# Evaluation of the Igneous Extrusive Scenario

The EPRI Project Team

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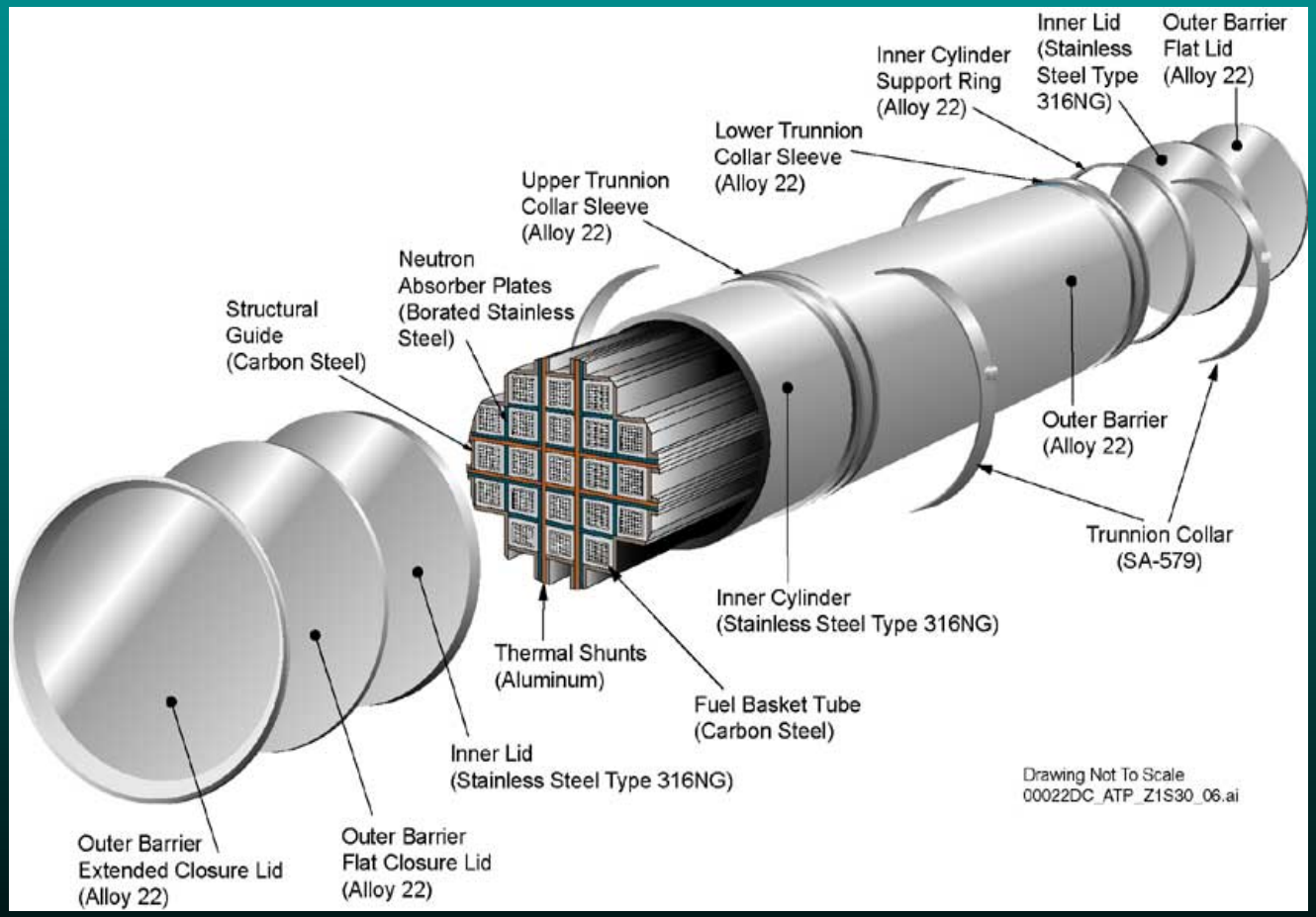
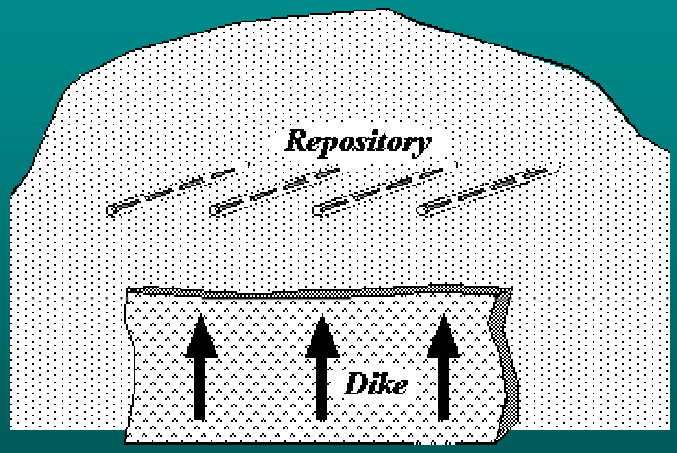
# Our Continuing Mission: To Boldly Go Where No Federal Agency Has Gone Before

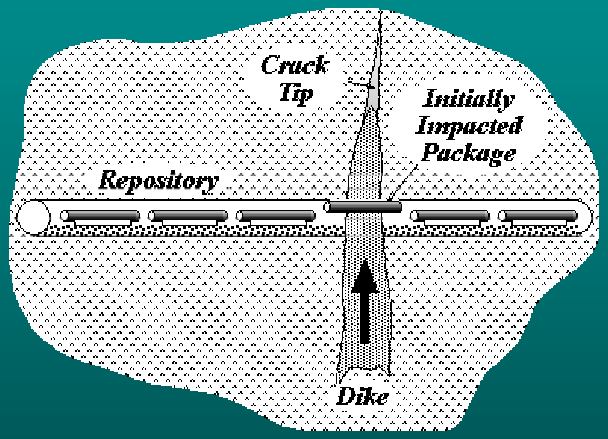


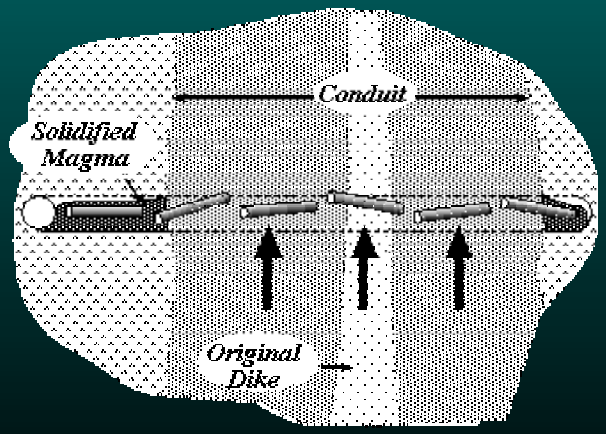
# Reasonable Expectation Case

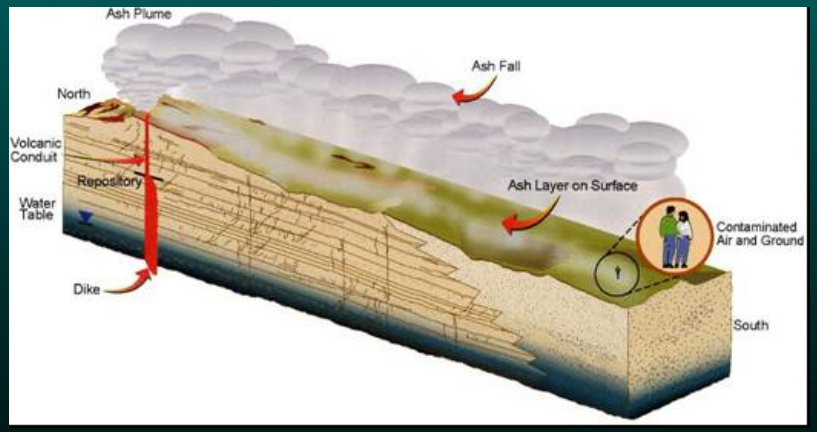
## Zero Release

# Sequence of Events



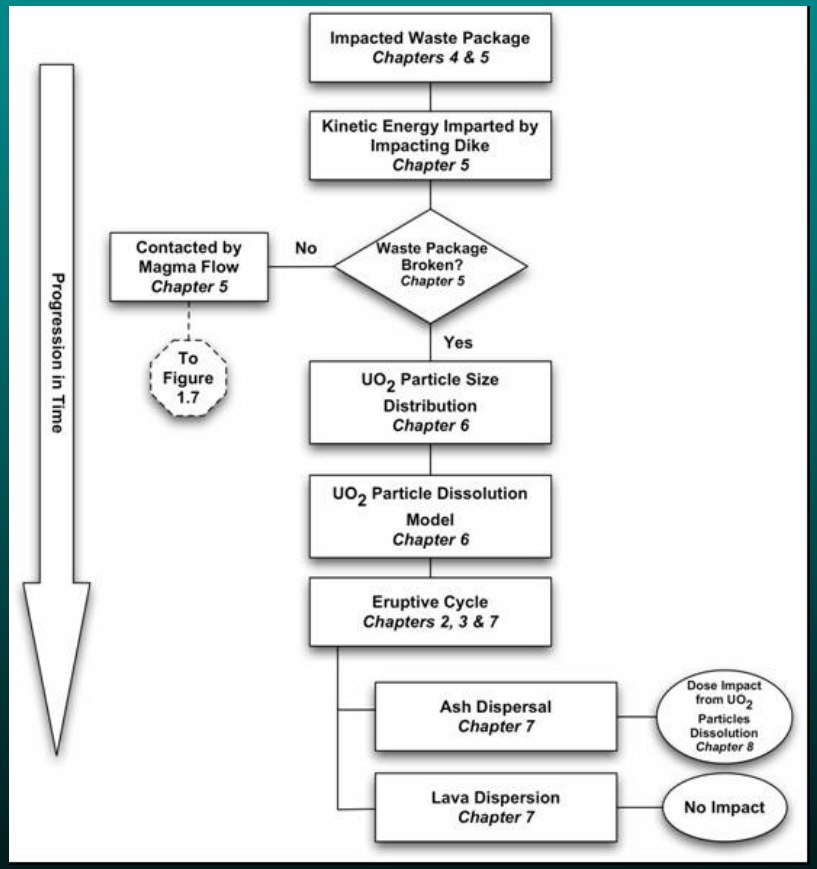



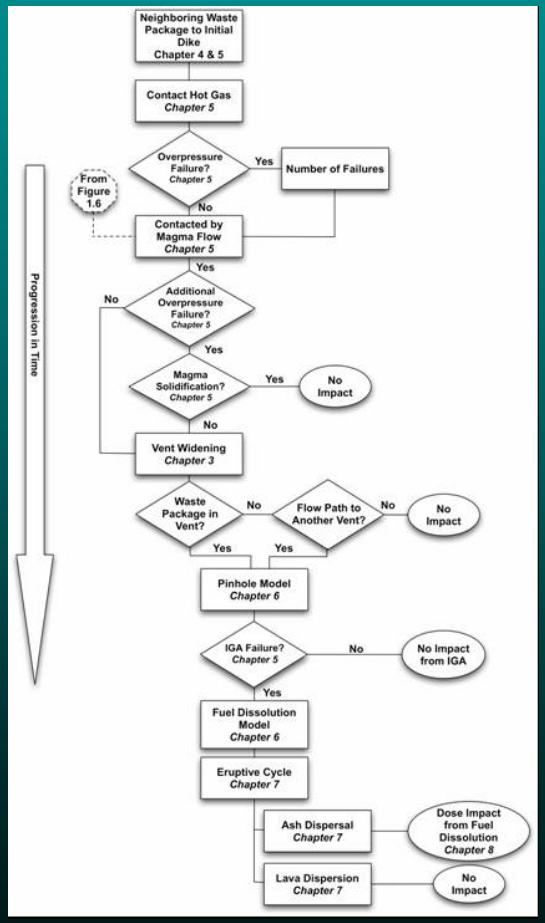
# Initially Impacted Waste Packages

- Initial impact of magma
- If waste package is severely damaged, account for entrainment of fuel
  - Evaluation of particle size distribution following damage
  - Evaluation of fuel dissolution in magma leading to particulate re-sizing during rise through the mountain
- Vent Formation
- Contamination released early in the eruption is in lava



# Waste Packages Away from Initial Dike

- Vent Widening
- Flow of magma down drift
- Evaluation of “dog-leg” magma flow
- Waste package failure

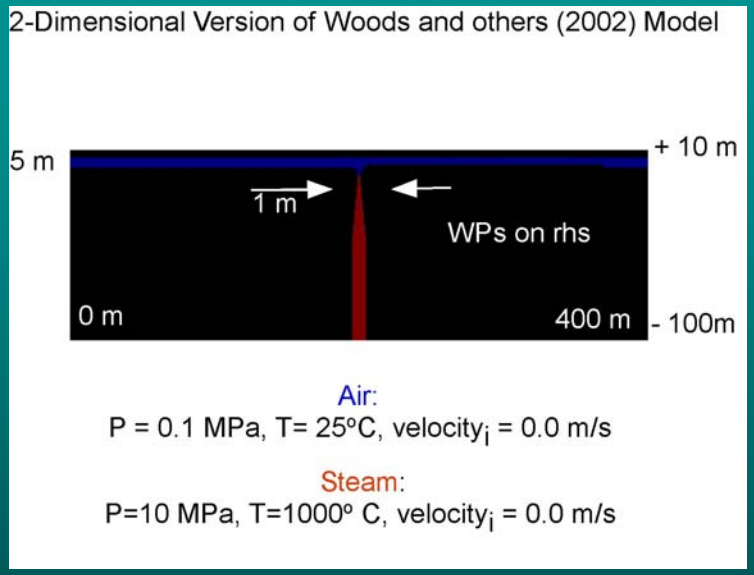


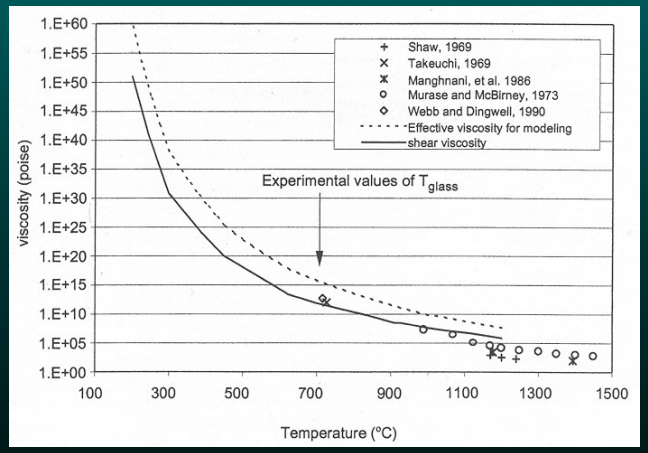
# New Constraints on Magma Behavior

- DOE magma temperature 1150 – 1200 C
- DOE Ascent Rate 0.01-10 m/s
- New observations (Nicholis and Rutherford, 2004)
  - magma temperature 975-1010 C
  - ascent rate of ~0.04 m/s
- New information since the assessment of the extrusive scenario

# Evaluation of Magma-Drift Interactions

- Model analysis using SAGE
- DOE assumes initial temperatures of 1200C and corresponding viscosities of 1-40 Pa-s
- The newly constrained eruption temperatures 975-1010C yield viscosities at least one order of magnitude greater with all other factors

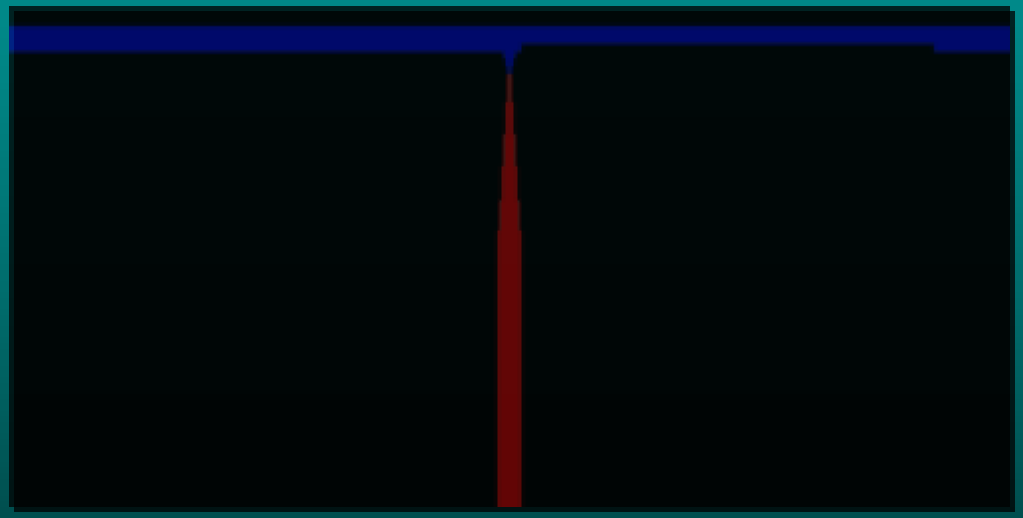


# Impact Analysis for Waste Packages Over a Dike

## Pressure Analysis

- After 0.05 seconds P above the dike reaches 2-3 MPa
- 5-6 MPa is the
- minimum horizontal stress = hydraulic fracture stress limit
- Eventually P above the dike = $P_{dike}$
- Implication: The dike continues upward, and no dog-leg path will occur



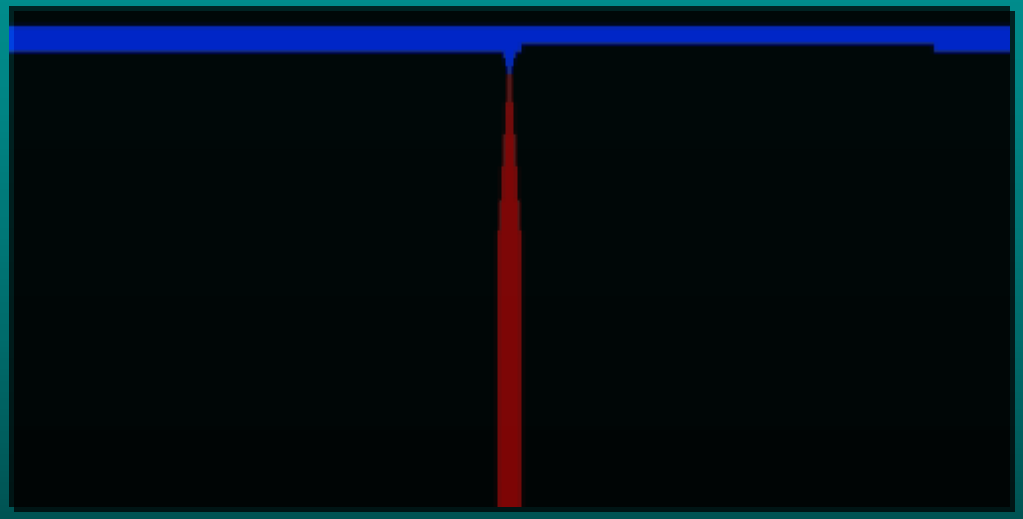
Red = 20 MPa; Blue = 0.1MPa

Shows 200 m of drift

# Impact Analysis for Waste Packages Over a Dike

## Temperature Analysis

- Assumes no heat transfer at boundaries
- Note complex temperature behavior



Red = 1000 C; Blue = 25 C

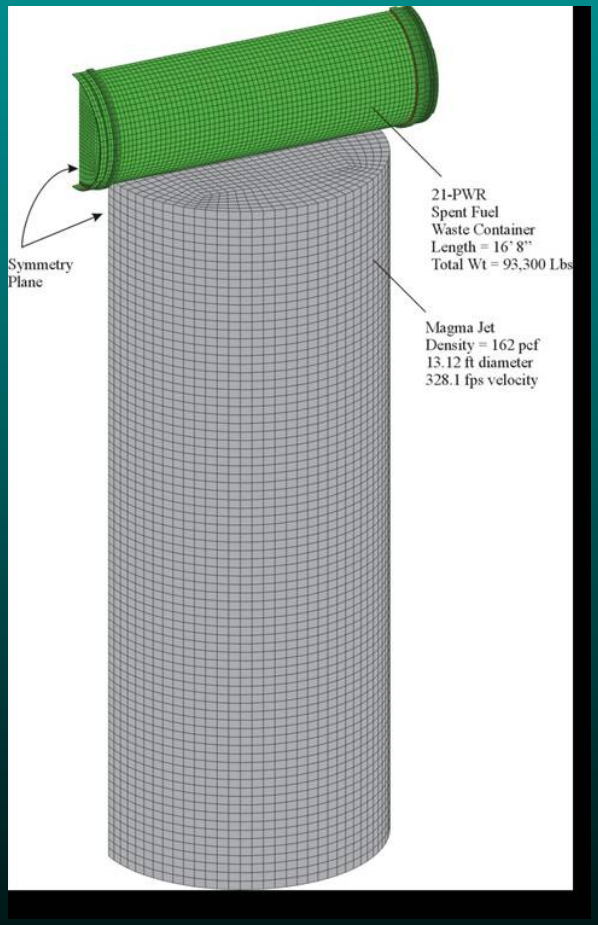
Shows 200 m of drift

# Implications of SAGE Modeling

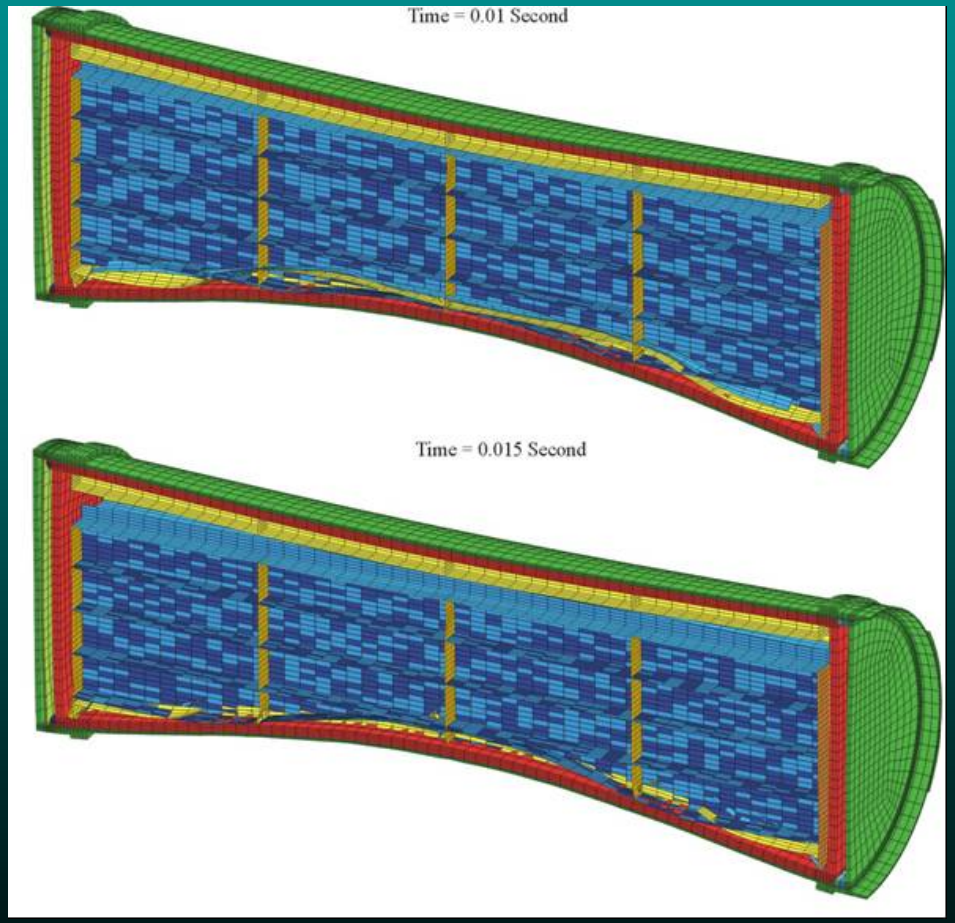
- Pressure down drift << pressure above dike
- Pressure above dike > fracture stress limit
- Dike will continue straight to the surface
- Woods et al. shock wave is an artifact of their 1-D model

# Mechanical Analysis of Initially Impacted Waste Package

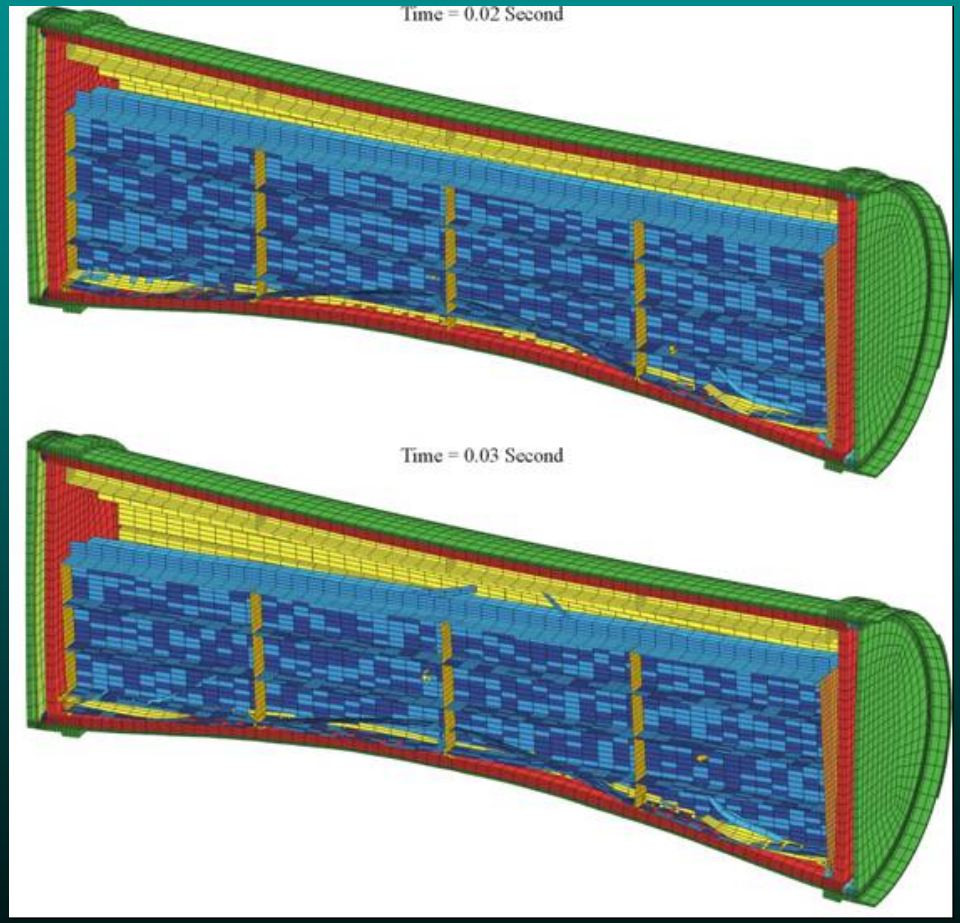
- Dike properties chosen to be extremely conservative
  - 4 m diameter with 100 m/s rise rate
  - Recent information suggests that values on the order of cm/s are more appropriate
- Detailed finite element modeling using ABAQUS/Explicit
- Modeled as impact of a magma jet with the waste package



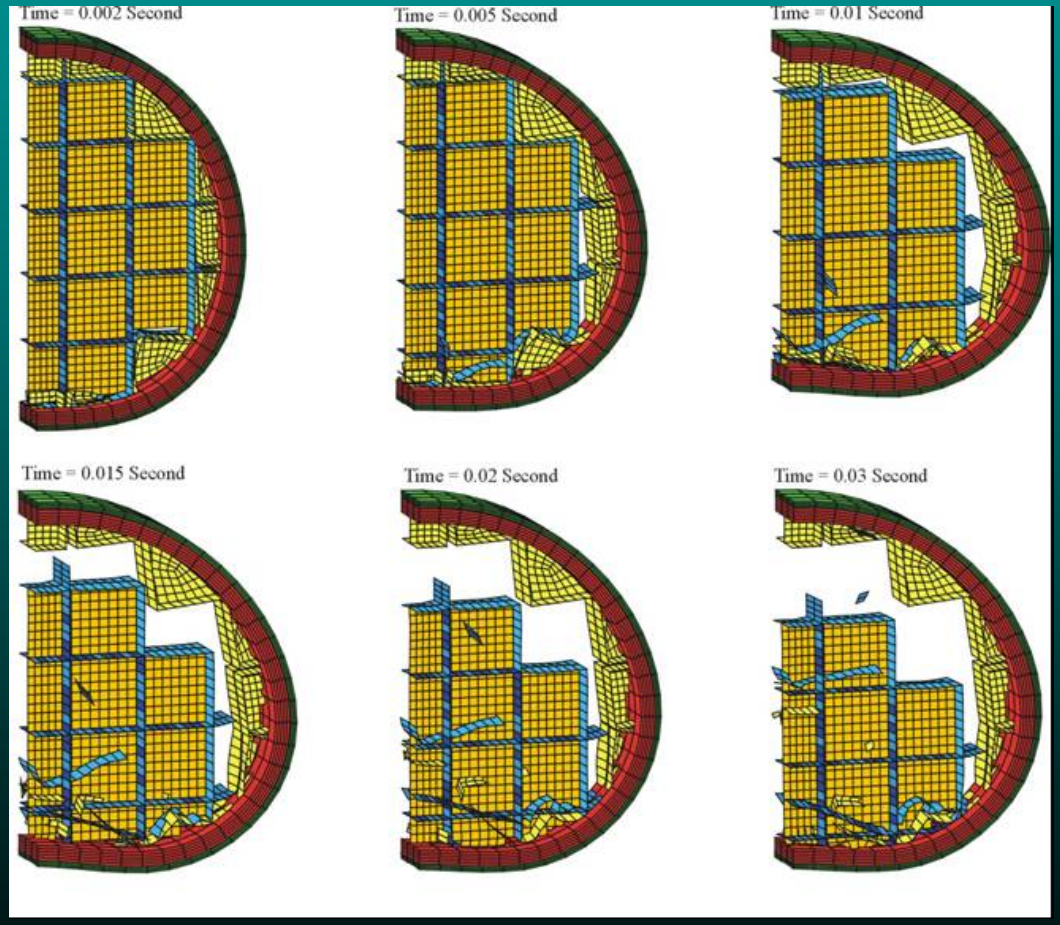
# Deformed shape for damage at 0.01 and 0.015 seconds



# Deformed shape for damage at 0.02 and 0.03 seconds



# Sequence of damage for center section cut



# Summary of Impact Analyses

- The energy applied to the waste package is 100 – 10,000 times the energy of the dike
- Recent information (June 2004) suggests dike rise rates on the order of cm/s rather than 1-10 m/s
- Even under these extreme conditions, the waste package is not breached
  - Structural dent with possible minor tearing
  - Damage to internal elements, but
  - No rupture of the internal structural shell
- Zero release from waste package

# Erosion Effects of Flowing Magma

- Alloy 22 is protected by an oxide (or sulfide) scale
- Erosion-corrosion during the eruption would amount to a maximum of 0.4-2.0 mm
- Erosion-corrosion effects found to be highly unlikely

# Failure by Internal Overpressure

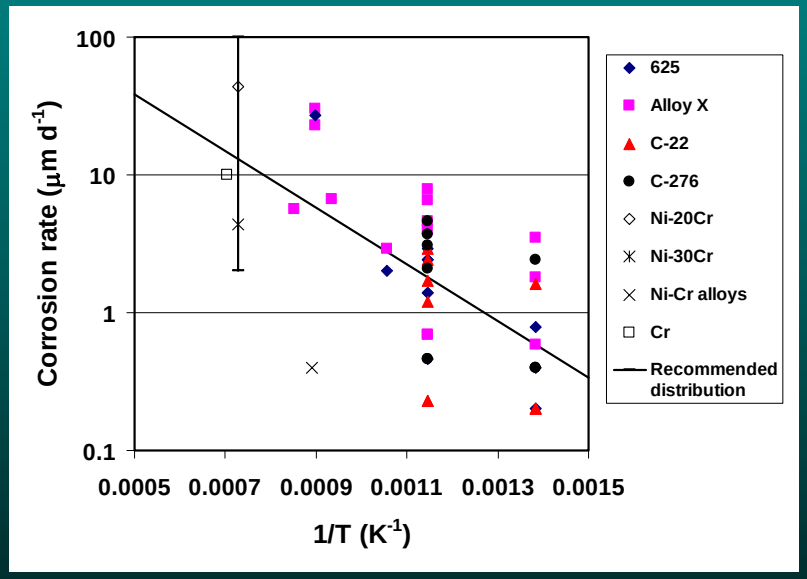
- Pressure inside waste packages increases from temperature
- If pressure exceeds threshold, failure may occur
- Material strength decreases at increasing temperature
- Internal pressure is offset by static pressure exerted by column of magma
  - After very short time, stress on waste package becomes compressive
  - Range of magma conditions considered
- Waste package does not fail from overpressure

# Creep Failure

- Creep data for Alloy 22 are not available (>900ºC); extrapolation from lower temperature necessary
- Contact temperatures of magma on the waste package are expected to be lower than has been considered by DOE or NRC
- For creep rupture to occur, the shell must be able to accumulate sufficient strain
- Creep failure of the Alloy 22 shell is unlikely because geometrical constraints limit the strain

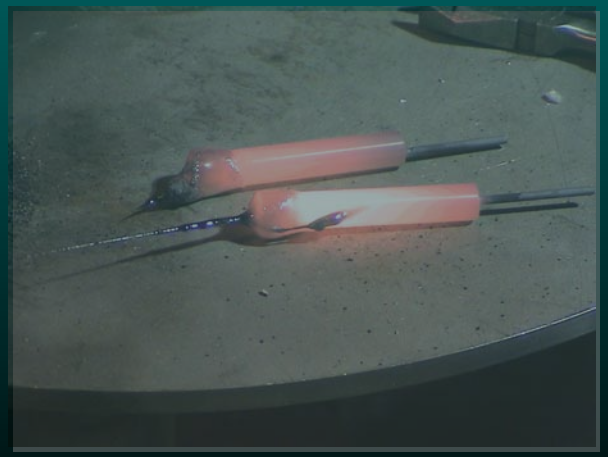
# Corrosion in Molten Magma

- Limited available data in magma
- Evaluation of literature data on Ni-Cr alloys in molten electrolytes
- Probabilistic analysis of corrosion based on literature data
- Alloy 22 samples were immersed in magma



# Results ~ 1 Hour Exposure

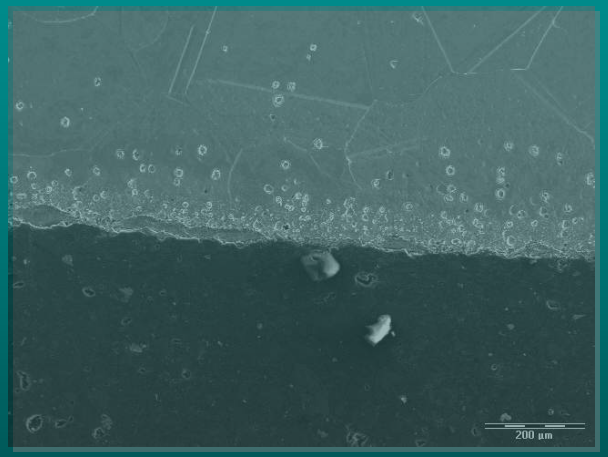
- Alloy 22 sample being removed from graphite crucible
- Magma solidifies within seconds

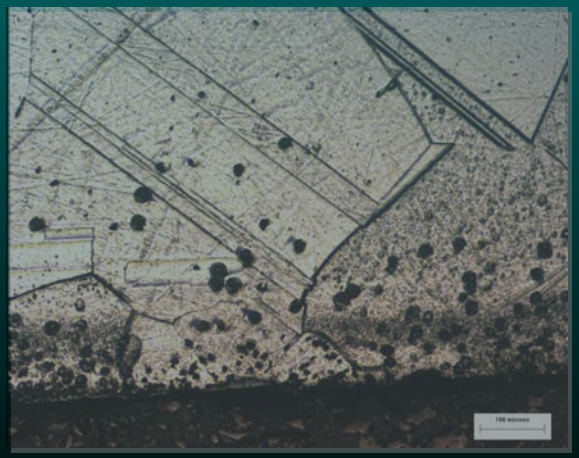


# Results ~ 1 Week Test

- "Old" magma used with inert gas purge for all 1 week+ tests.
- C22 remained intact during test and showed surface voiding
- No apparent evidence of Inter-granular Attack (IGA)

(top:~ 125X, lower:~ 250X )

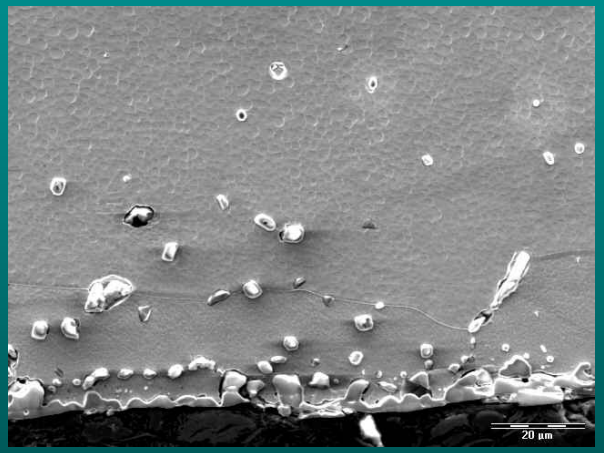


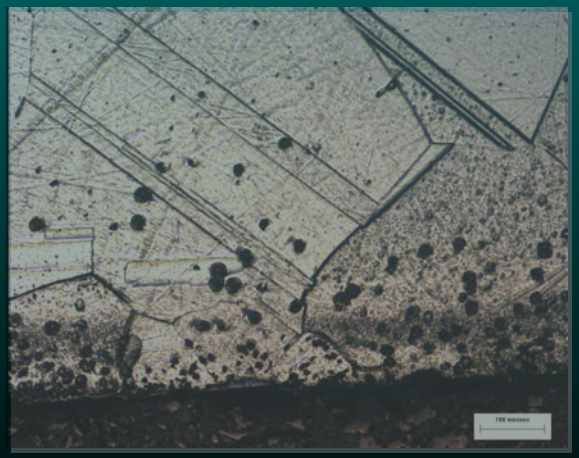



# Results ~ 2 Week Test

Top: 1000X of surface voids/inclusions.
Bottom: 200X with 225 micron bar

- Very similar results to 1 week test with increase in void/inclusion density.
- No evidence of Inter-granular Attack



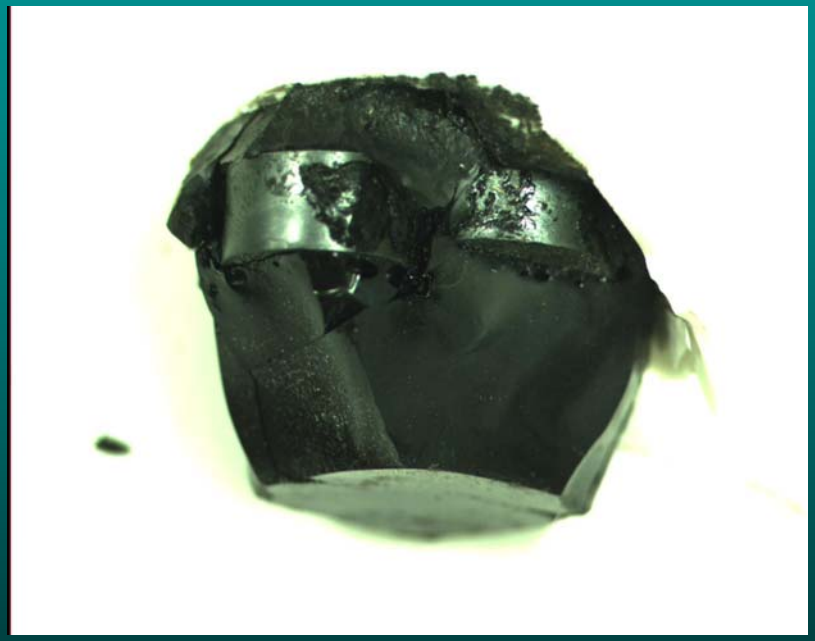



# Results ~ 1 Month Test

- Surface voiding was more extensive and deeper, up to 600 microns from surface
- No evidence of IGA or other degradation.

# The Net Result of Magma Contact

- C-22 shell not breached
- Inner steel shell not breached
- Waste package is embedded in basalt
- Potential increased corrosion rates
  - Leads to increased releases over time scales longer than the eruption
  - To be evaluated in intrusive scenario evaluation



# Conclusion:

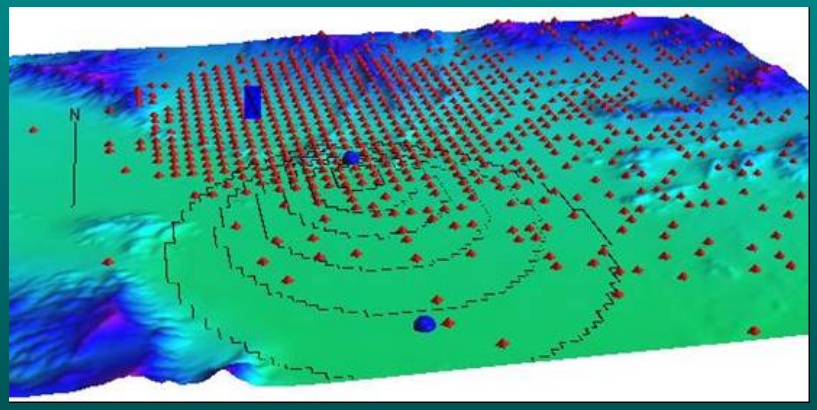
**There is reasonable expectation that no waste packages will fail during a postulated igneous event at Yucca Mountain**

# Additional Parts of the Analysis

- Ash dispersal modeling
- Biosphere analysis
- Sensitivity studies
  - Conditional results based on the assumption that releases occur
  - Intended to demonstrate defense in depth from each part of the system

# Ash Dispersal Modeling

- Evaluation with multiple models
  - ASHPLUME (TEPHRA)
  - BENT
  - PUFF
  - ATHAM
- Focus on results from TEPHRA
- Many realizations showing negligible accumulation
- ASHPLUME overestimates accumulations compared to other extant models
- Particle sizes at the receptor >> respirable size




Comparison of TEPHRA and PUFF

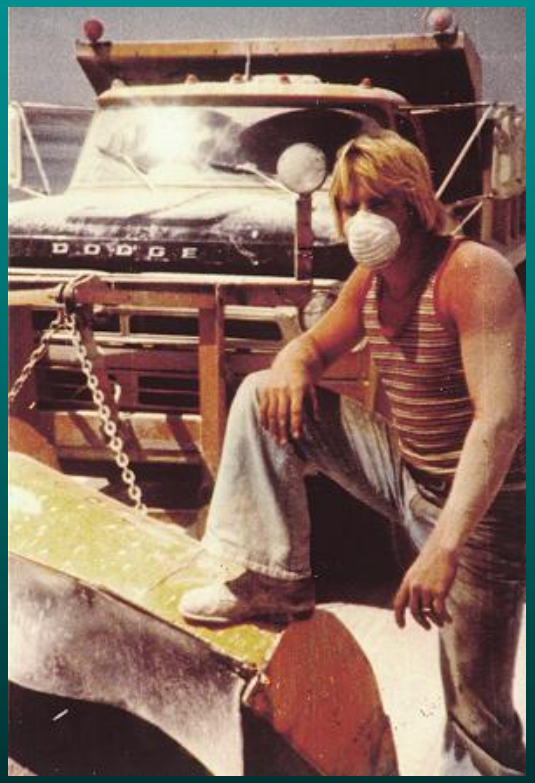
# Biosphere Modeling

- Use of past analogues
  - Human behavior in the aftermath of eruptions
  - Variation in behavior depending on depth of ash accumulation
  - Emergency preparedness plans throughout the Western US
- Conclusion: People clean up in the aftermath of an eruption
- This differs from assumptions by DOE and NRC

Cleanup activities following Mt. Pinatubo eruption

# Implications

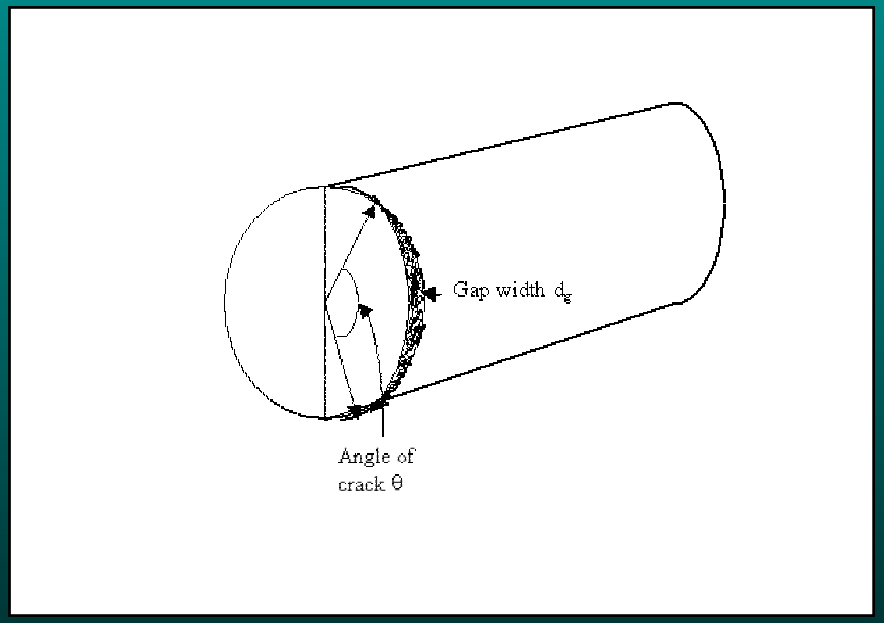
- Dose is predominantly in the first year
  - Doses do not need to be superposed over long time periods
  - Different pathways in first year and in later years
  - Several later years evaluated
- Ash particulates are not respirable
- BDCFs evaluated for differing particle size ranges and differing deposition thicknesses




Use of masks during cleanup

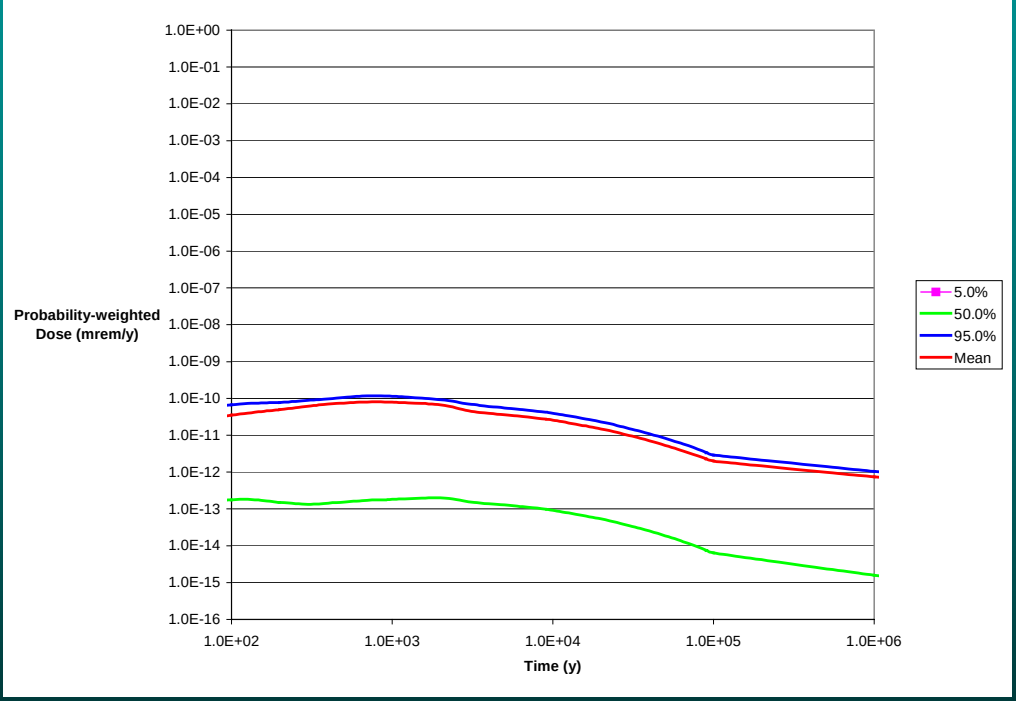
# Conditional Analyses
## Exploring Alternative Assumptions

- Assumes failure of waste packages in the vent
  - The dike is not diverted by thermally-generated stresses
  - The waste package does not limit releases from the fuel
  - No cleanup of ash occurs at the compliance point
  - Ash fall of respirable particles
  - Vents can form in between drifts
- Carried out in spite of the zero release assessment



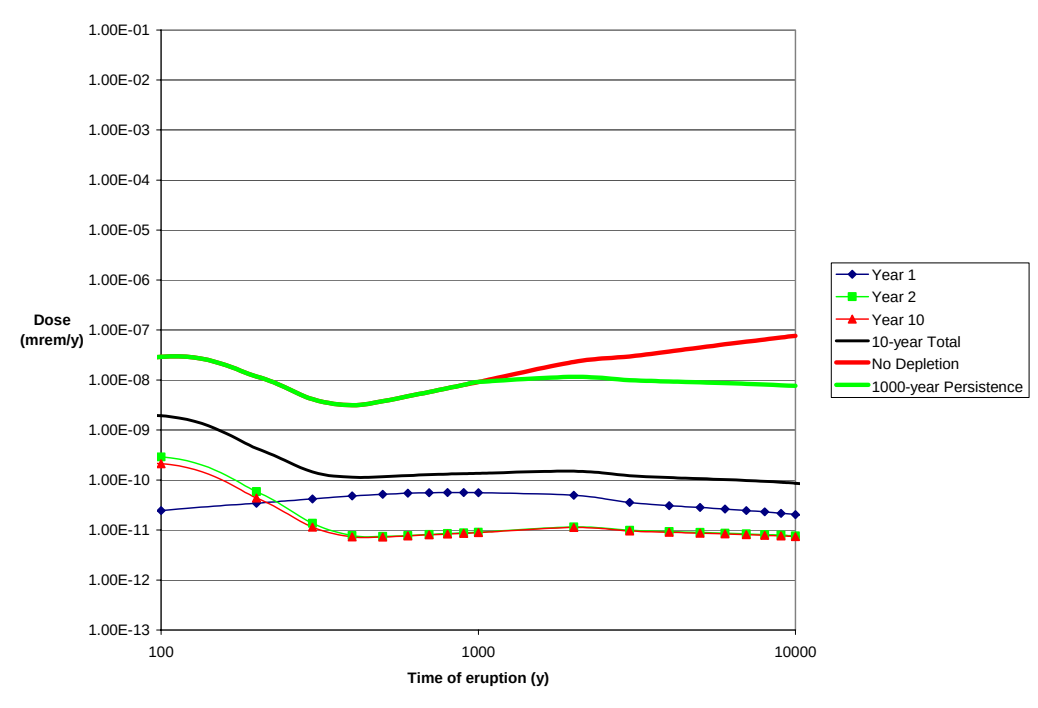
# Conditional Case 1

- Between 1-9 waste package failures
- Temperature dependent dike diversion
- About 9 orders of magnitude < TSPA-SR



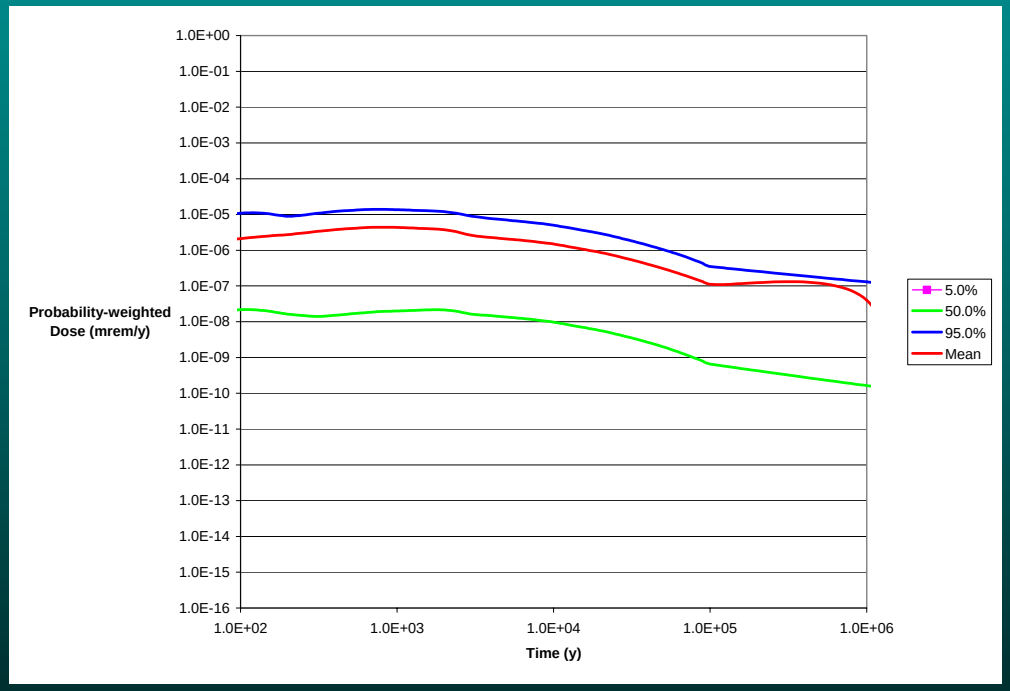
# Persistence in the Environment

- The EPRI analysis is not set up to evaluate this
- Carried out in an approximate manner
- Uses a conservative approach
- Increases doses 2-3 orders of magnitude
- Leads to very low doses (9 orders of magnitude below the dose standard)



# Effect of Waste Packages

- Assumes fully failed waste package
- Increases doses 5 orders of magnitude
- Leads to very low doses (6 orders of magnitude below the dose standard)

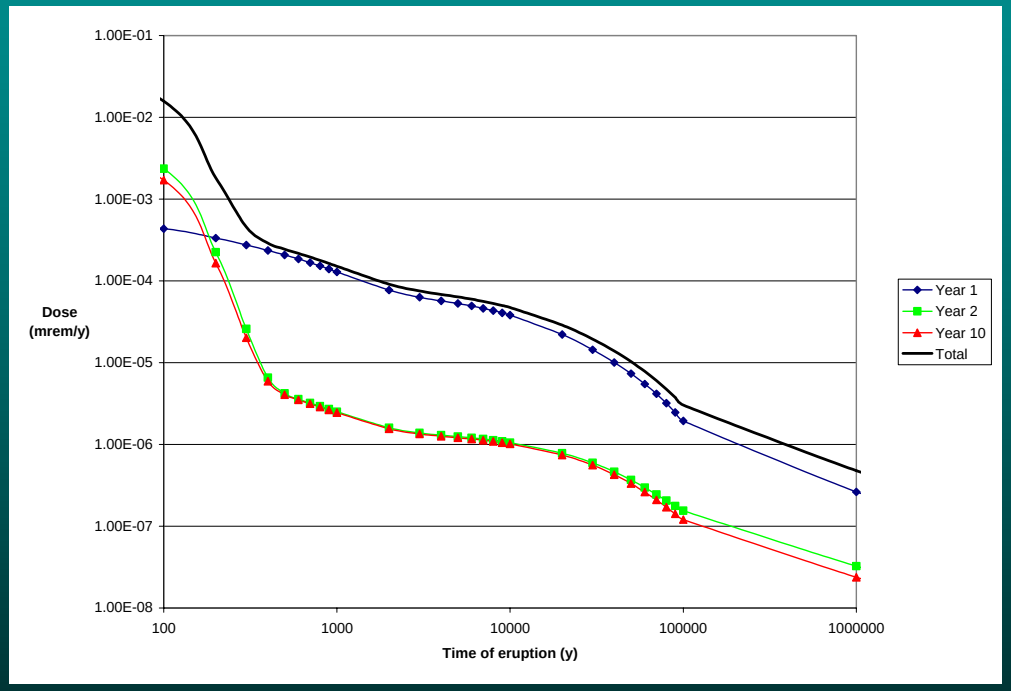


# Miscellaneous Effects

- Effect of Dike Diversion
  - Full dike diversion: zero dose for 2000 years, no effect thereafter
  - No dike diversion: < 1 order of magnitude increase
- Particle size respirable < 1 order of magnitude increase
- Conditional probability of a vent between drifts < 1 order of magnitude decrease

# Compounding Conservatisms

- Combine all of the conservatisms in our conditional cases
- Assume 10-year persistence in the environment
- At early times, the analysis approaches TSPA-SR doses
- Demonstrates the relative effect of each part of the analysis in providing conservatism



# Summary

- Reasonable expectation approaches lead to zero release during the eruption
- Multiple failure mechanisms for the waste package were examined
- Credible waste package failure was not found in any circumstances

# Key Lines of Evidence for Zero Release

- Conditions at the drift level are less extreme than has been assumed previously by the NRC and DOE.
  - Magma entering the drifts is less violent than has been assumed in the analyses of DOE and NRC
  - Conclusions drawn by Woods et al. (2002) have been discredited
- The waste package provides a very significant barrier to release
- Magma entering the drifts will cool and solidify to isolate the dike

# Conclusions

- DOE's analysis is seen to be extremely conservative
- Despite these conservatisms, the DOE analysis is seen to comply with the applicable regulations
- Any potential changes to the DOE analysis will significantly decrease calculated doses
- The EPRI analysis was able to demonstrate the amount of conservatism introduced by various part of the analysis