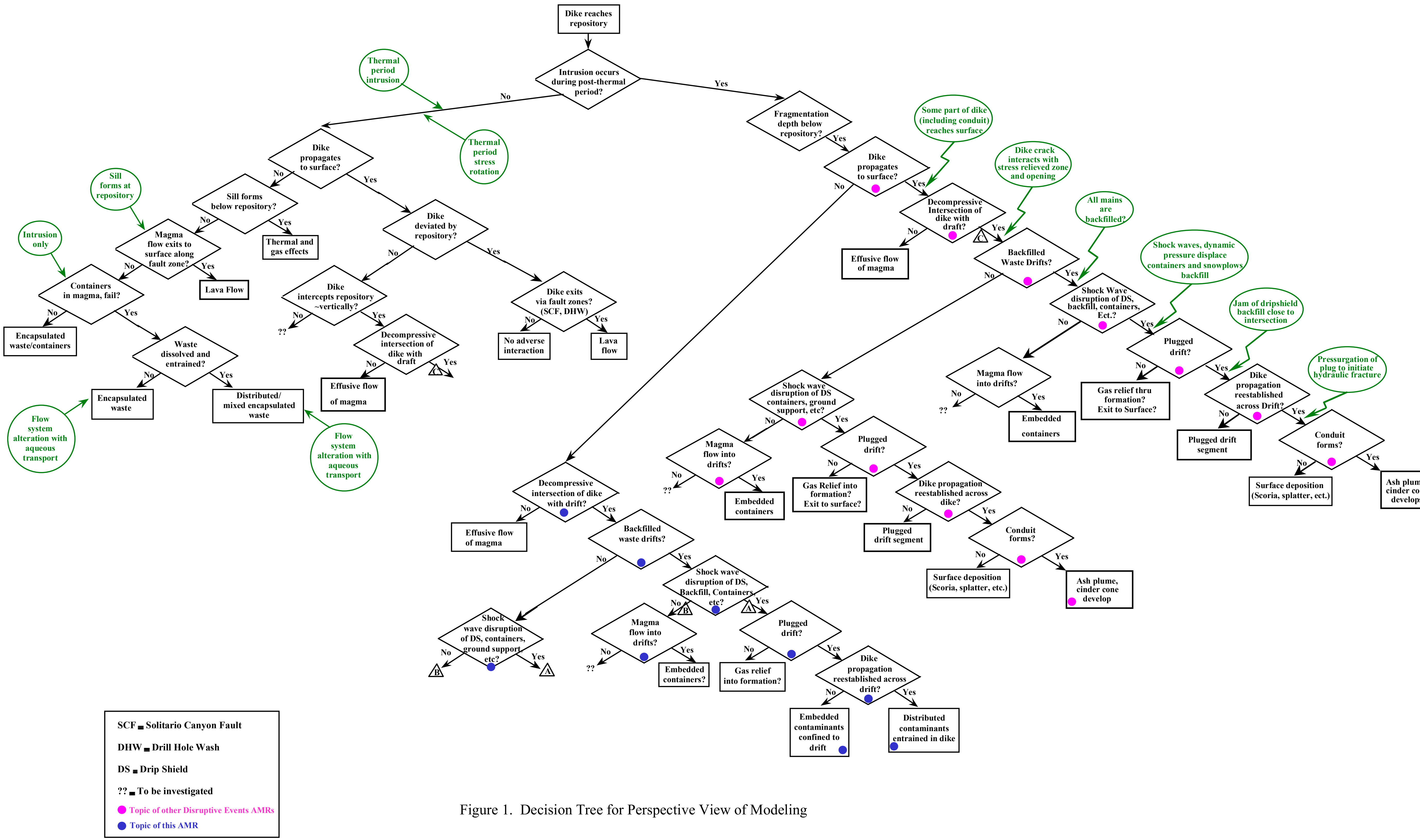


Figure 1. Decision Tree for Perspective View of Modeling

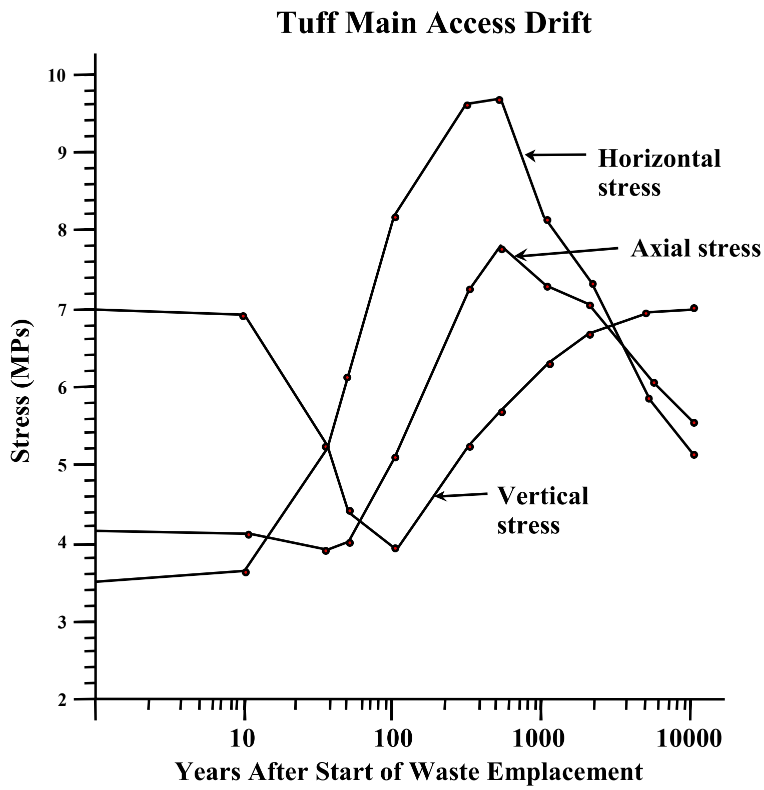


Figure 2. Thermo-Mechanical Response of the Stress State—Main Drift

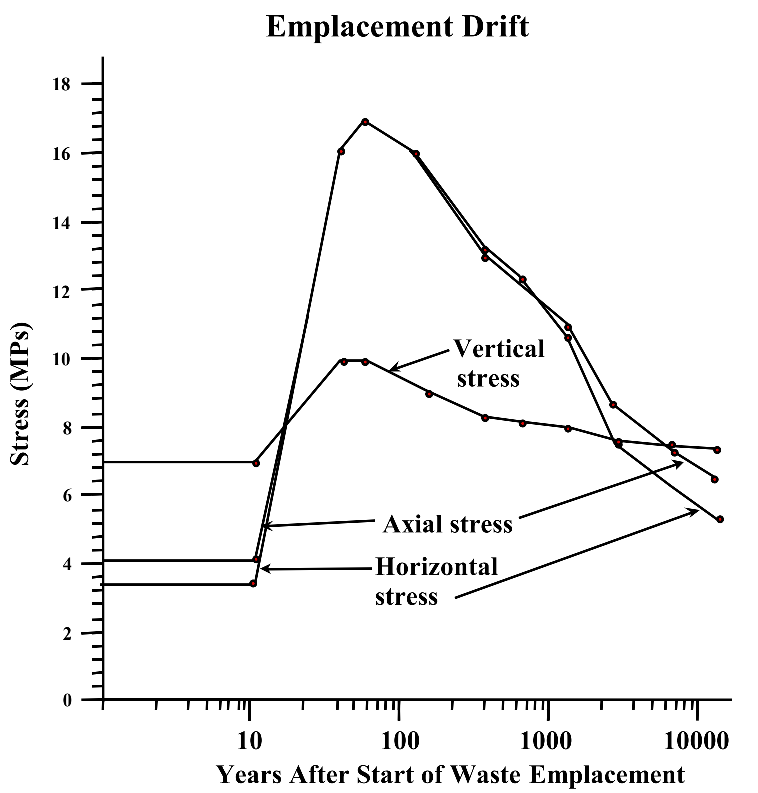


Figure 3. Thermo-Mechanical Response of the Stress State

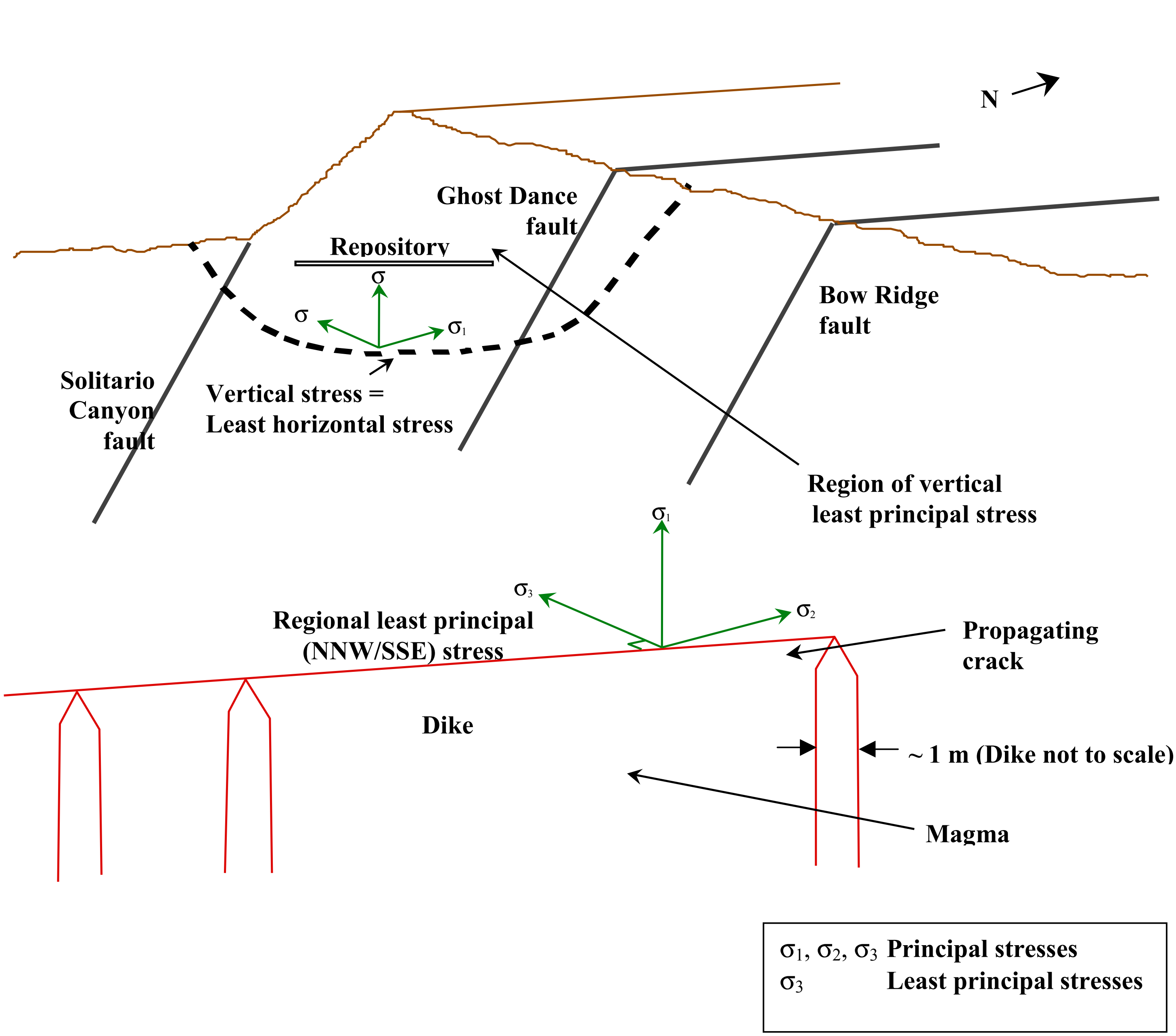


Figure 4. Generic Location of Transition from Horizontal to Vertical Least Principal Stress

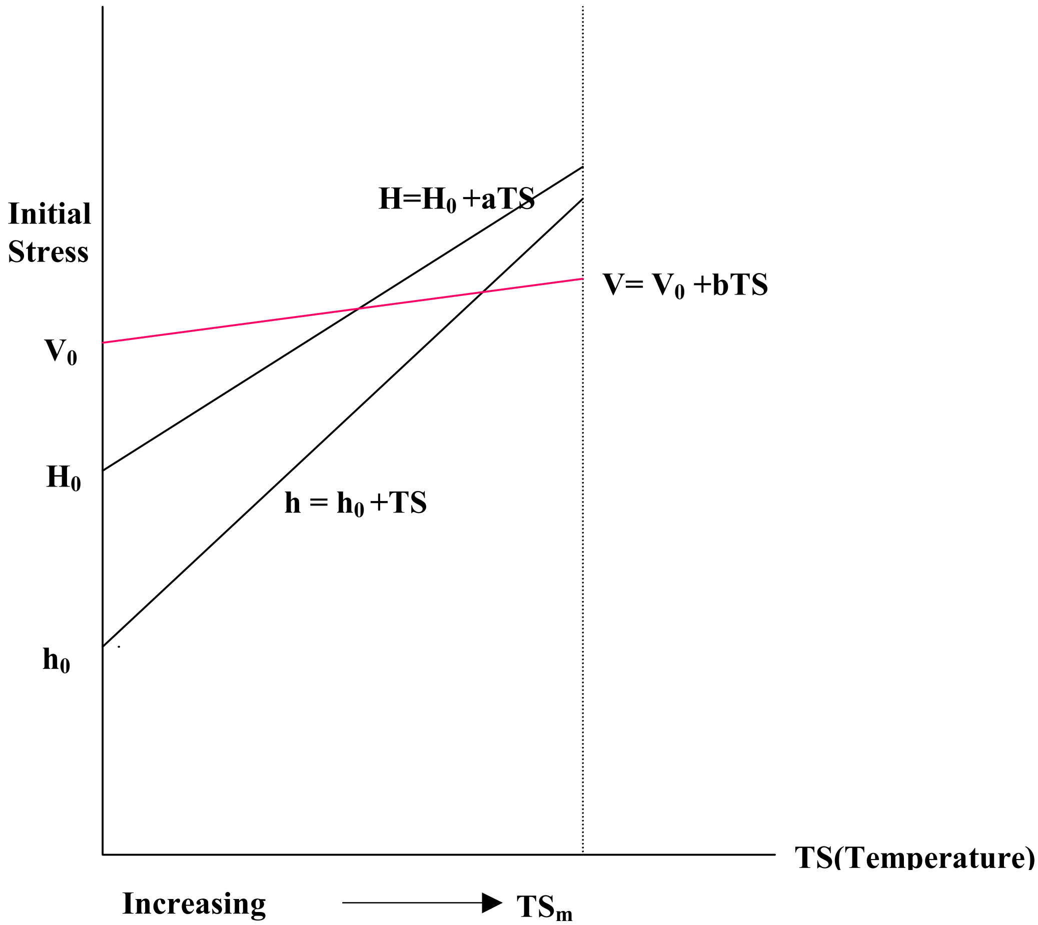
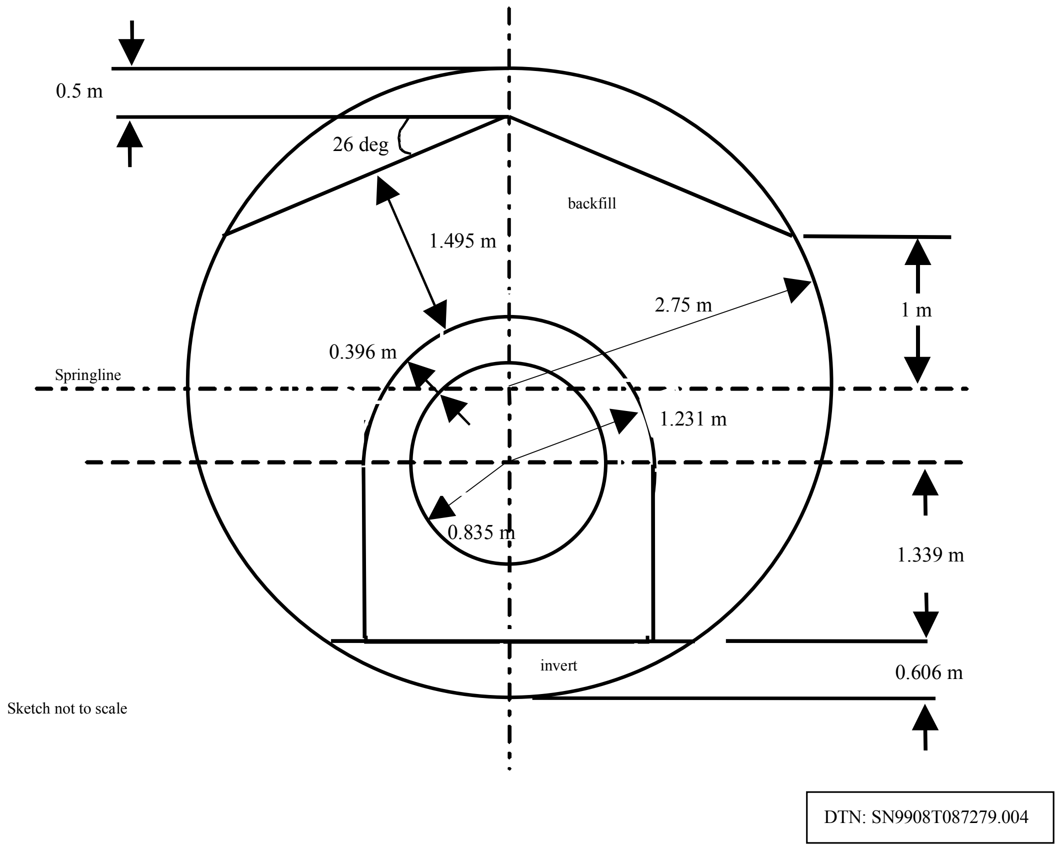


Figure 5. Idealized Stress Trajectory for the Mountain. Principal Stresses: V_o = Initial Vertical, H_o = Larger Horizontal, and h_o = Smaller Horizontal (Least Principal Stress), TS = Thermal Addition to Stress, TS_m = Maximum Additional Stress



NOTE: Sketch corresponding to In-Drift Data for Drift-Scale Models for TSPA-SR (Rev 01).

Figure 6. Design Cross-Section

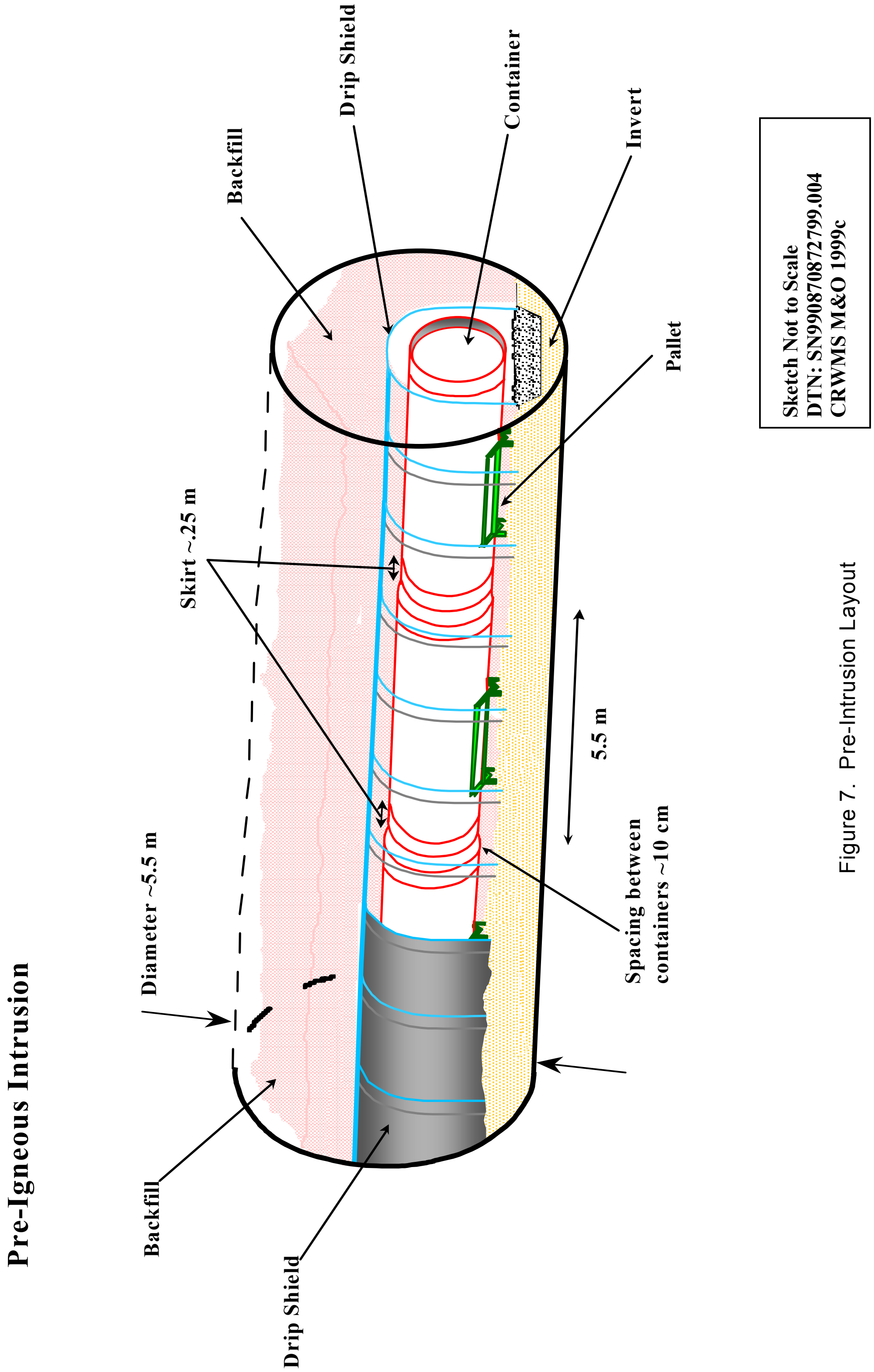


Figure 7. Pre-Intrusion Layout

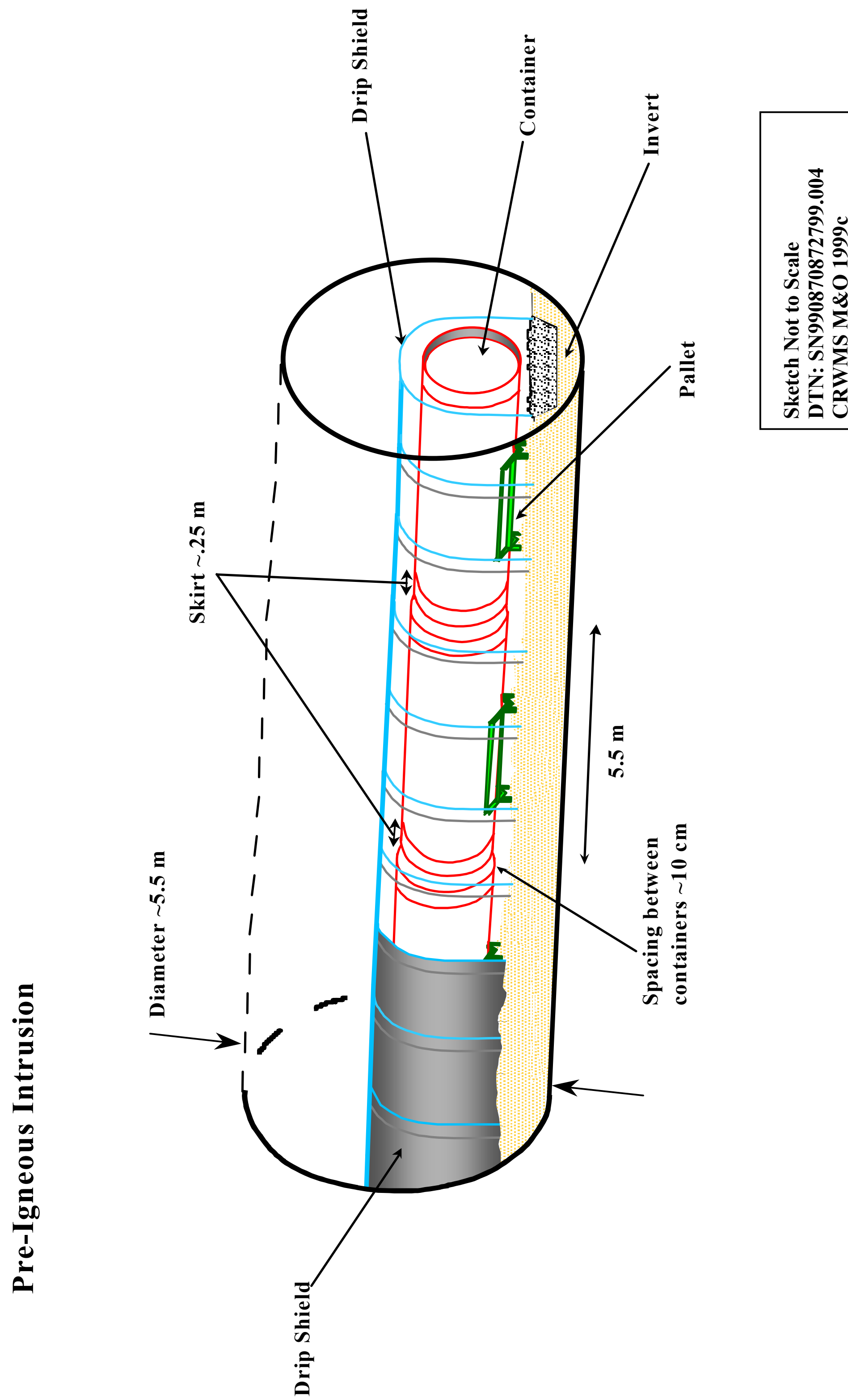


Figure 8. Pre-Intrusion Layout - Open Drift

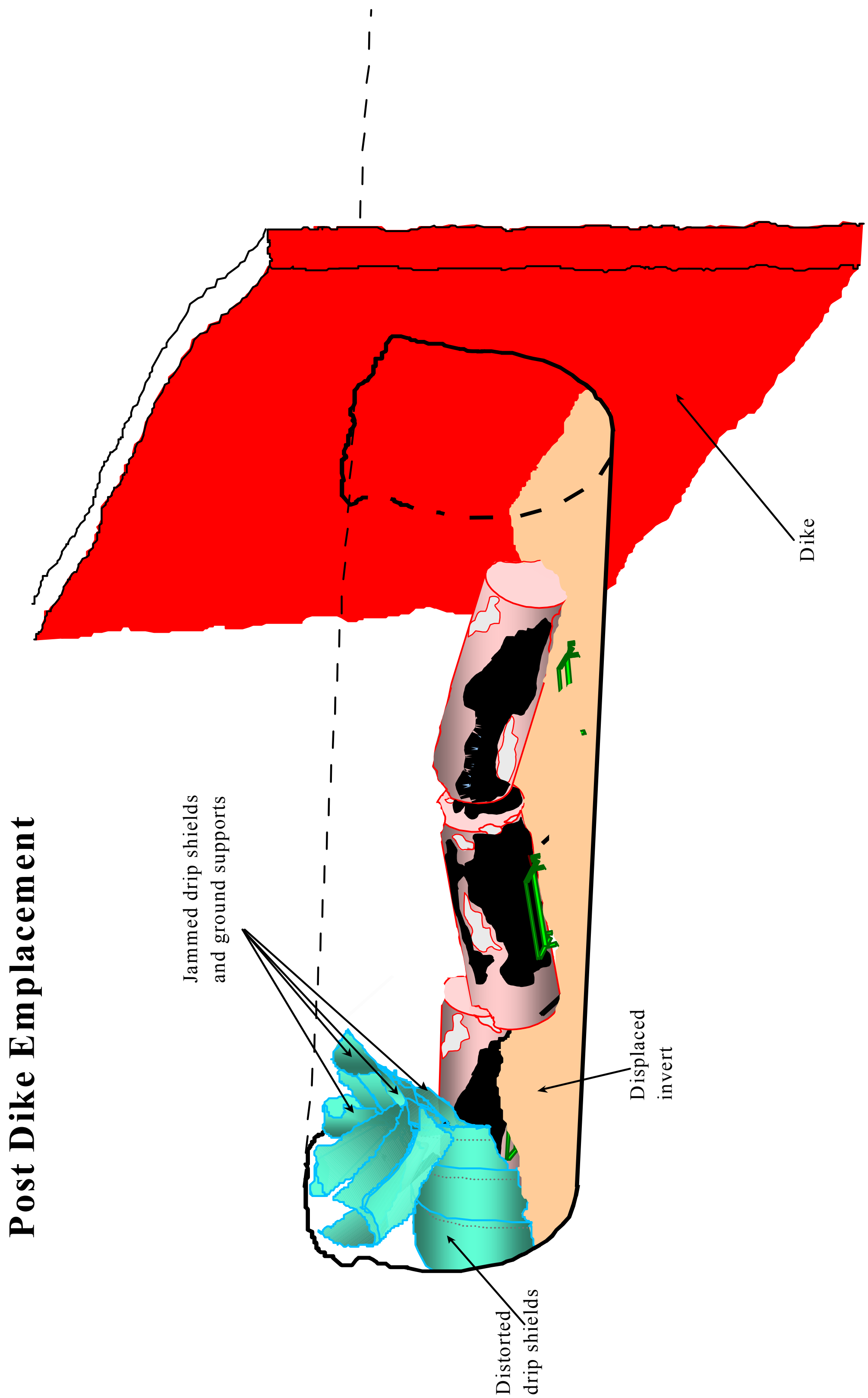


Figure 9. Post-Intrusion Disruption

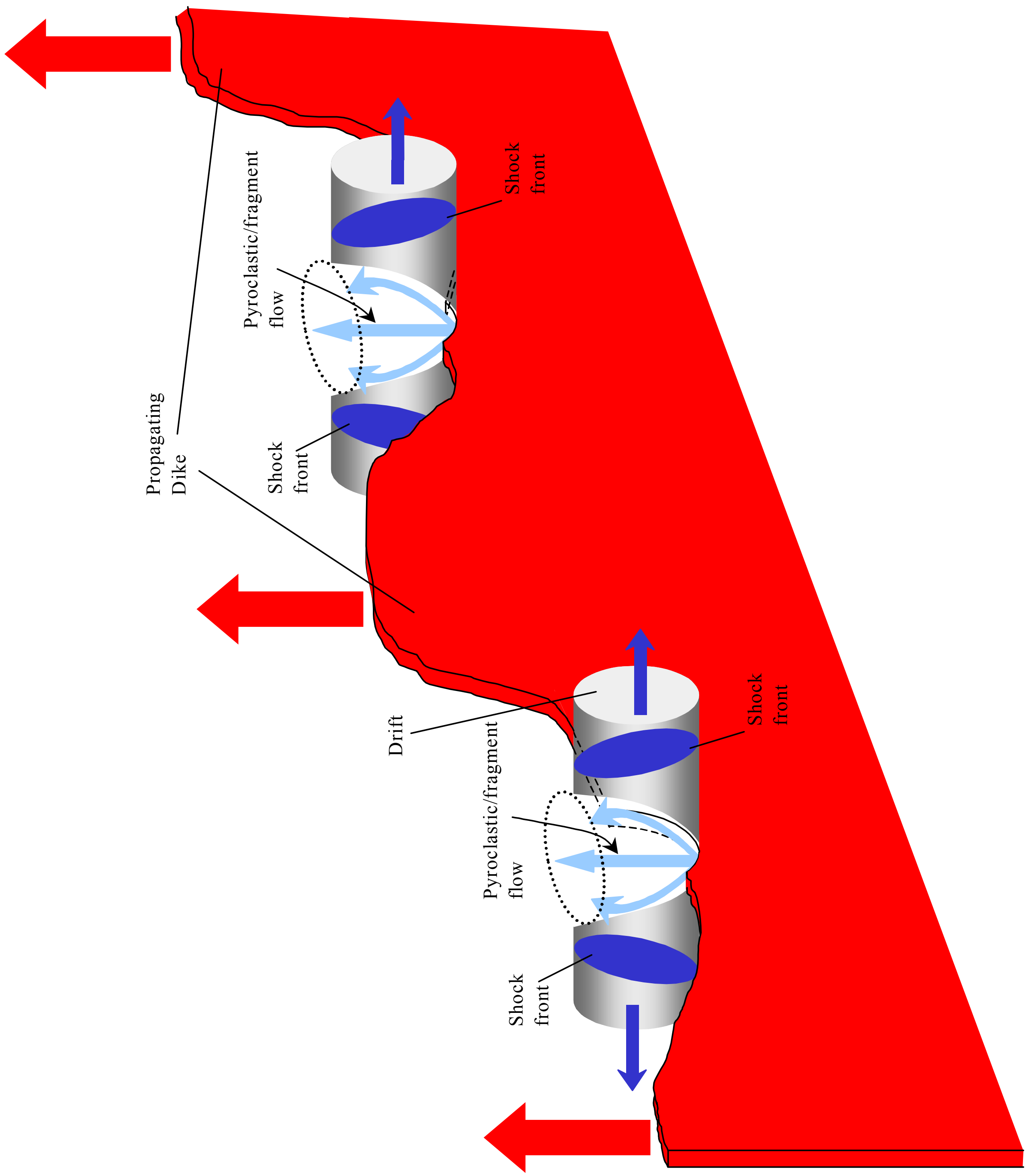


Figure 10. Development of shock wave

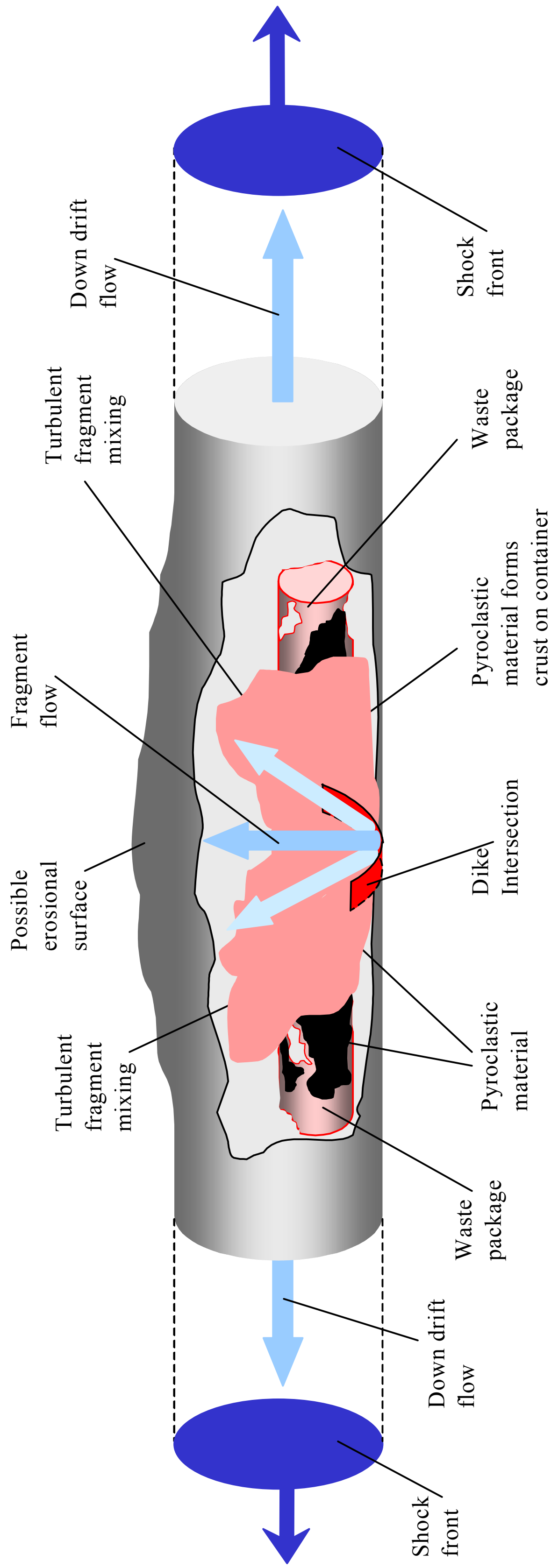


Figure 11. Development of shock wave and down-drift flow

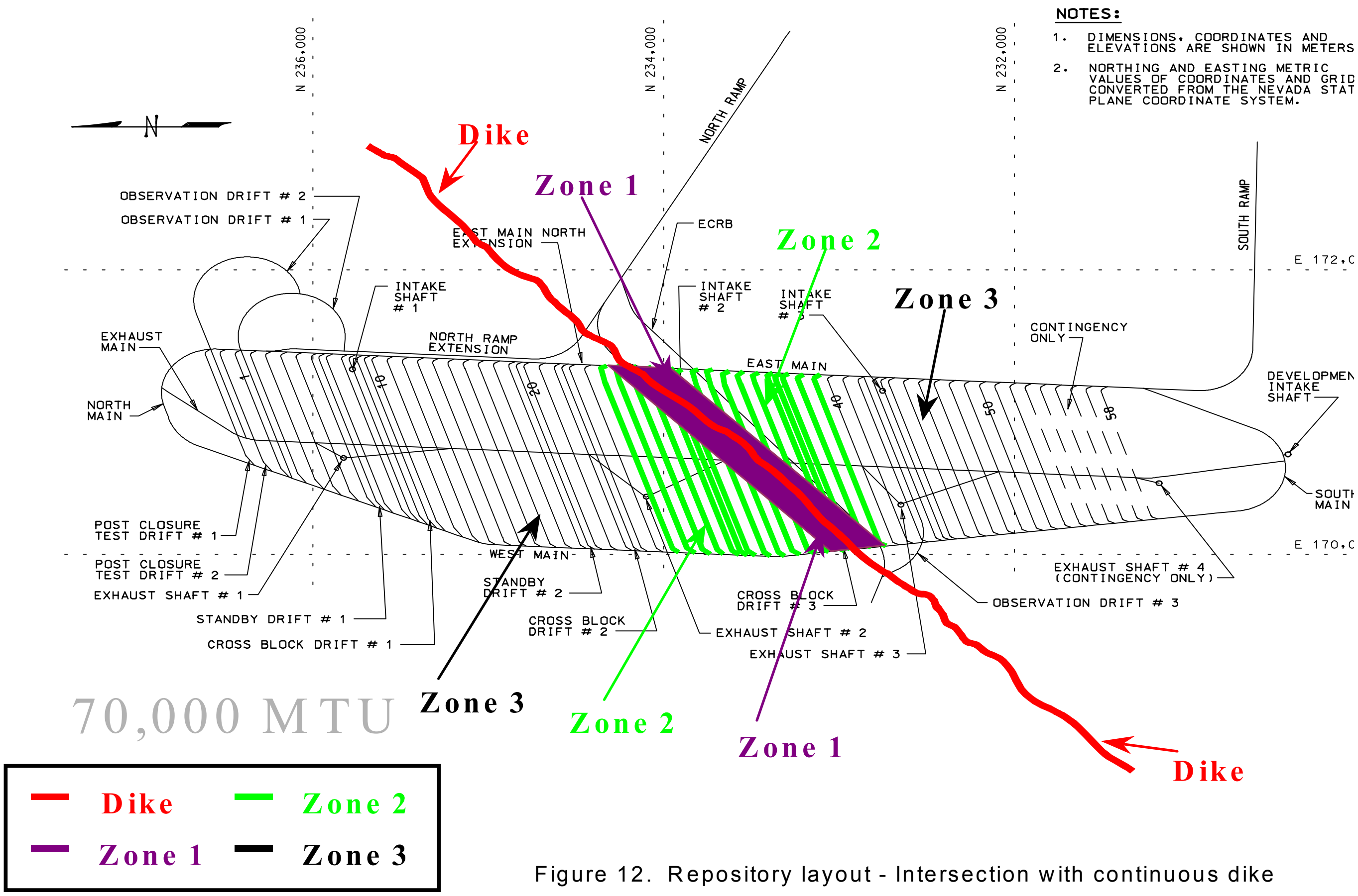


Figure 12. Repository layout - Intersection with continuous dike

Layout from CRWMS M&O 2000k, p. 5

Note – Obliterated and cut-off text in this figure has no technical impact on this document.

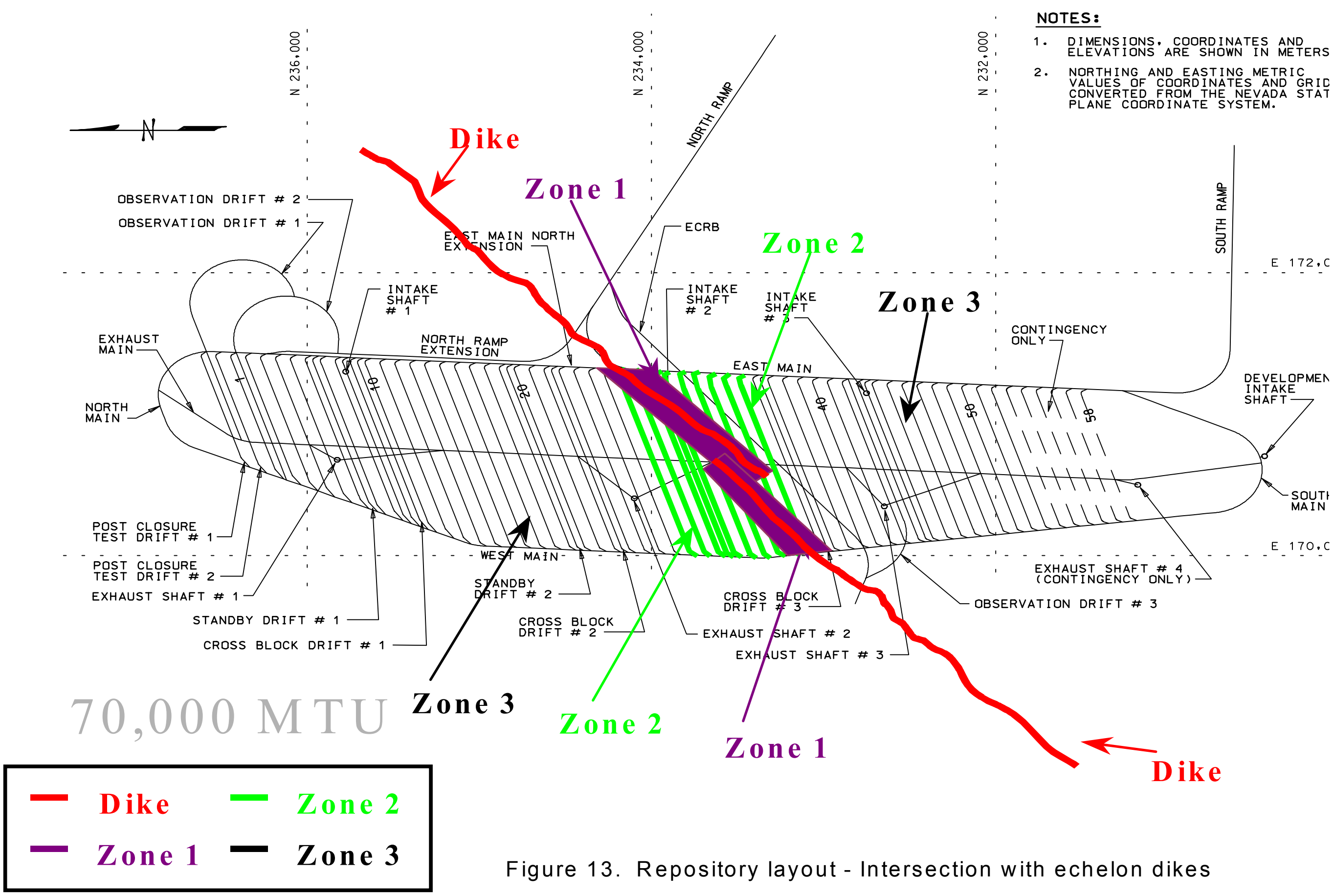


Figure 13. Repository layout - Intersection with echelon dikes

Note – Obliterated and cut-off text in this figure has no technical impact on this document.

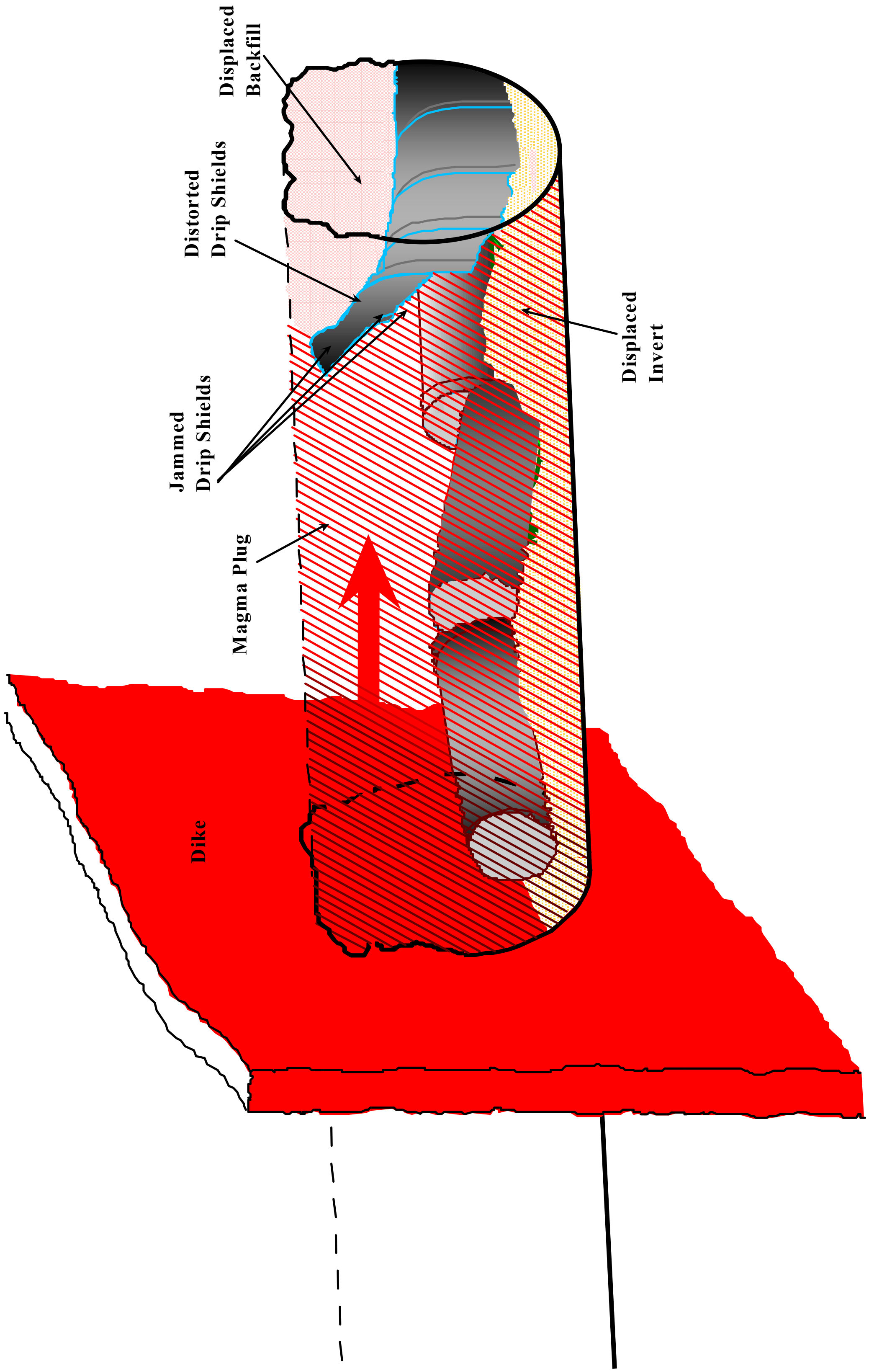


Figure 14. Post-dike emplacement; magma plug superimposed on Figure 9

ATTACHMENT I

Structural Performance of Waste Packages when Subject to High Temperature and Pressure due to Contact with Magma, Z. Ceylon

Basic relations of solid mechanics are used to determine the structural behavior of the waste package (WP) inner shell and inner lids under external pressure and high temperatures due to the contact between the WP and the magma. These preliminary calculations are conservative since the closed-form relations are applicable to elastic deformations. Future investigations should incorporate nonlinear plastic deformation of WP materials.

Due to its geometry, the WP lid is more vulnerable to external pressures than the shell. In the current design, since there is a gap between the outer and inner lids at the lower end of the WP and the outer lid is substantially thinner than the inner lid, the outer lid is expected to fail first. Therefore, no structural credit is taken for the WP outer lid.

The WP inner lid is subject to a similar boundary condition with a circular plate of constant thickness fixed at its circular edge. The maximum bending stress in a circular plate of constant thickness is located at its fixed edge. Therefore, the maximum bending stress is obtained from the relation given in reference 1, page 398:

$$\sigma = \frac{6 \cdot M}{t^2} \qquad (Att. - I, Eq. 1)$$

where:

F = maximum bending stress

M = maximum bending moment

t = circular plate thickness

The maximum bending moment (Ref. 1, p. 429) in a circular plate at the fixed edge is

$$M = \frac{q \cdot a^2}{8} \qquad (Att. - I, Eq. 2)$$

where:

q = external pressure on the plate

a = plate radius

Equations (1) and (2) are combined to give

$$q = \frac{8 \cdot t^2 \cdot \sigma}{6 \cdot a^2} \qquad (Att. - I, Eq.3)$$

The maximum bending stress is equal to the ultimate tensile strength of 316 stainless steel (SS) at the temperature of interest. The ultimate tensile strength of 316 SS is linearly interpolated between the highest temperature available for strength and the melting point as follows:

The value of strength at 871 °C is 124 MPa (Ref. 2). It is also known that the strength is zero (Ref. 3, p. 35) at the melting temperature, 1375 °C. (Because the curve for strength as a function of temperature is concave (Ref 2, p. 11), a linear extrapolation between the last datum and melt will lie above the cited curve and overestimate the tensile strength at 1100^{0}C.) Therefore:

316 SS ultimate tensile strength at 1100 °C = 124 * (1375 – 1100) / (1375 – 871)
= 68 MPa

316 SS ultimate tensile strength is 495 MPa (71.8 ksi) at 350 °C (662 °F) (Ref. 4, Table U).

The plate thickness is selected as the minimum lid thickness among all WPs, which is 0.08 m for 5-Defense High Level Waste (DHLW)/Department of Energy (DOE) Spent Nuclear Fuel (SNF) WP (Ref. 5, p. II-5). The same reference shows that the inner lid diameter is 1.886 m.

Therefore, at 1100 °C:

$$q = \frac{8 \cdot (0.08)^2 \cdot (68 \cdot 10^6)}{6 \cdot \left[\frac{1.886}{2}\right]^2} = 0.6\, MPa$$

At 350 °C:

$$q = \frac{8 \cdot (0.08)^2 \cdot (495 \cdot 10^6)}{6 \cdot \left[\frac{1.886}{2}\right]^2} = 4.7\, MPa$$

It is concluded from preceding calculations that the maximum allowable external pressure on WPs at 1100 °C and 350 °C are 0.6 MPa and 4.7 MPa, respectively.

References:

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2. Allegheny Ludlum 2000. "Technical Data Blue Sheet, Stainless Steels, Chromium-Nickel-Molybdenum, Types 316 (S31600), 316L (S31603), 317 (S31700), and 317L (S31703)." Pittsburgh, Pennsylvania. Allegheny Ludlum. Accessed July 31, 2000. http://www.alleghenytechnologies.com/ludlum/pages/products/t316_317.pdf. TIC: 248631.

3. American Society for Metals 1980. *Properties and Selection: Stainless Steels, Tool Materials and Special-Purpose Metals.* Volume 3 of *Metals Handbook.* 9th Edition. Metals Park, Ohio: American Society for Metals. TIC: 209801.

4. ASME (American Society of Mechanical Engineers) 1995. "Materials." Section II of *1995 ASME Boiler and Pressure Vessel Code.* New York, New York: American Society of Mechanical Engineers. TIC: 245287.

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