# THE COLLECTION AND USE OF EXPERT JUDGMENT FOR THE ANALYSIS OF HUMAN INTRUSION AT WIPP

**Presented to**

**National Academy of Sciences Review Panel**
**June 7, 1990**

**by**

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The goal of expert opinion elicitation is to encode beliefs into probability distributions. Expert judgment is used to determine what we know as well as what we know we do not know.

Codifying expert judgment as probability distributions does not create information or make the judgments inherently more accurate, but it does put the information in a form that makes the judgments amenable to the power of mathematical manipulation.

The human mind is the best available instrument for combining disparate, and perhaps conflicting sources of information.

Expert judgment is pervasive in complex analyses.

In an uncertainty analysis, care should be taken to use techniques that do not suppress diversity of viewpoints or understate the inherent uncertainty.

The use of carefully selected external experts can help insure the consideration of alternative viewpoints and elevate the credibility of the effort.

# COMPONENTS OF A EXPERT OPINION PROCESS

Issues
Experts
A strategy for organizing the experts
Elicitation procedures
Procedures for processing assessments
Documentation
Coordination and logistics

# SELECTION OF EXPERTS

## Substantive Experts

- Possession of or access to exceptional knowledge
- Recognition in the field
- Freedom from motivational biases
- Willingness to participate and accept responsibility
- Diversity of opinion among multiple experts
- Physical location of the experts may be important for teams

# NOMINATIONS OF EXPERTS

- Literature searches
- Professional organizations
- Research institutes
- Government organizations
- Public interest groups

# STRATEGIES FOR ORGANIZING THE EXPERTS

Individual expert(s) responding to isolated questions

Groups of experts responding to similar questions

Panels of experts exchanging information

Teams of experts analyzing a complex problem

# CONSIDERATIONS WHEN SELECTING A STRATEGY

Breadth of knowledge required

Potential diversity of approaches

Problem complexity

Communication requirements

The amount study and research required

Logistics and time requirements

# ELICITATION PROCEDURES

Preparation for elicitation
- Training of experts
- Issue definition, description, and decomposition
- Dissemination of supporting materials
- Scheduling and logistics

Elicitation methods
- Instruments
- Feedback and modification procedures
- Documentation of elicitation sessions

# DOCUMENTATION

The elicitation process
Implementation
Findings
Rationales

# COORDINATION AND LOGISTICS

Scheduling personnel
Physical facilities
Post elicitation activities

# TRAINING OF EXPERTS FOR ELICITATION

Training objectives

- Provide an overview of the process
- Develop confidence
- Introduce experts to the tasks they must perform
- Instill awareness and control of biases
- Practice making probabilistic judgments

# TYPES OF BIASES

Overconfidence
Availability
Anchoring
Optimism
Failure to consider base population rates
Failure to identify alternatives (completeness)

# SOME THOUGHTS ON TRAINING

Many scientists are skeptical of expert judgment because they believe it is a substitute for experiments and observation.

Proper training is essential for the acceptance of the process. Properly trained participants become supportive of the process.

Whenever possible, training should be customized to the issues and participants. Examples should be developed that mimic the tasks to be performed.

Training should be interactive and hands-on.

Four or more hours of training are usually required.

# TYPES OF ASSESSMENTS

- Judgments about facts versus judgments about values
- Creation of Scenarios
- Decompositions of problems
- Continuous variables versus discrete variables or events
- Dependencies among variables
- Direct versus indirect assessment tools

## SOME THOUGHTS ON ASSESSMENTS

Development of scenarios is a creative activity. Completeness becomes an important issue.

The rationale for an assessment must be well documented if the assessment is be trusted.

Differences among assessments should not be suppressed. They are among the most important findings of an uncertainty analysis.

## SOME THOUGHTS ON THE ELICITATION SESSIONS

Elicitation teams with a normative expert, a substantive expert who is a project analyst, and a documentalist seem to work well.

A very clear definition of the problem statement is required -- no ambiguities. Can the statement pass the clairvoyance test?

The rationale for the judgments is often as important or more important than the quantitative judgments.

# DECOMPOSITION OF COMPLEX PROBLEMS

Decomposition replaces a single difficult assessment with several easier assessments.

Decomposition is thought to yield better calibrated distributions.

The decomposition may be more important in determining the resulting distribution than the individual assessed distributions.

Decomposition forces explicit rationales for assessments.

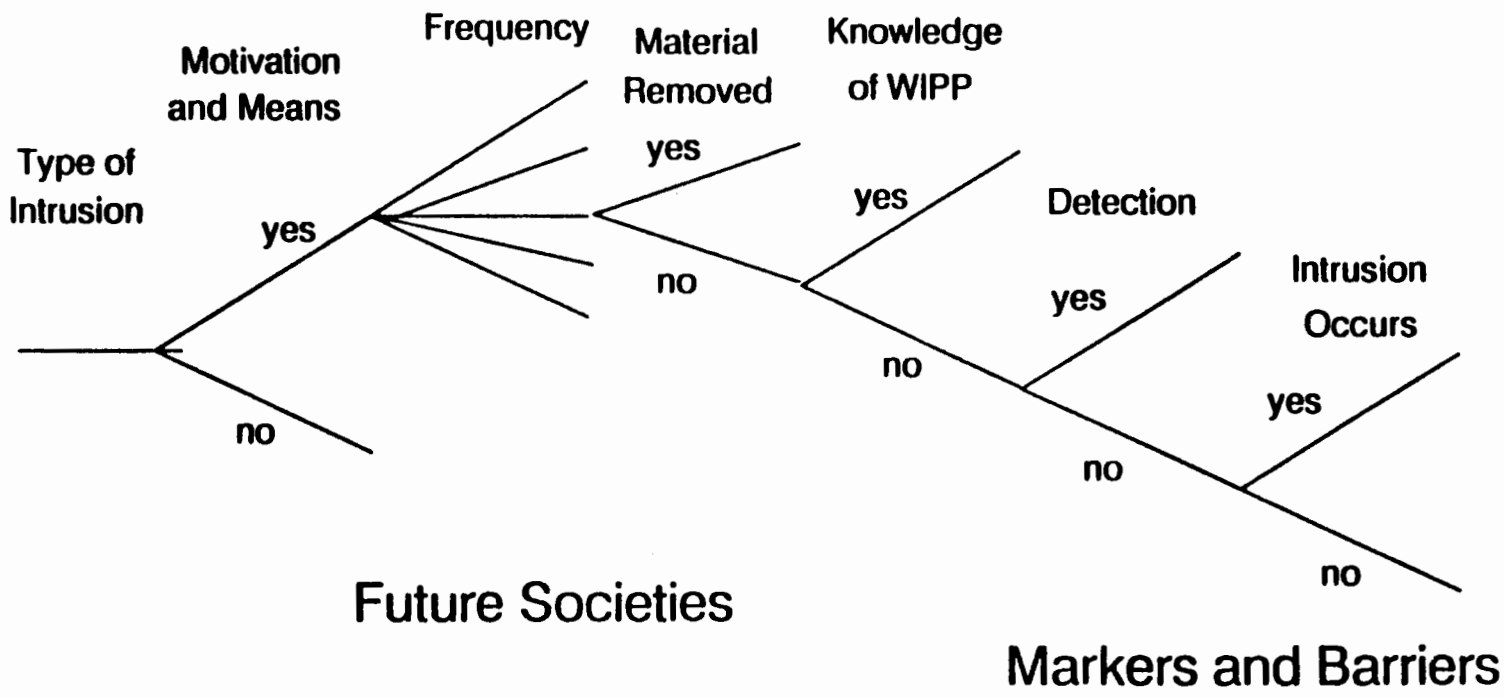
Differences in individual decompositions explain the uncertainty about the top event. Don't force all experts to use the same decomposition.

# PROPOSED STRUCTURE FOR THE WIPP EFFORT

## Distinct issue areas

- Possible states of future societies and the activities that could result in an inadvertent intrusion.
- Markers to prevent intrusion.
- Barriers to prevent intrusion.

# Logic Tree for Future Intrusions
# Given Time, Society, and Mode of Intrusion



# TENTATIVE SCHEDULE EXPERT ELICITATION ACTIVITIES
# HUMAN INTRUSION INTO WIPP

| Future of Society | Markers | Barriers |
|---|---|---|
| Request for Nominations May 15 | | |
| Letter to Nominees May 23 | | |
| Selection June 11 | | Begin Study of barriers to intrusion July 1 (if needed) |
| | Request for Nominations July 13 | |
| | Letter to Nominees August 3 | Request for Nominations August 3 |
| First Meeting August 13-15 | Selection August 17 | Letter to Nominees August 17 |
| Second Meeting October 10-11 | First Meeting October 10-12 | Selection August 31 |
| Processing Finished Nov 10 | | |
| | Second Meeting December 11-12 | First Meeting December 12-14 |
| Documentation Complete January 31 | Processing Complete January 31 | |
| | Documentation Complete March 3 | Second Meeting February 12-13 |
| | | Processing Complete March 30 |
| | | Documentation Complete May 4 |

# IDENTIFICATION OF INTRUSIVE ACTIVITIES

The types of potential intrusions depend upon the state of society.

- Technology
- Resource utilization
- Population

Alternative projections of basic trends.

Identification of events that may modify these projections.

Identification of scenarios that may result in a loss of knowledge about nuclear waste disposal and the technology to detect nuclear waste prior to intrusion.

Assessment of completeness.

# ASSESSMENTS OF THE FUTURE

Alternative Futures and Their Likelihoods
- Futures that preclude intrusion
- Futures that permit intrusion
- Futures that cannot be conceived

Judgments about:

Modes and numbers of intrusions

Persistence or rediscovery of information about WIPP

Technology to detect nuclear waste

The continuing existence of nuclear waste at WIPP

# FUTURES THAT PRECLUDE INTRUSION

Information about WIPP persists

Technology to detect nuclear waste exists and is used

Society does not perform potentially intrusive activities

The radioactive material has been removed or rendered harmless

# ORGANIZATION OF THE EFFORT TO ACCESS FUTURE SOCIETIES AND MODES OF INTRUSION

Multidisciplinary teams of experts
Three to four experts per team
Four teams of experts

Disciplines (examples)

Demography
Human Ecology
Environmental Sciences
Anthropology
Economics
Political Science
Exploration geology
Agriculture
Futurology
Sociology

# Format of Meetings

## First Meeting

- Introduction to issues
- Discussion of literature
- Approaches to the problem
- Visit to the WIPP site

## Off-site meetings

- Teams meet several times during a two month period

## Second Meeting

- Two days of presentation of assumptions and findings
- Elicitation of probability distributions

## Publication of position papers

# ASSESSMENTS OF THE FUTURE

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# FUTURES THAT PRECLUDE INTRUSION

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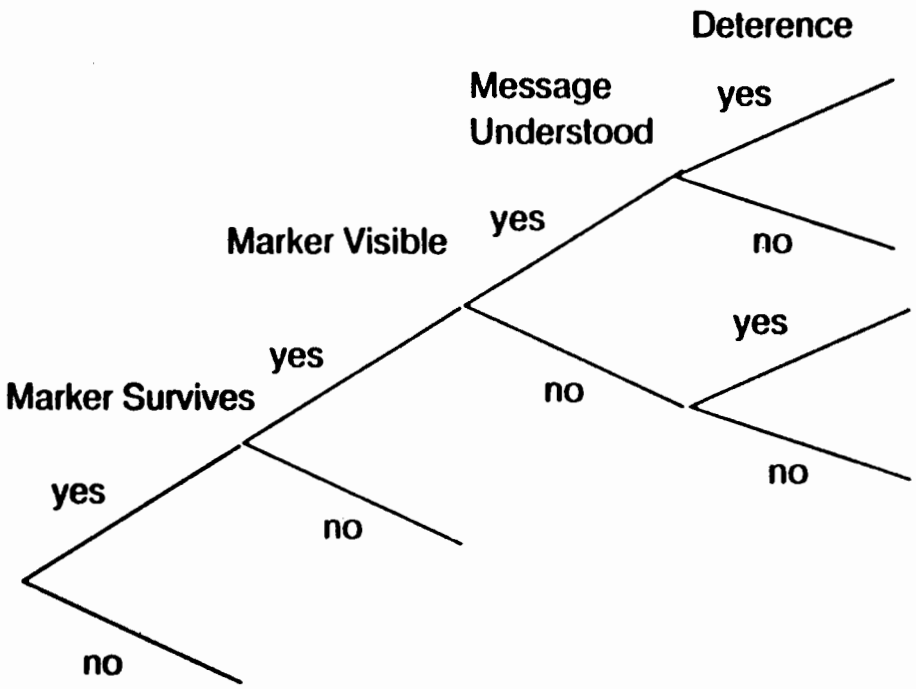
# EXPERT PANEL FOR MARKERS TO DETER HUMAN INTRUSION

Panel of six to ten members from the following disciplines:

Linguistics
Semiotics
Materials science
Human factors

Archeology
Anthropology
Climatology
Psychology

# Logic Tree for Deterrence by Markers
# Given Time, Society, Mode of Intrusion, and Marker Criteria



## Analysis Subject to the Findings of the Analysis of Future Societies

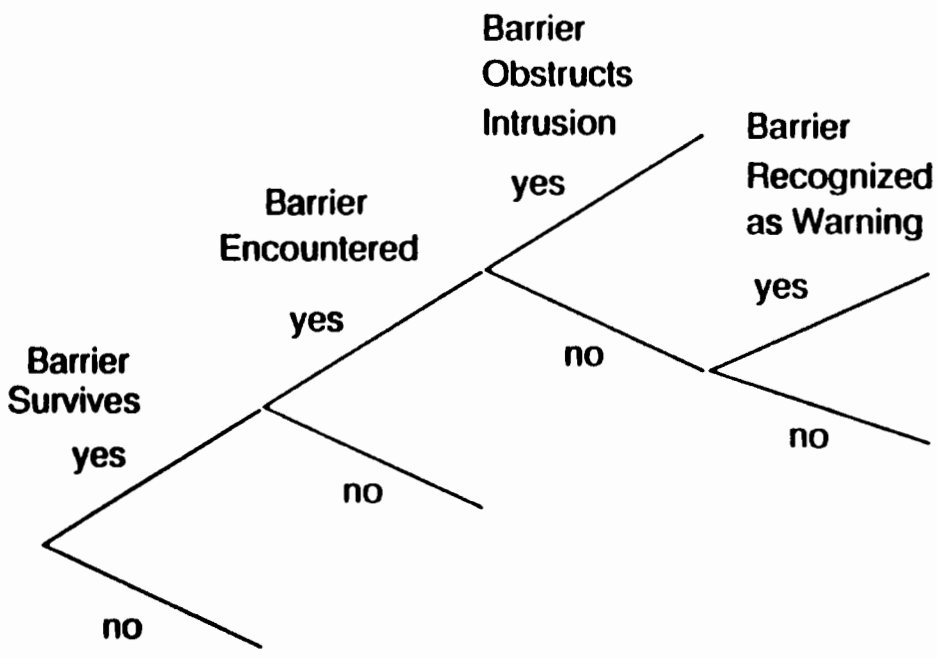
## Assumptions

- Modes of intrusion
- States of Society (knowledge, technology, etc.)

# EXPERT PANEL FOR BARRIERS TO PREVENT HUMAN INTRUSION

The design is dependent on the findings of the preliminary study.

# Logic Tree for Obstruction of Intrusion by Barriers Given Time, Society, Mode of Intrusion, and Barrier Criteria



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# Performance Assessment Presentations

June 7, 1990

WIPP Panel
Board on Radioactive Waste Management

by

D. R. (Rip) Anderson
M. Marietta
J. Helton

# Mini Agenda for PA NAS June 7, 1990

## Improvements to the PA computational system

- SECO2D (Regional and Local)
- STAFF2D (Transport)
- GENII
- Modules for:
  - Cuttings and eroded material
  - Pressurized Castile brine
  - Time-varying Salado brine inflow
  - Intrusion borehole including closure
- Empirical distributions for:
  - Culebra conductivities, porosities and retardations

# Mini Agenda for PA NAS June 7, 1990

**Planned Improvements in Conceptual Model (for Dec. 1990)**

- New data included
- SECO/STAFF - replace SWIFT & NEFTRAN
- HI multiple hit capability
- Different conceptual model for Culebra transport
- Geostatistical techniques for Culebra sampling
- Include complete brine pocket model in system
- Include crude room model with gas effects
- Sophisticated room models for parallel calculations
- Include passive marker systems

# Mini Agenda for PA NAS June 7, 1990

## Improvements in Compliance Assessment System (June 1990)

- New data
- Scenarios
- 2D-Transport in Culebra
- Dual Porosity in Culebra
- Climate variability
- Human Intrusion Borehole
  - Plug
  - Diameter
  - Time - regulation default value
  - 1 Intrusion
  - Cuttings & Eroded Particles - Model

- Brine Pocket
  - Pressure
  - Flow

- Waste Room
  - Pressure
  - Flow

# Mini Agenda for PA NAS June 7, 1990

**Results**

- **Sensitivity/Uncertainty Analysis**
- **Compliance CCDF's**
- **Risk**

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# WIPP Interface
# With International Programs

E. D. Gorham, Division 6344
J. R. Tillerson, Division 6346
D. R. Anderson, Division 6342

Sandia National Laboratories

# Interface With International Programs

Purpose

- Technology Exchange/Evaluation
- Code/Model Validation

# Agencies or Countries of Interest

NEA/OECD

Sweden

Federal Republic of Germany

Netherlands

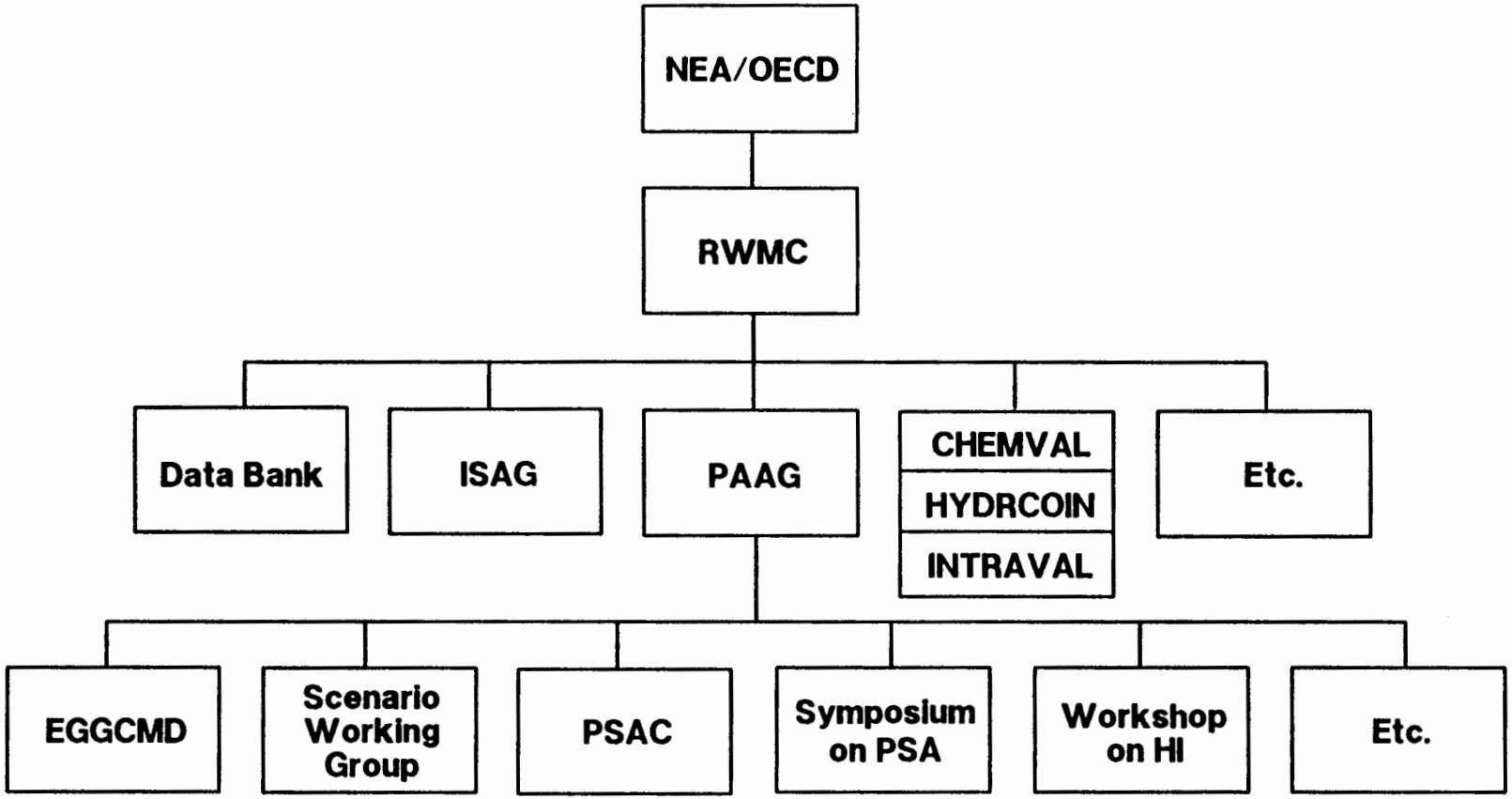
Canada

France

United Kingdom

Russia

# Partial NEA Organizational Structure




RWMC - Radioactive Waste Management Committee
NEA - Nuclear Energy Agency
ISAG - International Site Assessment Group
PAAG - Performance Assessment Advisory Group
EGGCMD - Expert Group on GeoChemical Model Development
PSAC - Probabilistic Safety Assessment Committee
PSA - Probabilistic Safety Assessment

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# Code/Model Validation

INTRAVAL Phase I and II

CHEMVAL

GEOVAL

# INTRAVAL Phase II

- Oriented towards flow and transport
- Phase II emphasizes PA orientation and issue resolution
- Managed by SKI (Swedish Nuclear Inspectorate)
- Participation via submission of test cases/work on test cases
- WIPP did not formally participate in Phase I
- WIPP has obtained formal participation in Phase II by submitting test case

# WIPP Salt Test Case

(See detailed handout)

- Does Darcy Flow from infinite, connected matrix describe brine flow in bedded evaporites?

- Integrated selected set of data
  - Pore pressure, permeability data in clay seam and anhydrite layer
  - Small scale brine inflow data
  - Selected Room Q data
  - All data in salt potentially available
  - Possible additional experiments

- Possibly investigate within Salt Working Group by
  - FRG
  - RIVM (National Institute of Public Health and Environmental Protection)
  - France

# WIPP Rock Mechanics and Sealing Programs - Principal Foreign Interactions

## Rock Mechanics

- Primary areas of exchange
  - Constitutive modeling of salt and crushed salt
  - Application of numerical models
- Countries
  - Federal Republic of Germany
  - Netherlands
  - France
- Mechanisms
  - Workshops on constitutive modeling
    Hannover, 1989
    Auchen, 1991 (planned)
  - Committee on constitutive modeling
  - Direct interactions
    WIPP visits - FRG (K. Kuhn and Associates),
    French (CEA-Saclay, ANDRA)
    European visits - 1989, 1990

# WIPP Rock Mechanics and Sealing Programs - Principal Foreign Interactions

## Rock Mechanics (cont.)

- Highlights
  - Benchmark exercises for geomechanical codes completed
  - Viscoplastic models of salt and crushed salt behavior proposed (thermal, elastic, and secondary creep included)
  - Stressmeters provided for pillar tests at Asse
  - Laboratory test specimens exchanged

# WIPP Rock Mechanics and Sealing Programs - Principal Foreign Interactions

## Sealing

- Primary areas of exchange
  - Bentonite behavior
  - Salt consolidation
  - Seal design concepts
  - Large-scale seal tests

- Countries
  - FRG, Netherlands, Sweden, Canada

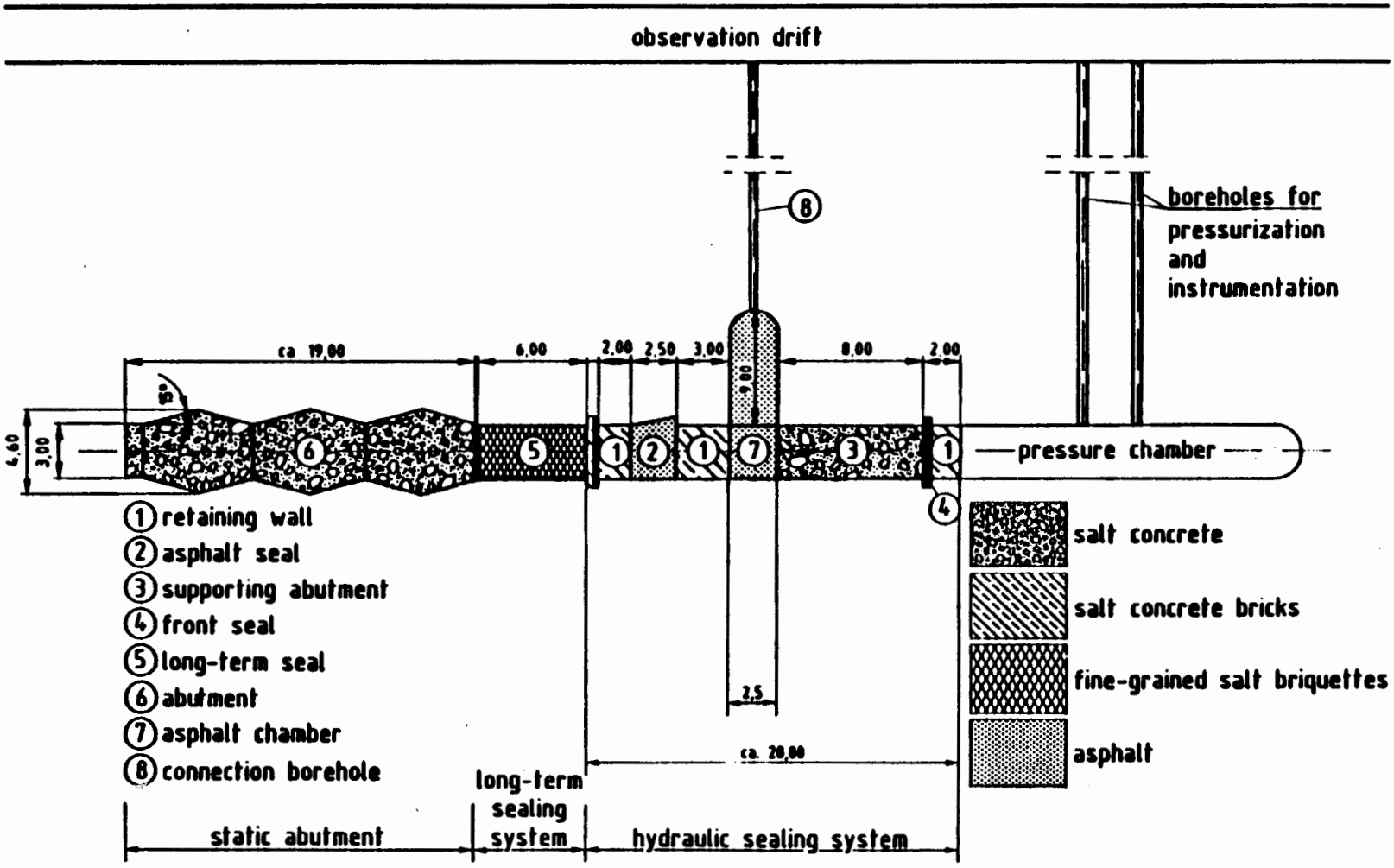
- Mechanisms
  - NEA/CEC workshop on sealing
  - Stripa program interactions
  - Direct interactions
    European visit - 1989

# WIPP Rock Mechanics and Sealing Programs - Principal Foreign Interactions

## Sealing (cont.)

- Highlights
  - Lab and in situ data indicate host rock creep significantly effects crushed salt consolidation but back pressure on host rock is negligible
  - Bentonite testing (mostly in granite) indicates tight interface can be maintained, wetting proceeds at rate predicted by diffusion-type models, and fractures can be penetrated and sealed
  - Salt sealing concepts very similar
  - Large-scale seal test planned in Asse Mine
    - Multiple organizations (BGR, DBE, GSF)
    - Test design completed
    - Pretest characterization nearly complete
    - Test dam to be built and instrumented in 1990/1991 - with ensuing measurement phase

# Proposed Test Dam in Asse Mine



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# PROPOSAL FOR THE WASTE ISOLATION PILOT PLANT SALT TEST CASE INTRAVAL PHASE II

## I. INTRODUCTION

### A. Pilot Group

The name of the Pilot Group is the United States Department of Energy Waste Isolation Pilot Plant in Carlsbad, New Mexico, USA, 88221. The pilot group leader is Jerry Carr, Hydrologist, Waste Isolation Pilot Plant, Carlsbad, New Mexico, USA, 88221. The alternate pilot group leader is Vernon Daub, Manager, Waste Isolation Pilot Plant, Carlsbad, New Mexico, USA, 88221.

The technical contact is Elaine D. Gorham, Supervisor, Fluid Flow and Transport Division 6344, Sandia National Laboratories, Albuquerque, New Mexico, USA, 87185.

As the first underground repository in the USA for disposal of radioactive wastes, the Waste Isolation Pilot Plant (WIPP) is subject to rigorous scientific scrutiny. Validation of WIPP computer models used to resolve technical issues important to performance assessment is of great interest to Sandia National Laboratories and the US Department of Energy. Both Sandia National Laboratories and the Department of Energy are committed to such validation. INTRAVAL provides an opportunity to discuss validation methods, participate in varies validation activities, and obtain validation of some WIPP models. The Department of Energy expects its commitment to validation and the INTRAVAL to continue throughout Phase II of INTRAVAL. This commitment includes participation in test cases addressing technical issues that be of importance to WIPP performance assessment. The Department of Energy's commitment to the WIPP Salt Test Case includes data and modeling support from Sandia National Laboratories, timely submission of data from ongoing experiments, adjustments of ongoing experiments, and possible new experiments if needed to resolve test case issues. The Department of Energy and Sandia National Laboratories are committed to a high level of interaction between test case modelers and the Sandia experimental team.

### B. Experiment Location and Brief Description

The WIPP, located in Carlsbad, southeastern New Mexico, USA, is an underground research and development repository intended to demonstrate that radioactive wastes can be safely disposed in bedded salt. The WIPP, scheduled to open in late 1990, is planned to be a permanent repository for low-level and transuranic wastes generated by United States defense programs.

Sandia National Laboratories supports the Department of Energy with scientific research on issues related to performance assessment and compliance with US Environmental Protection Agency standards. A number of technical issues are important to the WIPP's performance. One issue, the

rate of brine flow through WIPP bedded evaporites, provides the basis for the proposed test case. A related issue is the rate of gas flow through the bedded evaporites.

The WIPP repository lies 655 m below ground surface within bedded evaporites, primarily halite, of the Permian Salado Formation. Three geologic formations are important to the expected performance of the WIPP: the Salado Formation, in which the repository is located; the Rustler Formation, which contains an aquifer overlying the Salado Formation; and the Castile Formation, which underlies the repository and contains pockets of pressurized brine. Field experiments are conducted in all three formations. The Salado Formation's hydraulic behavior is the focus of the present test case.

This test case is based on experiments to determine the nature of brine flow through the Salado Formation. The experiments are designed to provide a variety of data with which to determine whether Darcy's Law for a porous, elastic medium correctly describes the flow of brine through evaporites, or whether a different model is more appropriate. The test case is concerned with the validation of models used in test interpretation and in modeling of brine inflow to the WIPP repository.

The test case will obtain data from three types of experiments: small-scale brine-inflow experiments; pore-pressure and permeability experiments; and a large-scale integrated experiment. The brine-inflow experiments consist of in situ experiments on a variety of small scales in a variety of locations throughout the repository and intersecting a variety of strata. The pore-pressure and permeability experiments also intersect a variety of strata throughout the repository. The large-scale integrated experiment combines the measurement of brine inflow to a room-sized excavation with pore-pressure measurements and permeability experiments in the surrounding strata. Because the total quantity of data available from these experiments is very large, only selected data will be submitted as part of the test case. However, all data will be described and made available to test-case participants upon request.

Small-Scale Brine-Inflow Experiments. Brine-inflow rates are being measured at three scales: in 10-cm-diameter boreholes, in 1-m-diameter boreholes, and in a 2.9-m-diameter cylindrical room. The 10-cm- and 1-m-diameter boreholes are oriented vertically downward or horizontally, and extend from 3 to 6 m. The boreholes are open their entire lengths, and are sealed between inflow measurements to prevent moisture loss through evaporation and air circulation. In some cases, humidity measurements aid in quantifying the total moisture entering a borehole. Data are also available from chemical analyses of brines collected.

Brine-inflow measurements in 10-cm-diameter boreholes generally show rapidly declining flow rates for the first few months, followed by steady or slowly declining flow rates for periods as long as 2 years. Initial inflow rates have ranged from about 5 to 25 g/day, while steady flow rates range from about 2 to 10 g/day. The WIPP Salt Test Case will initially include data from experiments DBT10, DBT11, DBT12, and DBT13 (see Figure 1). Figure 2 shows example data from DBT11. Additional data from these

ongoing experiments will be made available. Brine-inflow rates to the 1-m-diameter boreholes are more erratic. Horizontal holes drilled into pure halite have not yielded any brine at all, although the humidity data evince levels near that known to be in equilibrium with free brine. Data from a horizontal 1-m-diameter experiment and a horizontal 10-cm-diameter experiment drilled into argillaceous halite will also be included in the test case.

**Pore-Pressure and Permeability Testing.** Pore-pressure measurements are made in 10-cm-diameter boreholes 2 to 27 m long drilled at a variety of orientations. Pore pressures are measured in brine-filled, packer-isolated intervals of the boreholes. Factors other than the formation pore pressure that could contribute to pressures observed in a borehole (e.g., temperature changes and borehole closure) are also monitored.

Observed pore pressures range from 0.3 MPa (measured within 2 m of a room) to 11.6 MPa (measured more than 22 m from a room). The lithostatic pressure at the depth of the WIPP repository is 14.8 MPa. In general, a depressurized zone appears to exist around the repository, but a continuous pressure gradient has yet to be defined. Stratigraphic heterogeneity may have a major effect on observed pressures. For instance, pure halite units having permeabilities too low to measure may prevent propagation of pressure transients between overlying and underlying units.

Permeability experiments are also conducted in the 10-cm-diameter boreholes. Both pressure-pulse tests and constant-pressure flow tests are used to determine permeabilities. Double-packer tools are used to measure pressures and temperatures both in the test interval between the bottom packer and the bottom of the hole and in the guard zone between packers. Packer pressures, radial borehole deformation, and borehole elongation are also measured. Flow rates during the constant-pressure flow tests are measured using differential transducers connected to pressurized vessels of different sizes. All data are collected on computerized data-acquisition systems.

During the pressure-pulse tests, gas tends to accumulate in the boreholes. This gas is thought to evolve from Salado Formation brine in response to the lower pressures around the borehole relative to those in the far field. Gas volumes are measured during pulse withdrawals and at the end of testing, and gas compositions are analyzed.

Pressure-pulse tests have been interpreted using a Darcy flow model, and have provided permeability estimates for argillaceous halite between $10^{-20}$ and $10^{-22}$ $m^2$. However, some tests show apparent hydraulic boundary effects within only 1 to 2 m of the borehole. Anhydrite interbeds are locally fractured, and have permeabilities 2 to 3 orders of magnitude higher than that of the argillaceous halite. No hydraulic responses have been observed in pure halite that are interpretable in terms of permeability.

The WIPP Salt Test Case will initially include two sets of permeability and pore-pressure experiments from argillaceous halite layers (tests in holes

SOP01 and L4P51). One set demonstrates apparent hydraulic boundary effects and one does not. Figures 2 through 11 show part of the data set from SOP01. Data from an interval including one of the important anhydrite layers and an associated clay seam will be included later.

**Integrated, Large-Scale Experiment.** A horizontal cylindrical room has been mined to a length of 107 m (see Figure 12) for the purpose of measuring brine inflow to a room-sized excavation. The room intersects five distinct stratigraphic units and slopes slightly upward from front to back to follow the natural dip of the bedding. The room diameter is 2.9 m. The cylindrical brine room was mined in July 1989 and sealed in October 1989. Humidity within the room is now being measured. Salt efflorescences resulting from brine evaporation on the surface of the room are regularly mapped. Amounts of brine collecting in the room will also be regularly measured, although as of May 1990, no brine had yet appeared in the room.

Before the cylindrical brine room was mined, 15 4-cm- and 10-cm-diameter boreholes 23 to 25 m deep were drilled in the rock surrounding the planned entrance to the room. The holes were angled so as to all end at a plane normal to the axis of the room at a distance of 23 m into the room while defining lines of measuring points above, below, and horizontally away from the room at distances ranging from 2.4 to 13.7 m from the centerline of the room (see Figure 13). The holes were instrumented with packers and other instruments to allow monitoring of pore pressures and borehole diameters in test zones at the end of the boreholes, and to allow permeability experiments to be performed. Pore-pressure measurements were taken continuously before, during, and after mining the room, and permeability experiments were performed before and after the mining. In addition, a series of 4-cm- and 10-cm-diameter boreholes will be cored in various directions from within the room. The boreholes will extend up to 14 m from the surface of the room, and will be oriented either parallel or perpendicular to the bedding of the surrounding rock. These boreholes will also be instrumented to allow permeability experiments and measurement of pore pressure, borehole deformation, and brine inflow in different intervals of the holes. The holes should be completed and instrumented in the fall of 1990.

Since excavation was completed, the dimensions of the room have been measured as a function of time. Also, electrical-resistivity measurements are being used to estimate the room's departure from the unfractured conditions of the surrounding rock as a function of time.

Brine inflow, humidity, and room closure will continue to be measured past January 1992. Pore-pressure measurements around the room will also continue past January 1992. Pore-pressure and permeability-test data from holes completed in two stratigraphic units above the room (QPP03 and QPP04 in Figure 13) and in two units below the room (QPP11 and QPP12 in Figure 13) for the pre- and post-mined configurations will be included in the WIPP Salt Test Case. In addition, selected humidity, brine-inflow, closure, and resistivity data, as well as additional pore-pressure and permeability-test data, will be included as they become available.

## C. Original Purpose of the Experiments

Before WIPP excavation began, it was postulated that Salado Formation brine was present in the form of stable fluid inclusions. It was anticipated that excavation activities would release very little brine from the inclusions. However, after excavation, instances of small, steady brine release from the formation were observed. Many of the experiments that compose this test case were initiated to understand the mechanism for the brine inflow and to allow prediction of brine inflow during the period between closure of the repository and complete reconsolidation of the backfill. The saturation state of the repository following closure is an important parameter in performance-assessment calculations.

Several postulated brine-inflow mechanisms produce widely varying predictions of long-term flow into the repository. Use of all postulated mechanisms produces unacceptable uncertainty in the performance-assessment predictions of radionuclide release for some scenarios. Thus, experiments were recently refocused on validation of a single mechanism for brine inflow. A Darcy flow model assuming fluid-pressure-driven flow through continuous interconnected porosity is the most "pessimistic" model for long-term inflow to the repository, in the sense that the amount of fluid available for flow into the repository is effectively infinite. Another postulated mechanism involves connection of otherwise unconnected intergranular pores by dilatancy and salt creep, creating a continous pathway for grain-boundary fluids to flow towards the repository. The amount of fluid available for flow into the repository under this mechanism is limited to that contained within the newly interconnected porosity. Other possible flow mechanisms, such as one which uses salt creep as the driving force for brine flow, are also being evaluated. Additional measurements that could become part of the WIPP Salt Test Case are being made to define the state of the formation surrounding the repository and, in some cases, of the area immediately surrounding the experiment test zones.

This test case is related to another important performance assessment issue, the ability of waste-generated gas to flow from the repository into the formation. The ability of the formation to accept gas is dependent on the existing relative saturations of the formation with respect to brine and gas, and on relative permeabilities to brine and gas. Resolution of the brine-inflow issue will contribute to resolving the gas-flow issue.

## D. Objectives of the Test Case in INTRAVAL Phase II

The test case objective is to integrate the results of all the experiments in a comprehensive and consistent model of brine flow through evaporites. The pore-pressure measurements provide boundary and initial conditions, the permeability measurements quantify the apparent hydraulic parameters controlling flow, and the brine-inflow measurements reflect the output of the system. The applicability of a Darcy flow model should be investigated, with possible refinements dealing with two-phase flow and rock creep effects. Alternative models, in which porosity becomes interconnected as a result of creep or as brine is squeezed out of the salt, could also be evaluated.

## E. Validation Aspects

Predictions of brine inflow to bedded salt repositories are highly uncertain because of a lack of understanding of the basic nature of brine flow through evaporites. This test case examines brine-flow mechanisms on scales ranging from 4-cm-diameter boreholes to a 2.9-m-diameter room, and uses both pressure-transient and flow-transient testing techniques to provide information on different properties of the flow system. It is important to determine whether or not a classical model of Darcy flow through a porous medium is applicable to evaporites. If not, an alternative model consistent with all of the experimental data must be formulated. The INTRAVAL Phase II efforts may identify additional measurements and/or experiments needed to validate, modify, or invalidate Darcy flow and alternative models.

Therefore, the aim of the test case is to validate a model of brine flow through evaporites that can accurately simulate all types of tests performed at all scales examined. Validation of the model is assumed to include validation of all relevant processes/phenomena (continuous pore-pressure gradients in evaporites, continuous interconnected porosity, gas-driven brine flow, creep effects, etc.) that go into the overall model. This validated model should then be defendable when used for performance-assessment calculations.

Given the importance of the WIPP, validation efforts supported by INTRAVAL on this test case will probably receive intensive scientific and public scrutiny.

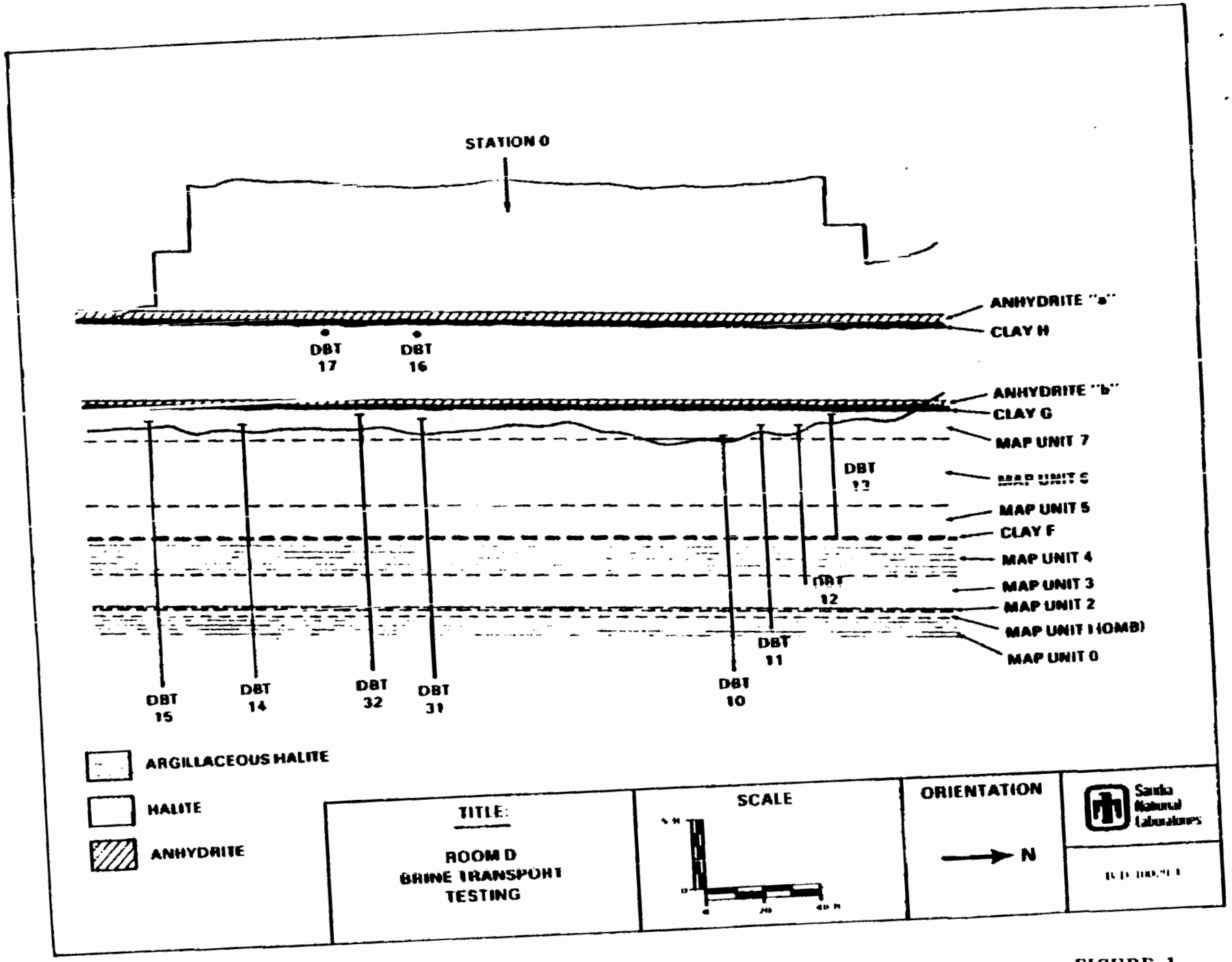
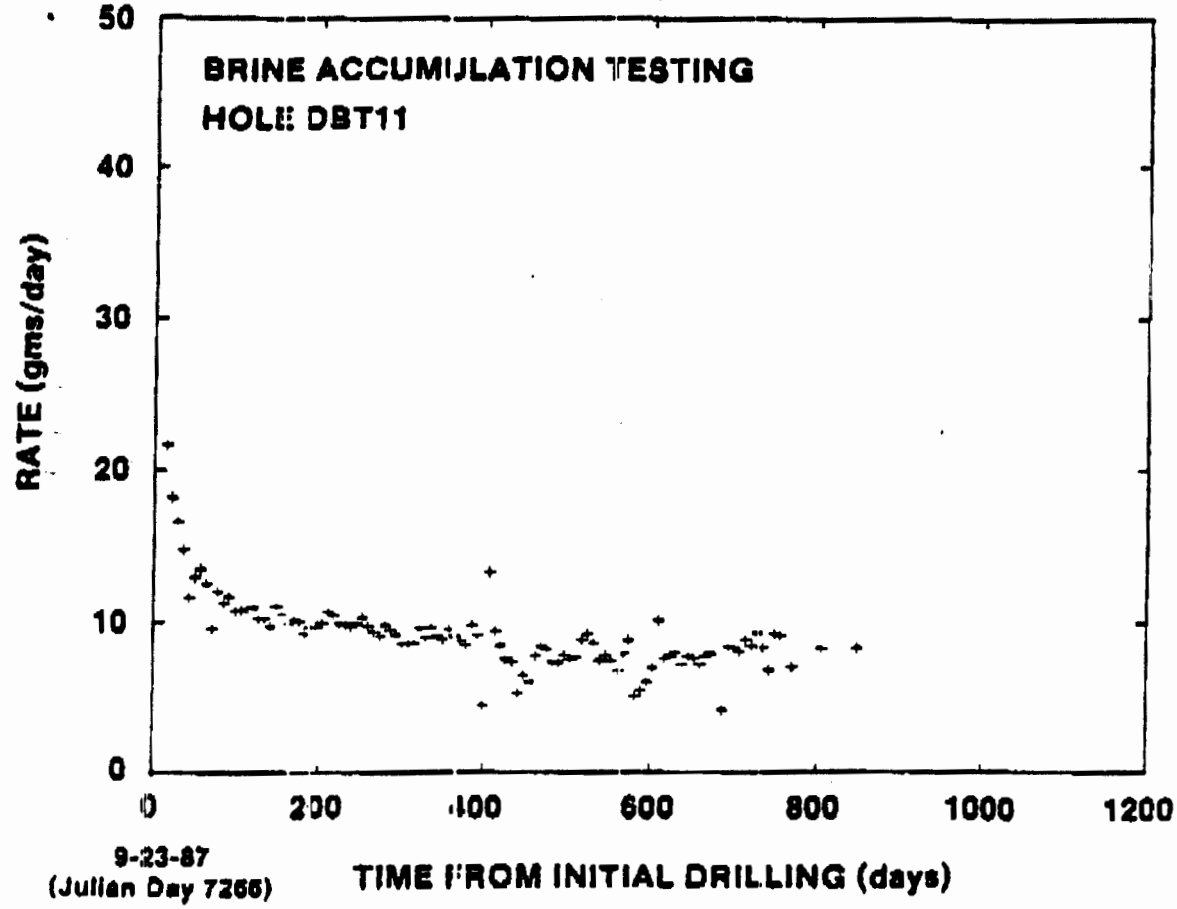

STATION 0
ANHYDRITE "a"
CLAY H
DBT 17
DBT 16
ANHYDRITE "b"
CLAY G
MAP UNIT 7
DBT 13
MAP UNIT 6
MAP UNIT 5
CLAY F
MAP UNIT 4
DBT 12
MAP UNIT 3
MAP UNIT 2
MAP UNIT 1 (OMB)
DBT 11
MAP UNIT 0
DBT 15
DBT 14
DBT 32
DBT 31
DBT 10
ARGILLACEOUS HALITE
HALITE
ANHYDRITE
TITLE:
ROOM D
BRINE TRANSPORT
TESTING
SCALE
ORIENTATION
N
Sandia National Laboratories

FIGURE 1


BRINE ACCUMULATION TESTING
HOLE DBT11
RATE (gms/day)
50
40
30
20
10
0
0
200
400
600
800
1000
1200
9-23-87
(Julian Day 7266)
TIME FROM INITIAL DRILLING (days)

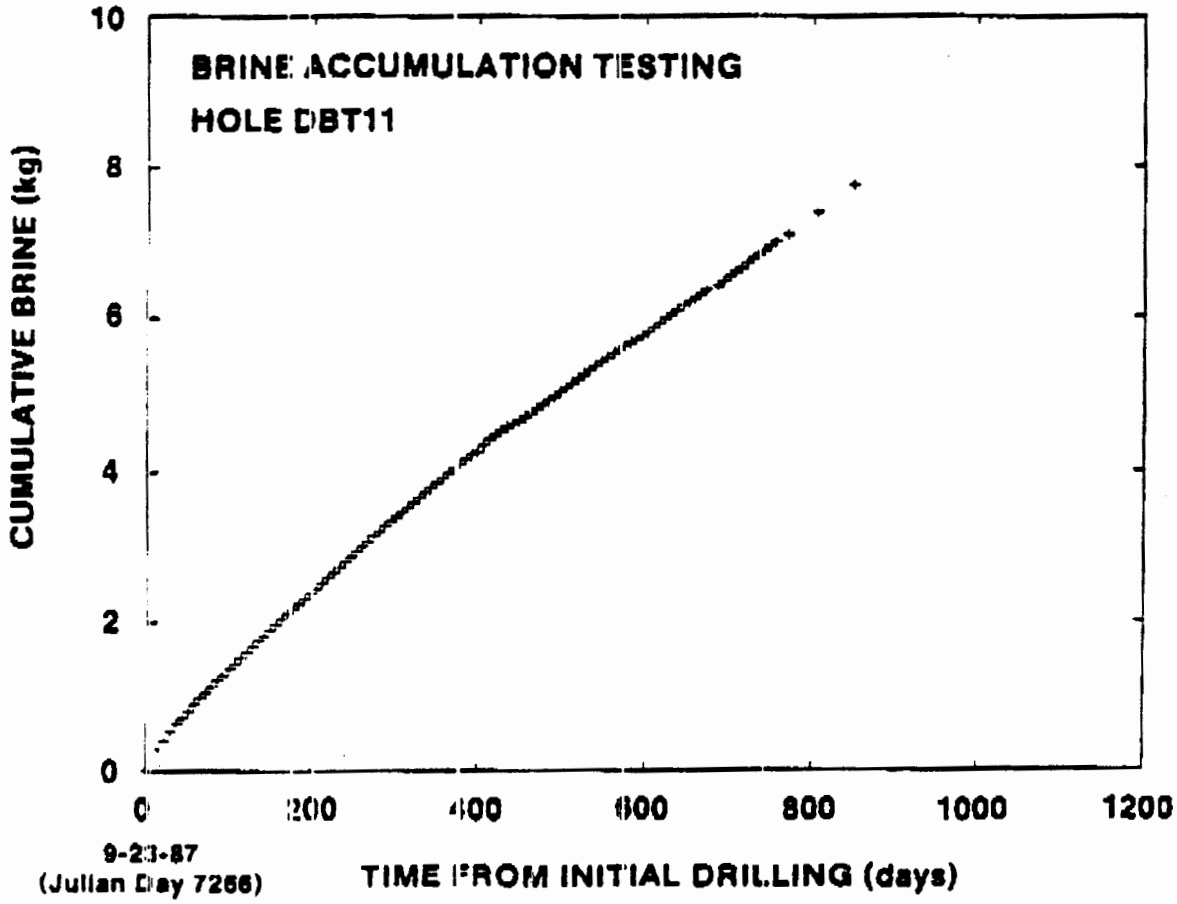

BRINE ACCUMULATION TESTING
HOLE DBT11
CUMULATIVE BRINE (kg)
10
8
6
4
2
0
0
200
400
600
800
1000
1200
9-23-87
(Julian Day 7266)
TIME FROM INITIAL DRILLING (days)

FIGURE 2

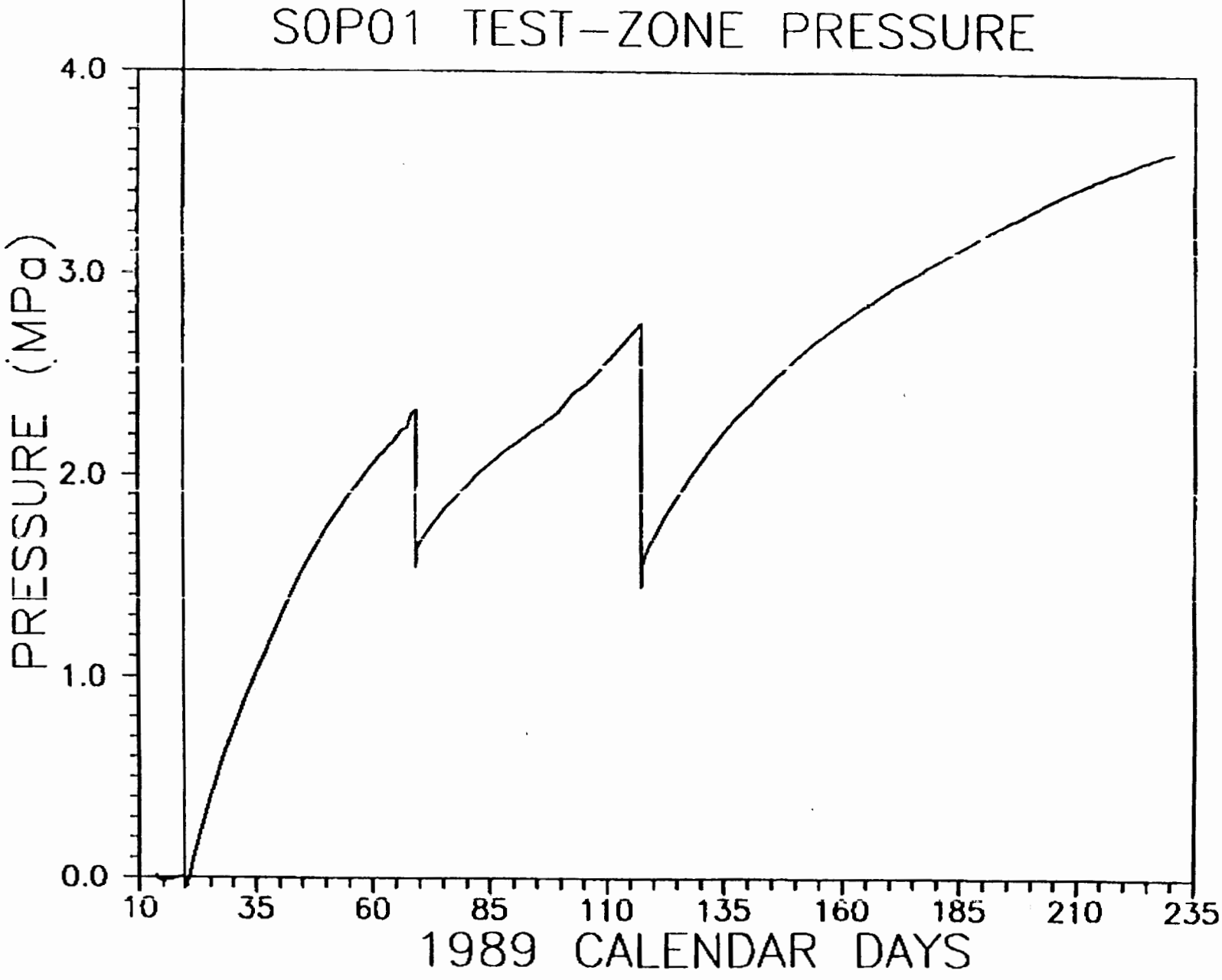



FIGURE 3

06/07/90 08:20 SANDIA NAT. LABS DEPT 6330 004

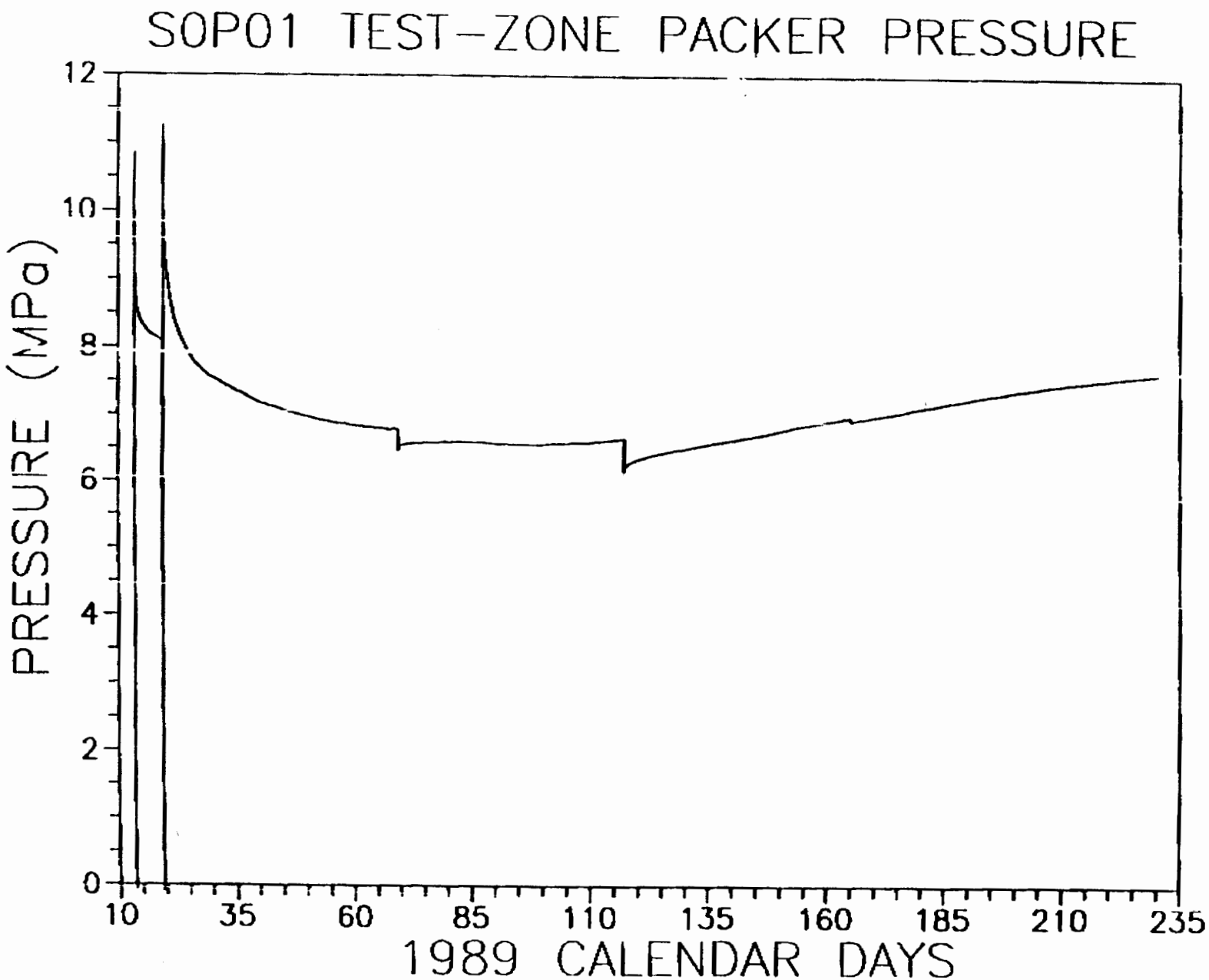



FIGURE 4

06/07/90 08:20 SANDIA NAT. LABS DEPT 6330 005

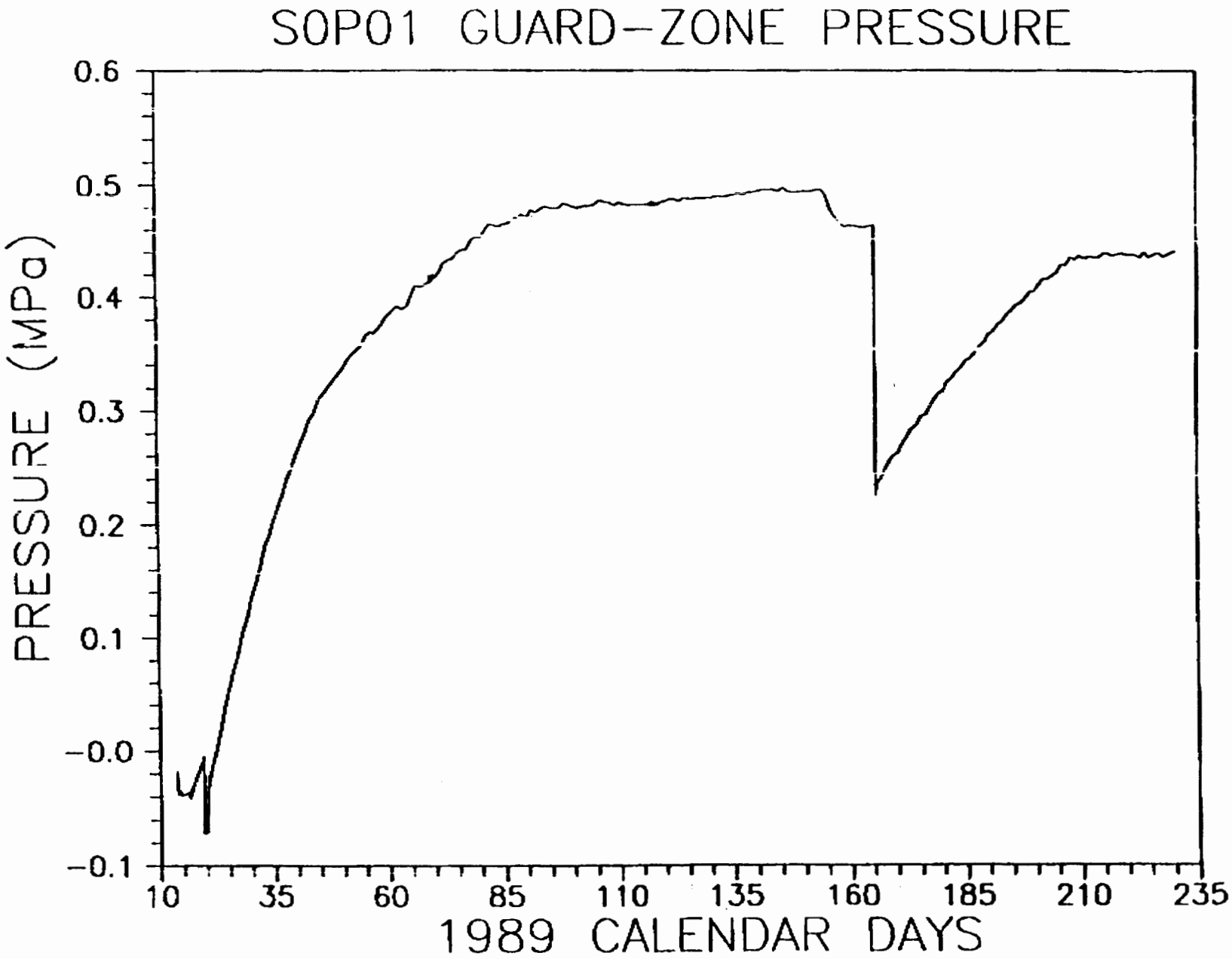



FIGURE 5

06/07/90 08:21 SANDIA NAT. LABS DEPT 6330 006

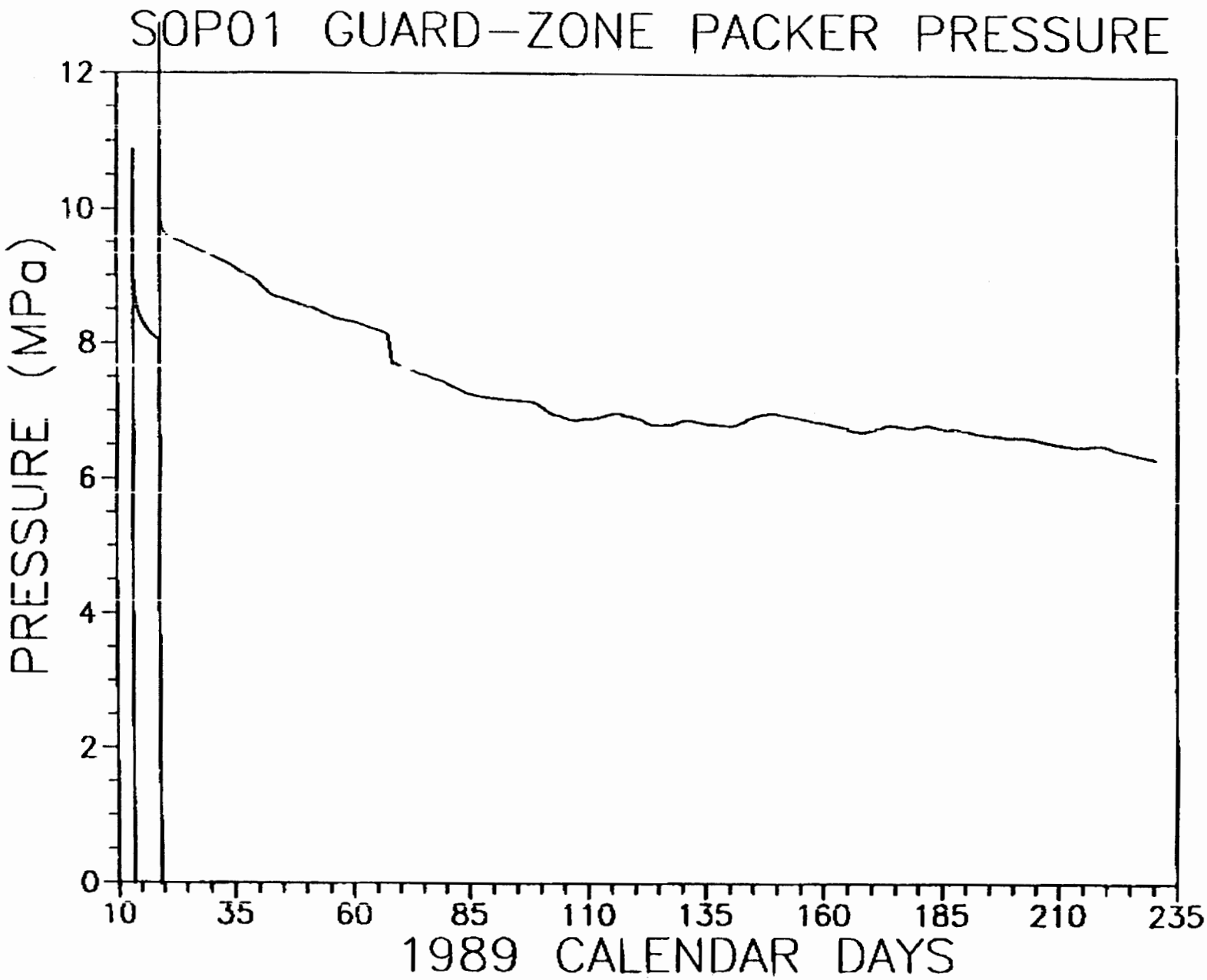



FIGURE 6

06/07/90 08:21 SANDIA NAT. LABS DEPT 6330 007

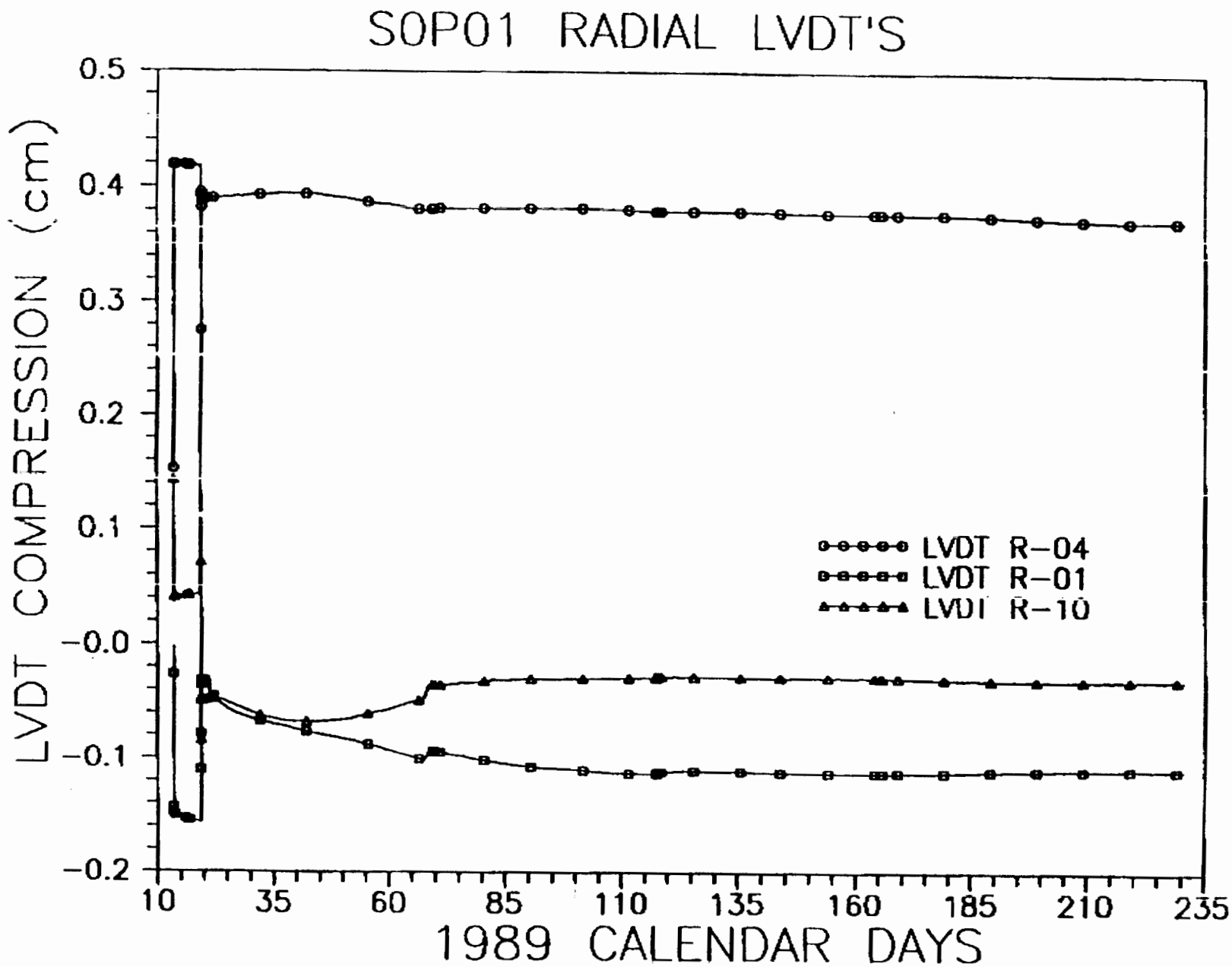

SOP01 RADIAL LVDT'S
LVDT COMPRESSION (cm)
0.5
0.4
0.3
0.2
0.1
-0.0
-0.1
-0.2
10
35
60
85
110
135
160
185
210
235
1989 CALENDAR DAYS
LVDT R-04
LVDT R-01
LVDT R-10

FIGURE 7

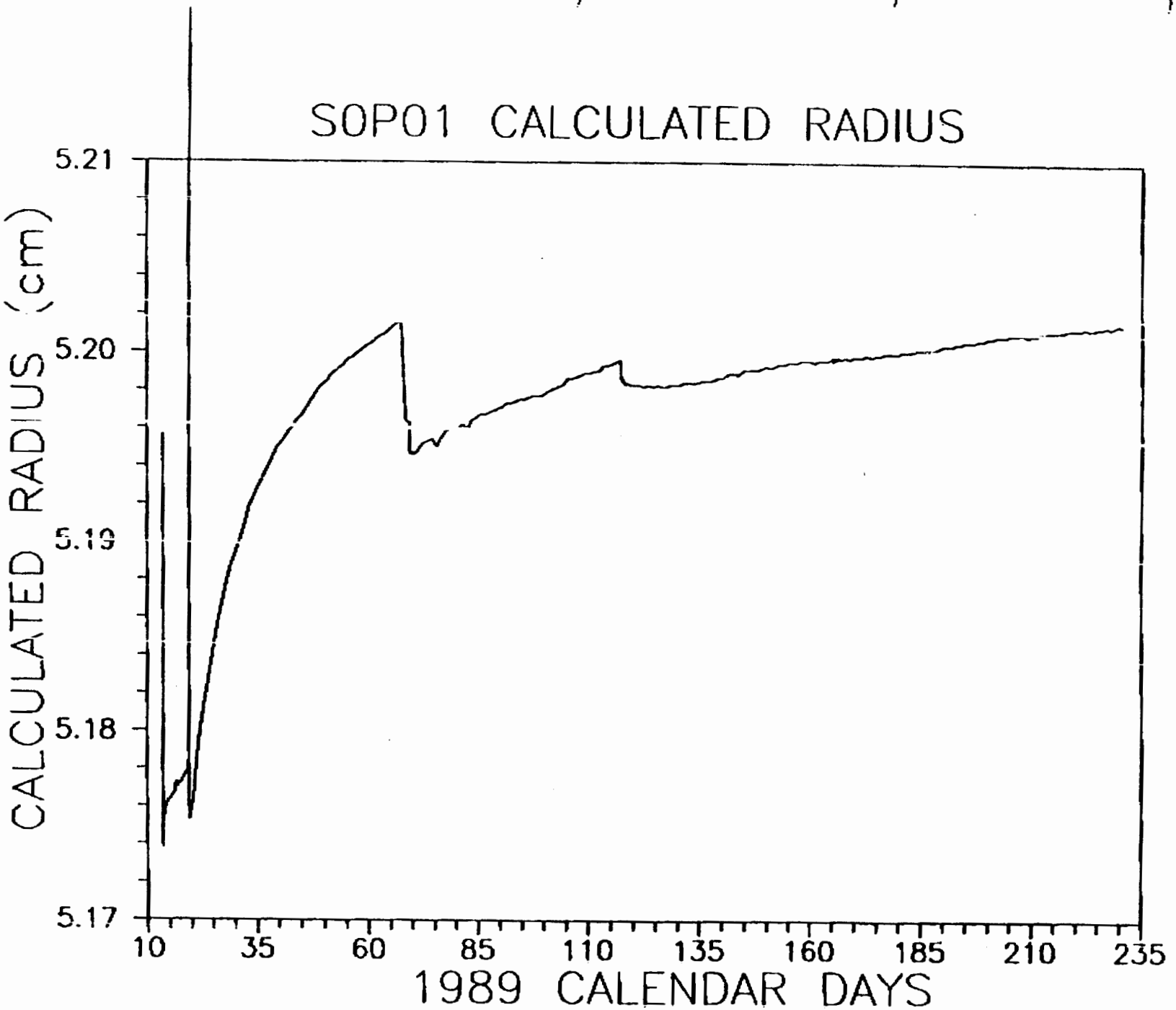



FIGURE 8

06/07/90 08:22 SANDIA NAT. LABS DEPT 6330 009

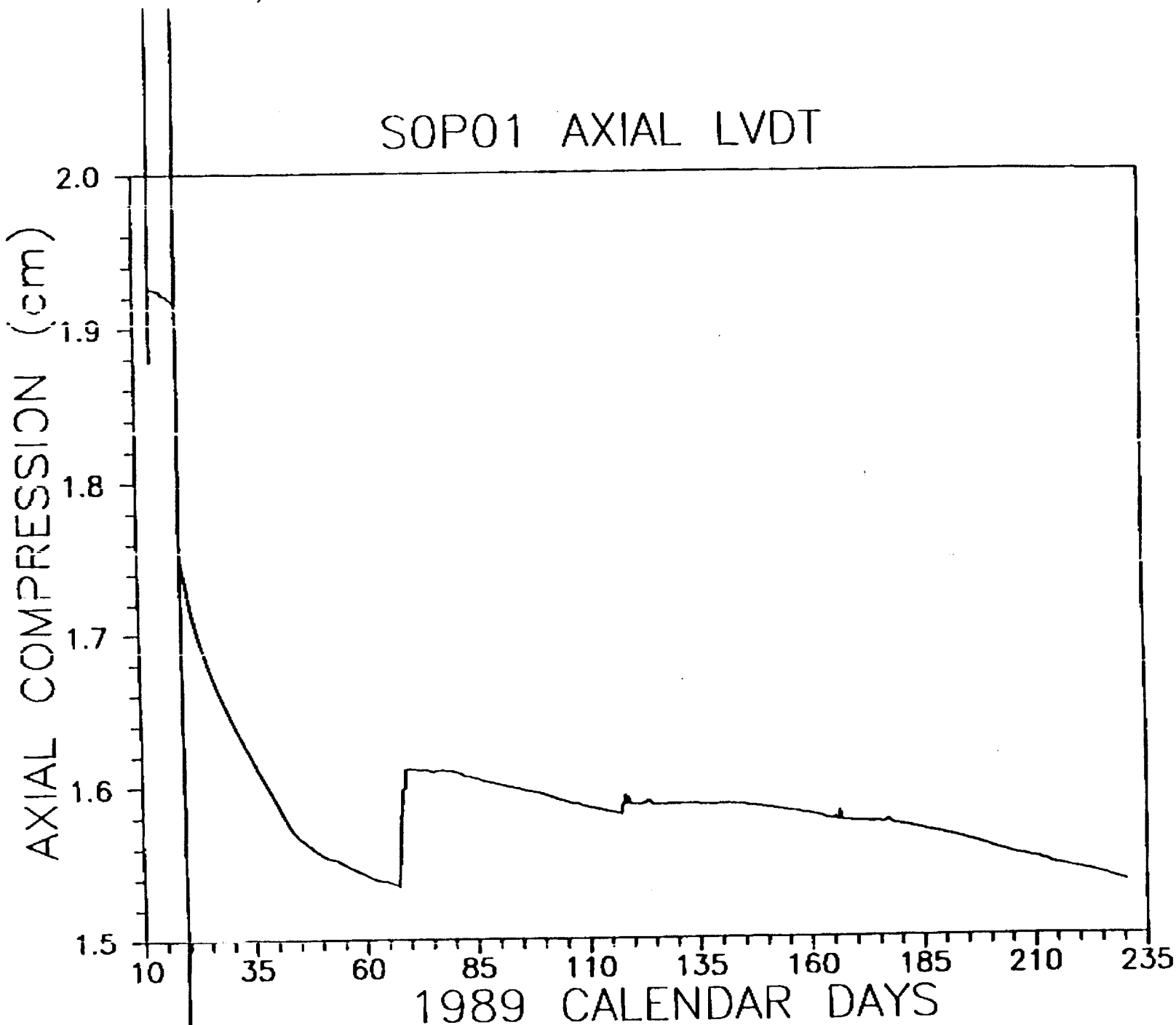



FIGURE 9

06/07/90 08:23 SANDIA NAT. LABS DEPT 6330 010

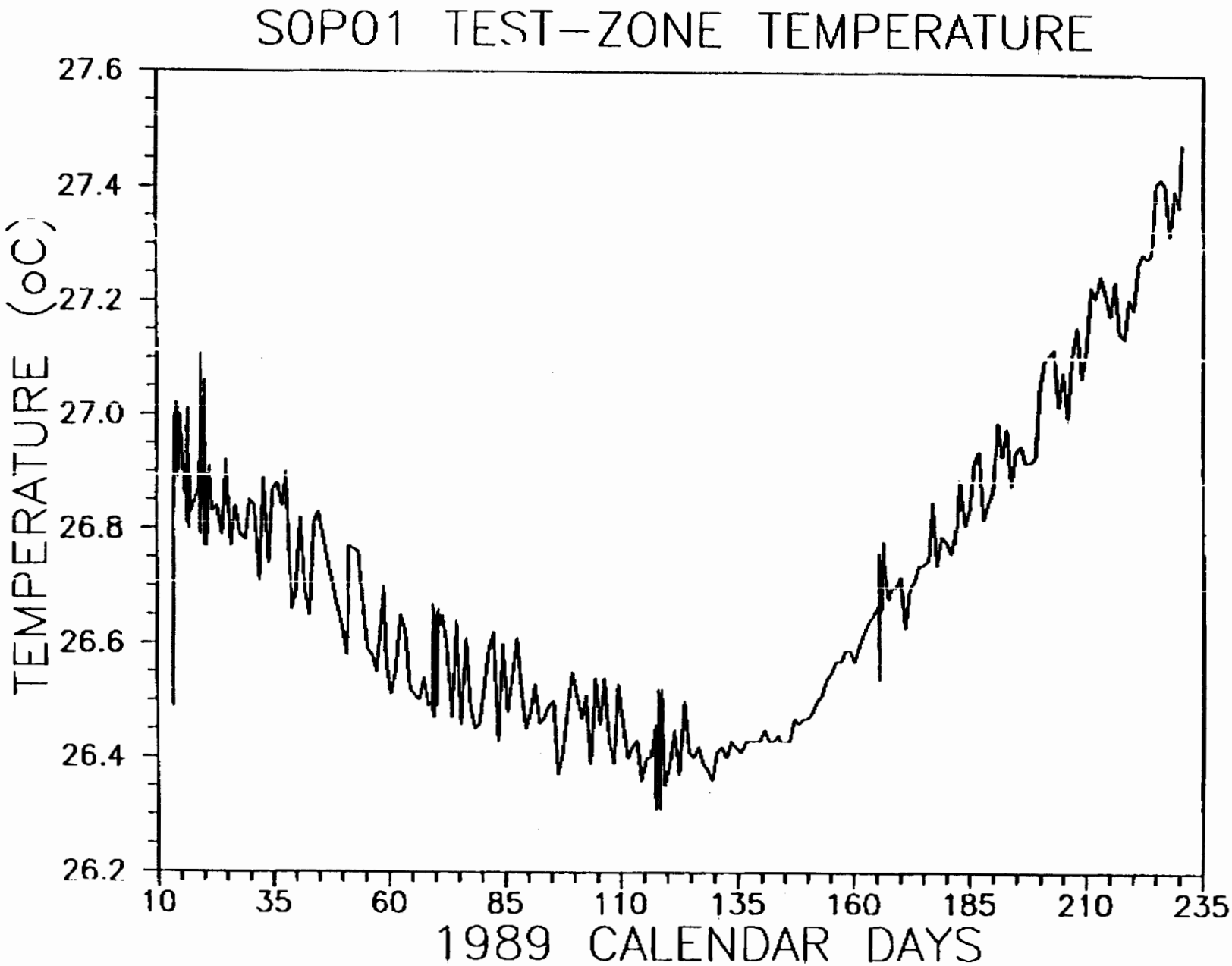

SOP01 TEST-ZONE TEMPERATURE
TEMPERATURE (oC)
27.6
27.4
27.2
27.0
26.8
26.6
26.4
26.2
10
35
60
85
110
135
160
185
210
235
1989 CALENDAR DAYS

FIGURE 10

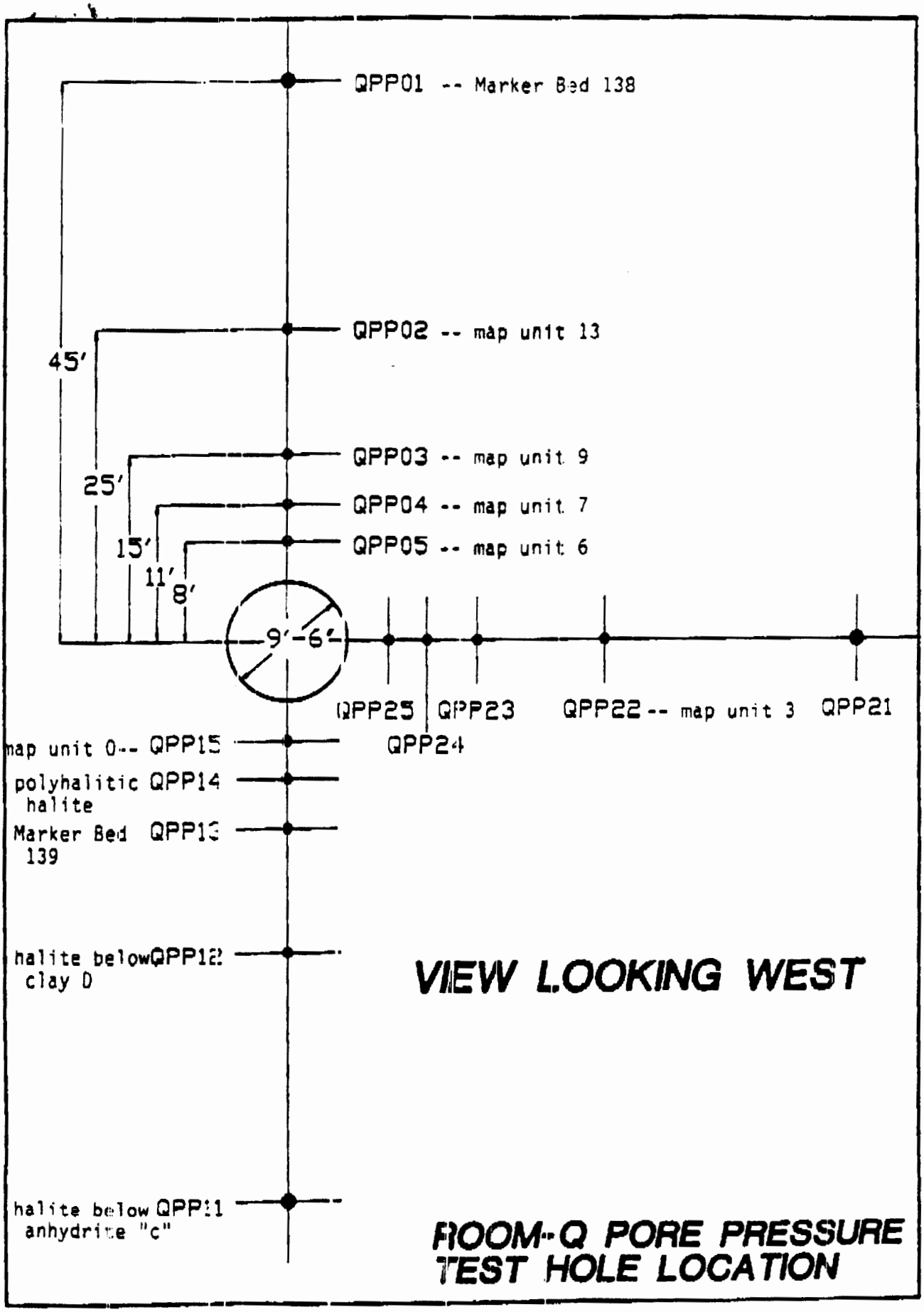

QPP01 -- Marker Bed 138
QPP02 -- map unit 13
45'
QPP03 -- map unit 9
25'
QPP04 -- map unit 7
15'
QPP05 -- map unit 6
11'
8'
9'-6'
QPP25
QPP23
QPP22 -- map unit 3
QPP21
QPP24
map unit 0-- QPP15
polyhalitic halite QPP14
Marker Bed 139 QPP13
halite below clay D QPP12
VIEW LOOKING WEST
halite below anhydrite "c" QPP11
ROOM-Q PORE PRESSURE TEST HOLE LOCATION

FIGURE 13

6/1/90

# Performance Assessment

D.R. (Rip) Anderson
J.C. (Jon) Helton
M.G. (Mel) Marietta

June 7-8, 1990

Sandia National Laboratories

TRI-6342-415-0

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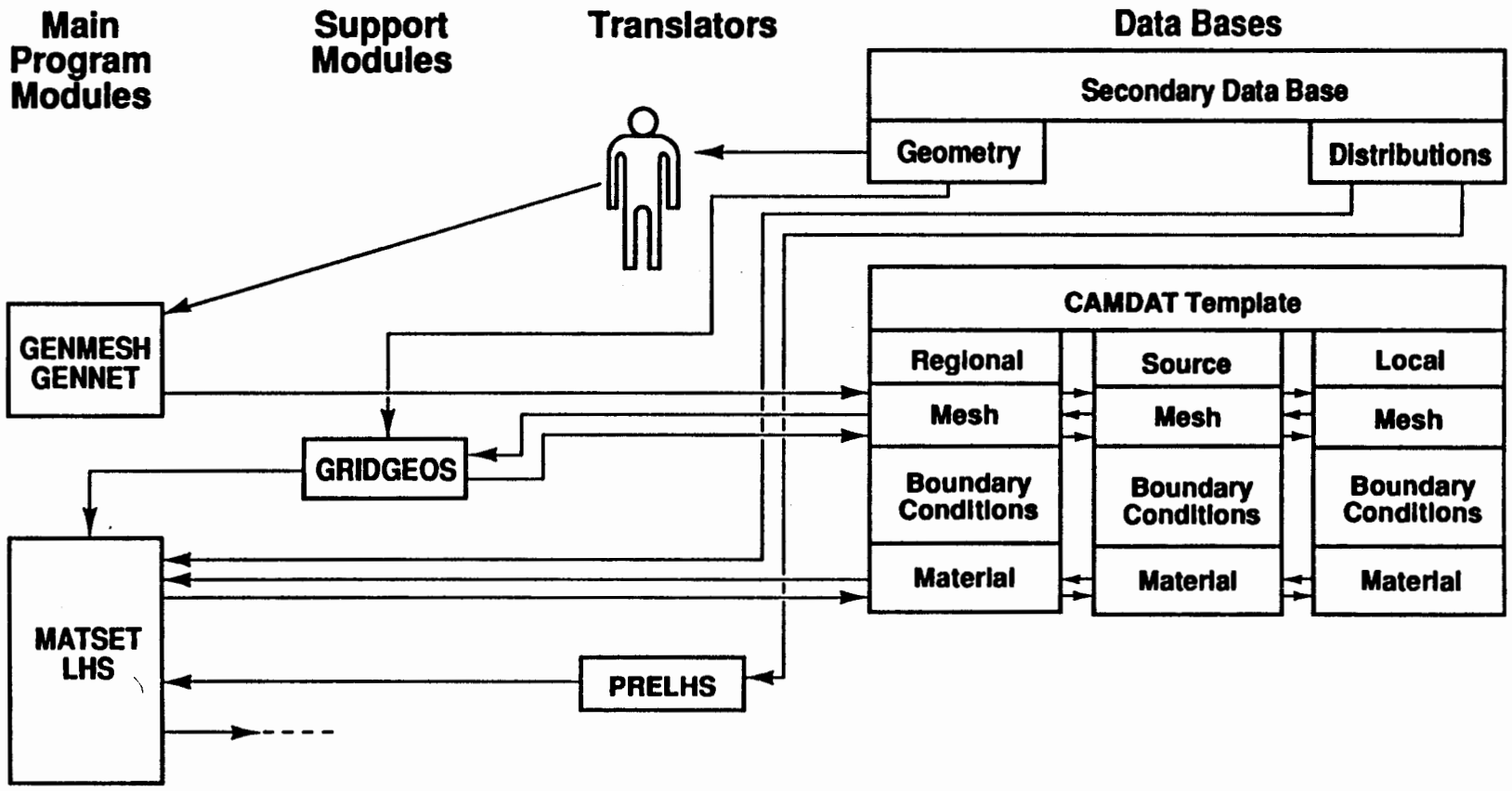
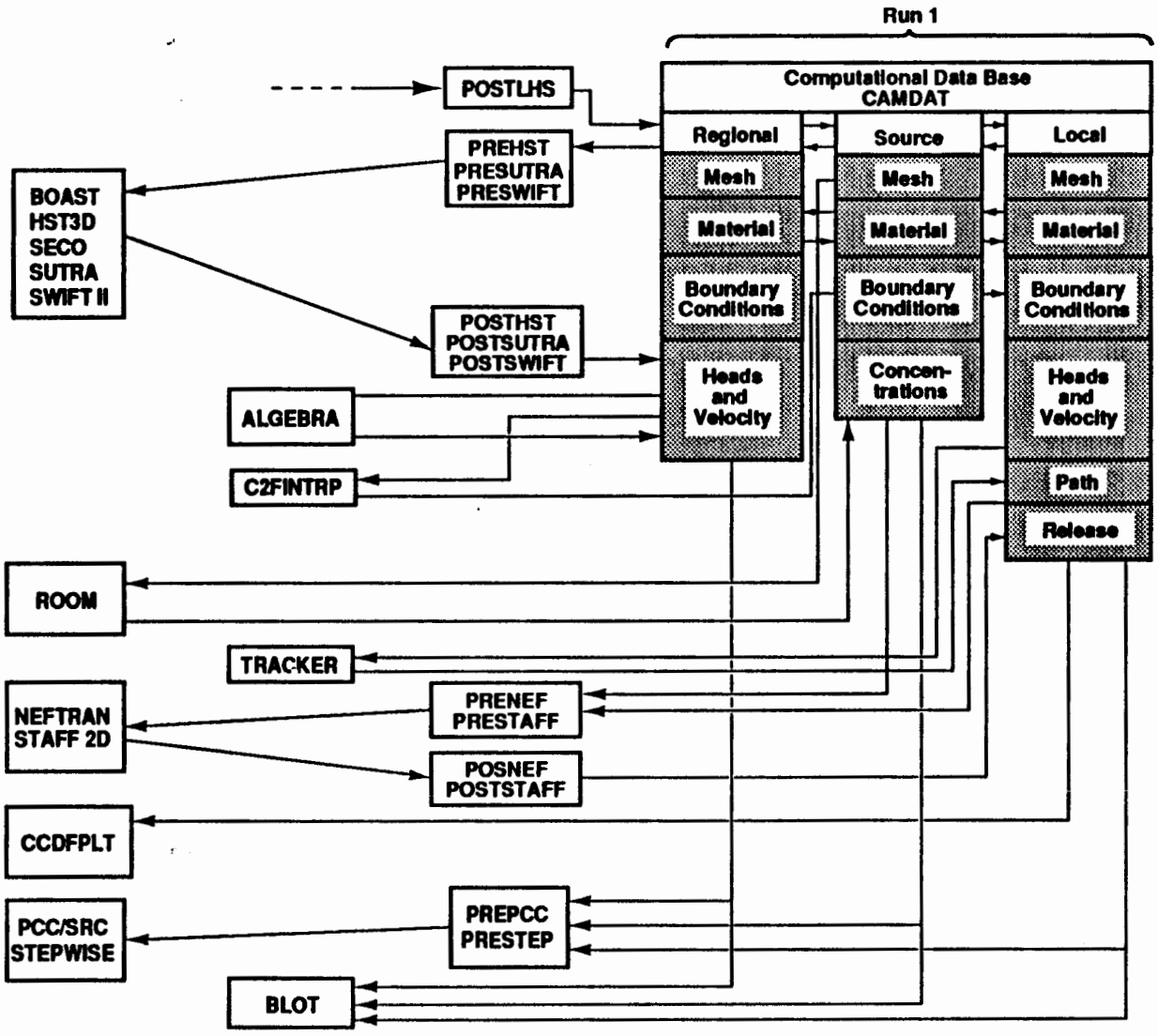
TRI-6342-416-0

# CAMCON




TRI-6334-184-1

# CAMCON




TRI-6334-185-1

# SWIFT II
# INTERA, Inc
# M. Reeves et al

- 3-D finite-difference single-phase solute-transport code
- Both single- and dual-porosity approaches
- Dominant-species miscible displacement (brine)
- Trace-species miscible displacement (including radionuclide chains)

# SUTRA
# USGS
# C.I. Voss

- 2-D finite-element saturated-unsaturated fluid-density-dependent ground-water flow code
- Chemically-reactive single-species solute or energy transport
- Specified-head boundary conditions
- Cartesian or cylindrical coordinate system

# SECO Darcy Flow Codes (Sandia-Ecodynamics)

SECO codes solve the same fundamental equation for hydraulic head as the USGS code "MODFLOW." Additional capabilities:

- Regional and local area grid solutions
- General boundary conditions
- Efficient problem definition and output
- Options for cell-centered or node-centered grids
- Automated specification of grid spacing
- Automated specification of time steps
- Parameterized climatic variations
- Particle tracking capability
- Efficient multigrid (semi-coarsening) solvers

TRI-6342-433-0

# SECO Enhancements

- Non-orthogonal feature-adapted grid generation
- 3-D
- Automatic estimation of discretization error
- Brine transport
- Dual porosity

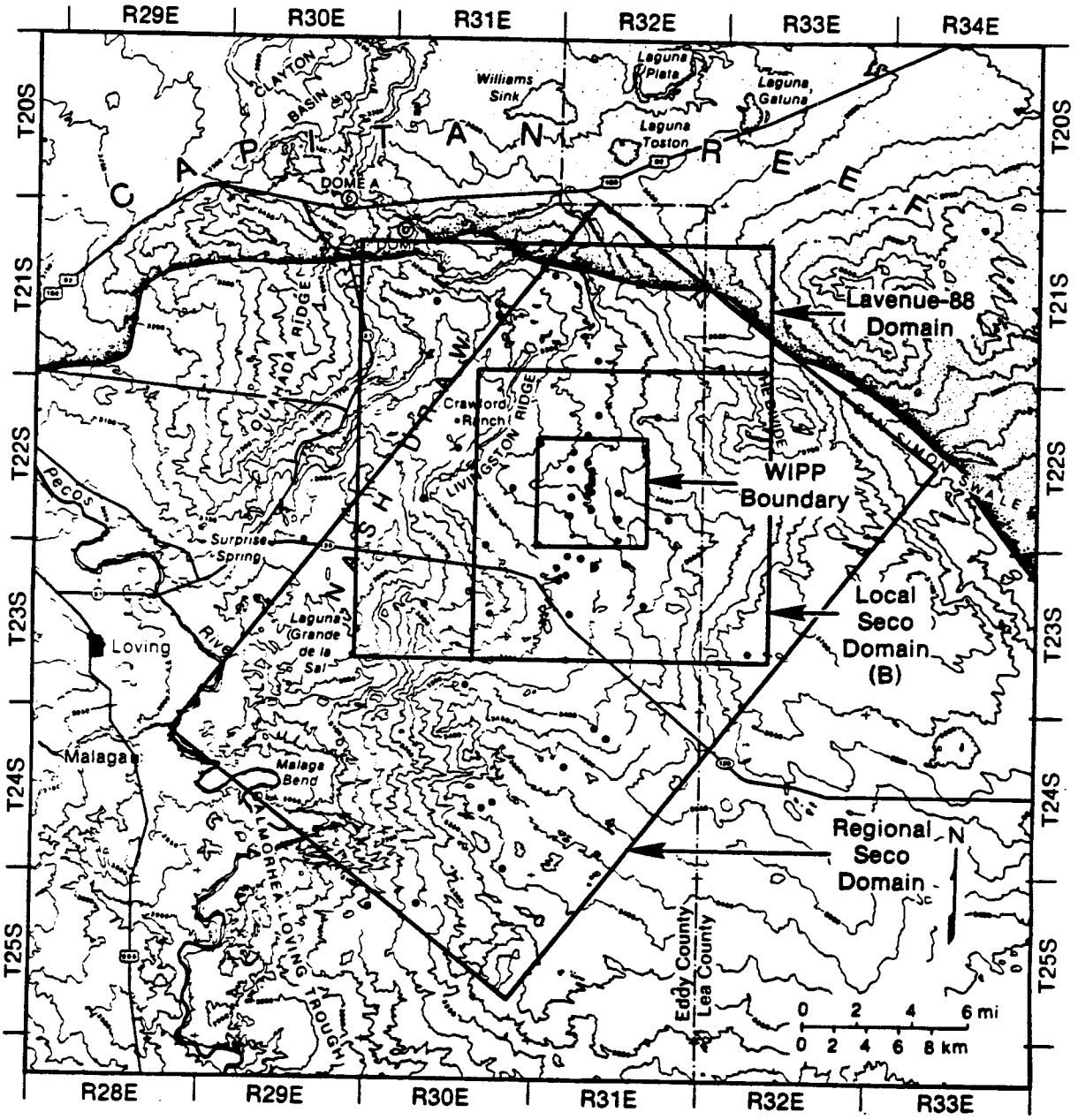
# STAFF2D
# HydroGeologic, Inc
# P.S. Huyakorn

- 2-D Finite-element single-phase flow and solute-transport code
- Both discrete-fracture and dual-porosity approaches
- Fracture-skin effects

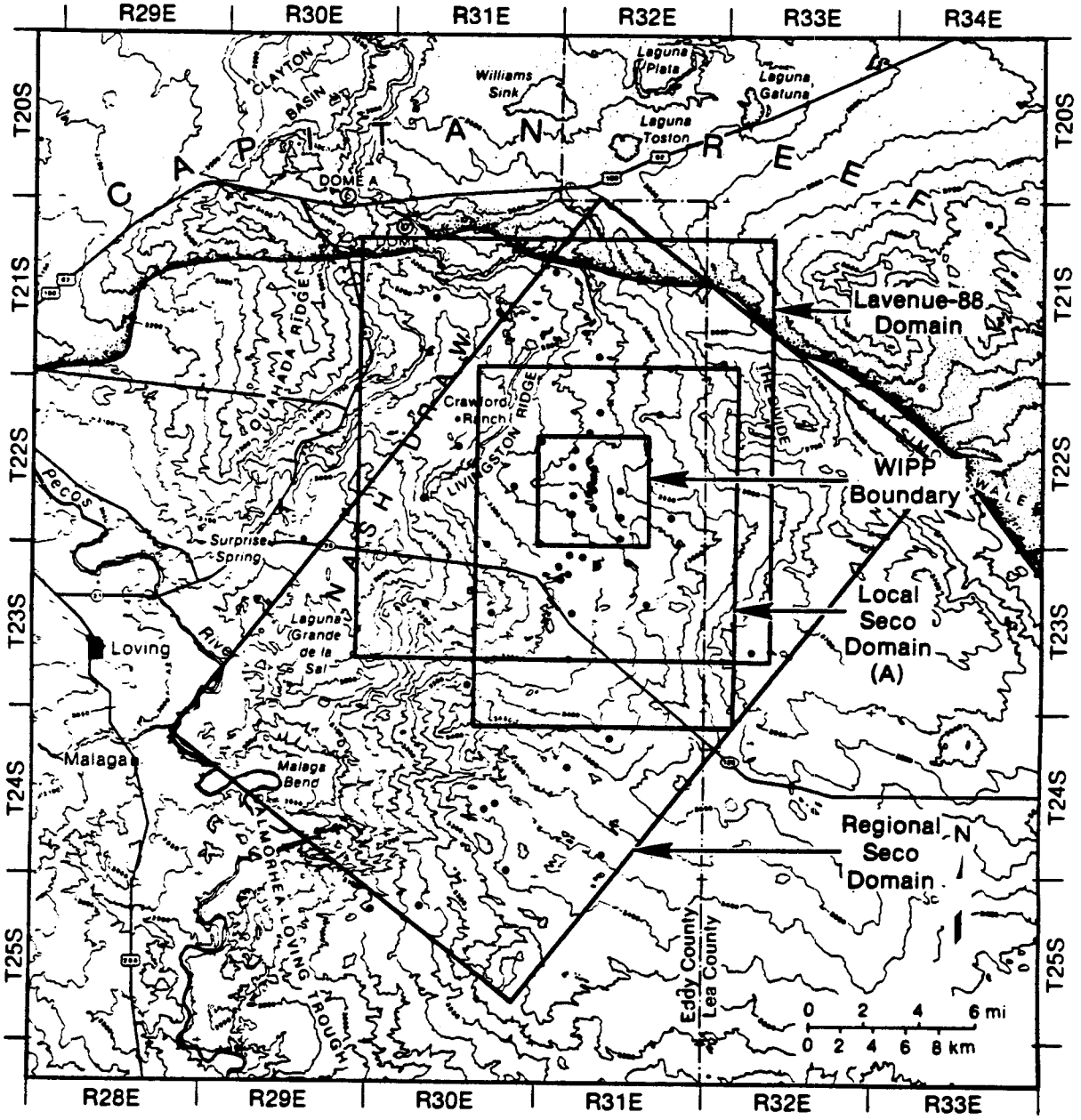
SNL modifications: Five-radionuclide chain capability, multigrid-solver option, transient-flux boundary conditions, upstream weighting factors, and dimensioning.

# GENII
# Pacific Northwest Labs
# B. Napier et al.

- Well-documented, extensively peer-reviewed, DOE-funded code
- Incorporates internal dosimetry models recommended by ICRP
- Calculates radiation dose for acute and chronic releases with options for annual dose, committed dose, and accumulated dose
- Includes exposure pathways for external exposure via water, soil, and air, and internal exposure via inhalation and ingestion
- Releases can be to water and soil or to air from ground-level or elevated sources
- Wide variety of potential exposure pathways

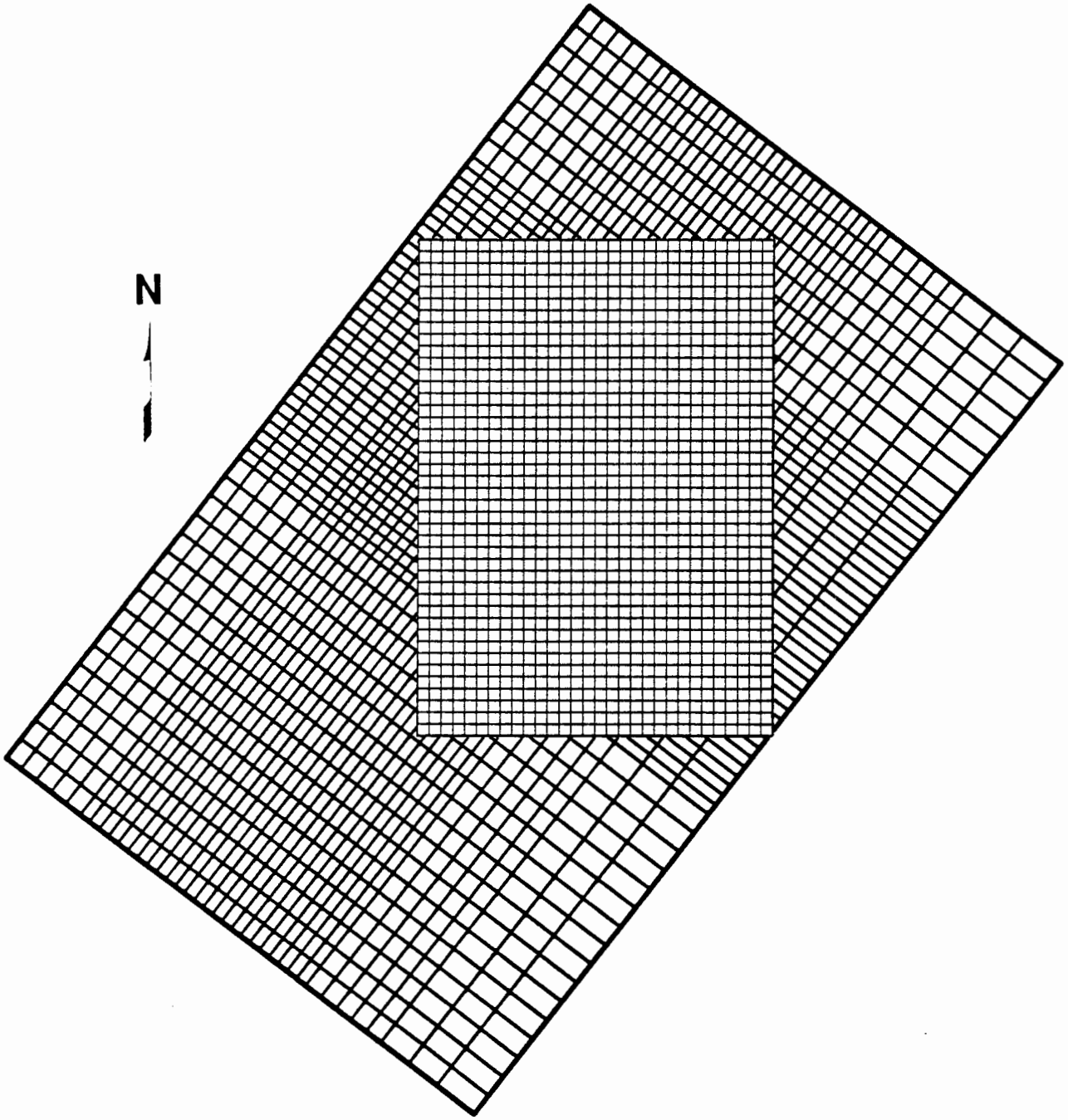



TRI-6342-347-0

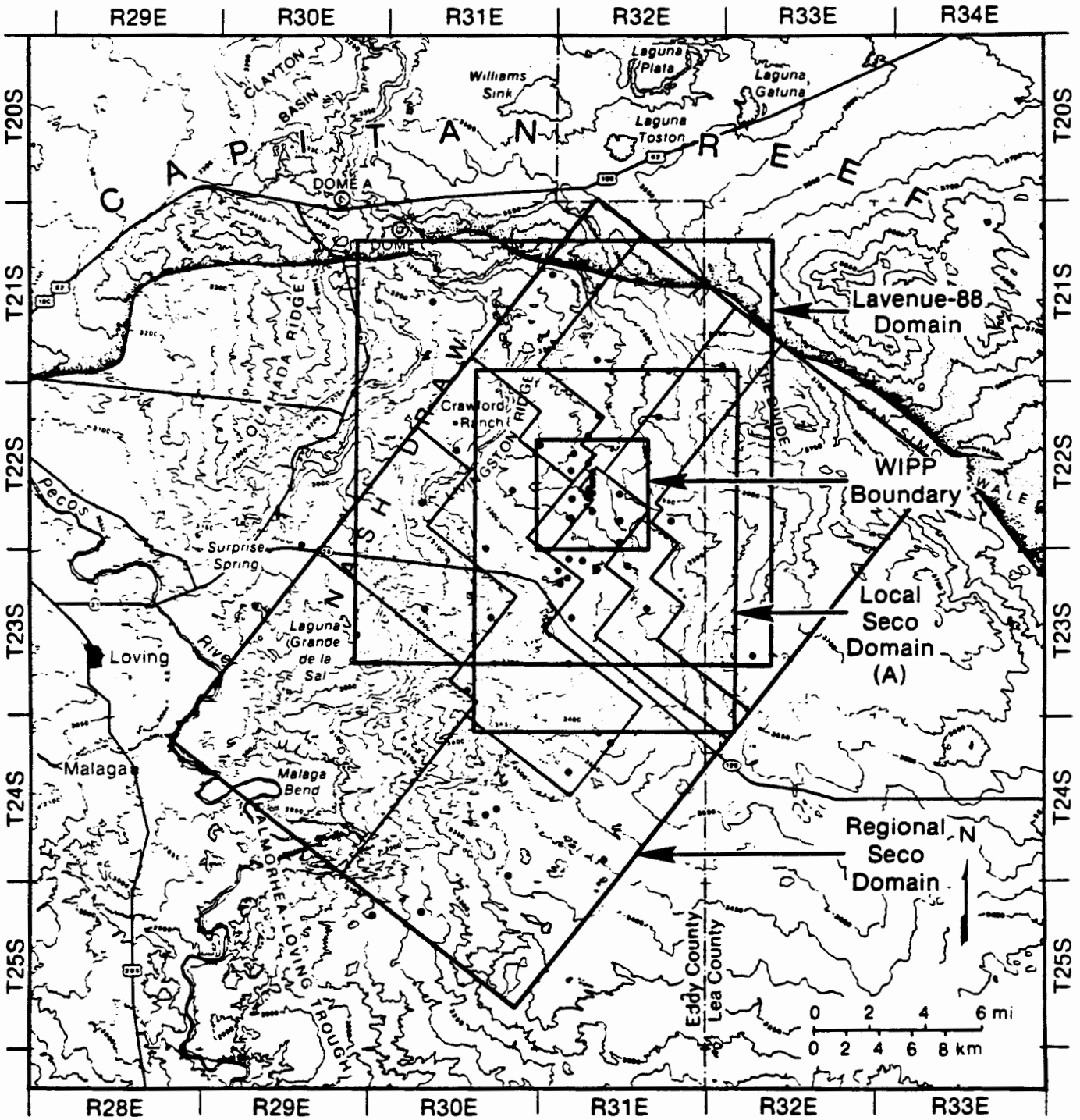



TRI-6342-346-0

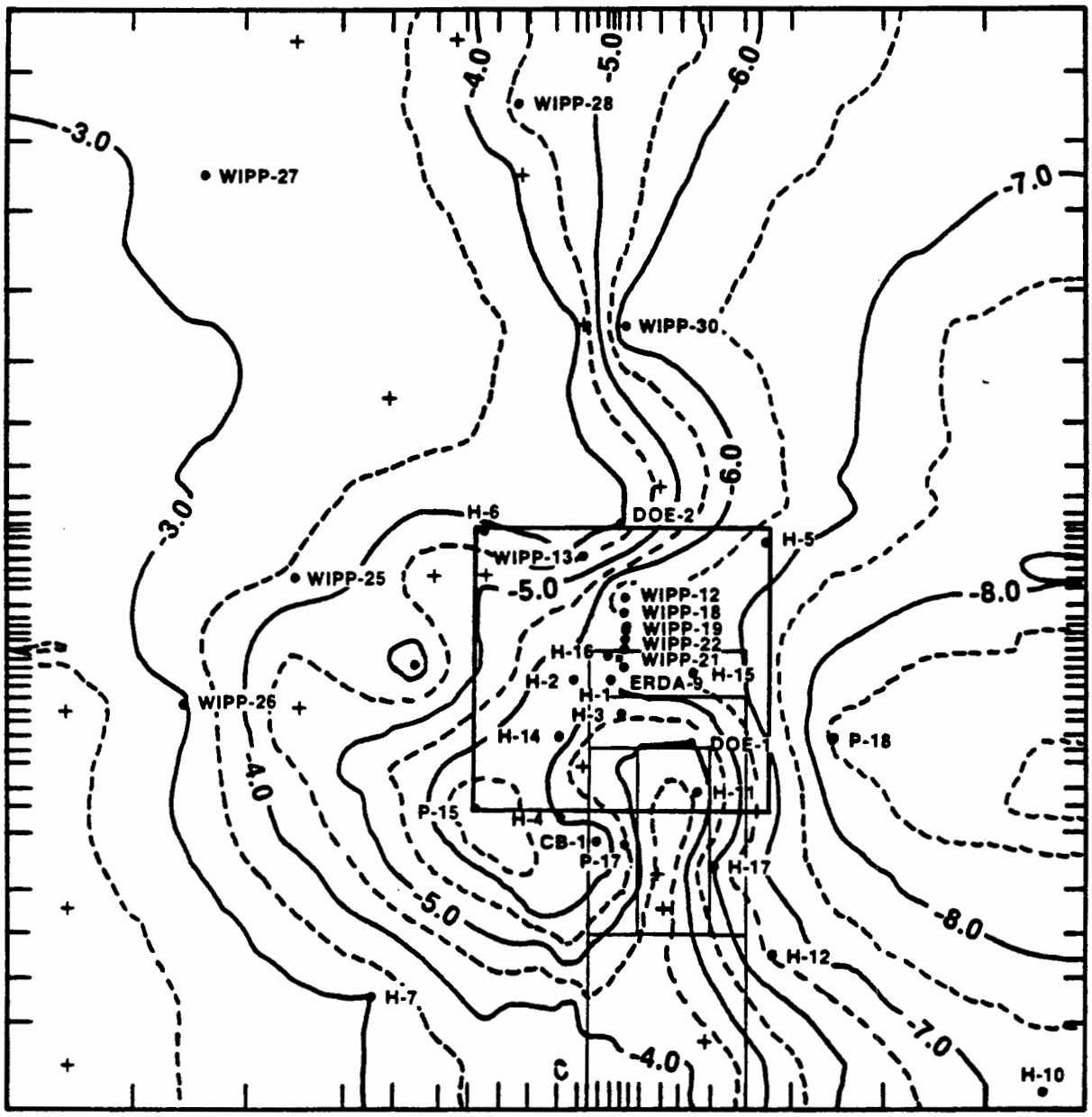
# Regional Seco and Local Seco (A) Domains




TRI-6342-399-0




TRI-6342-346-1




0 1 2 3 Miles

0 2 4 6 km

● Observation Well

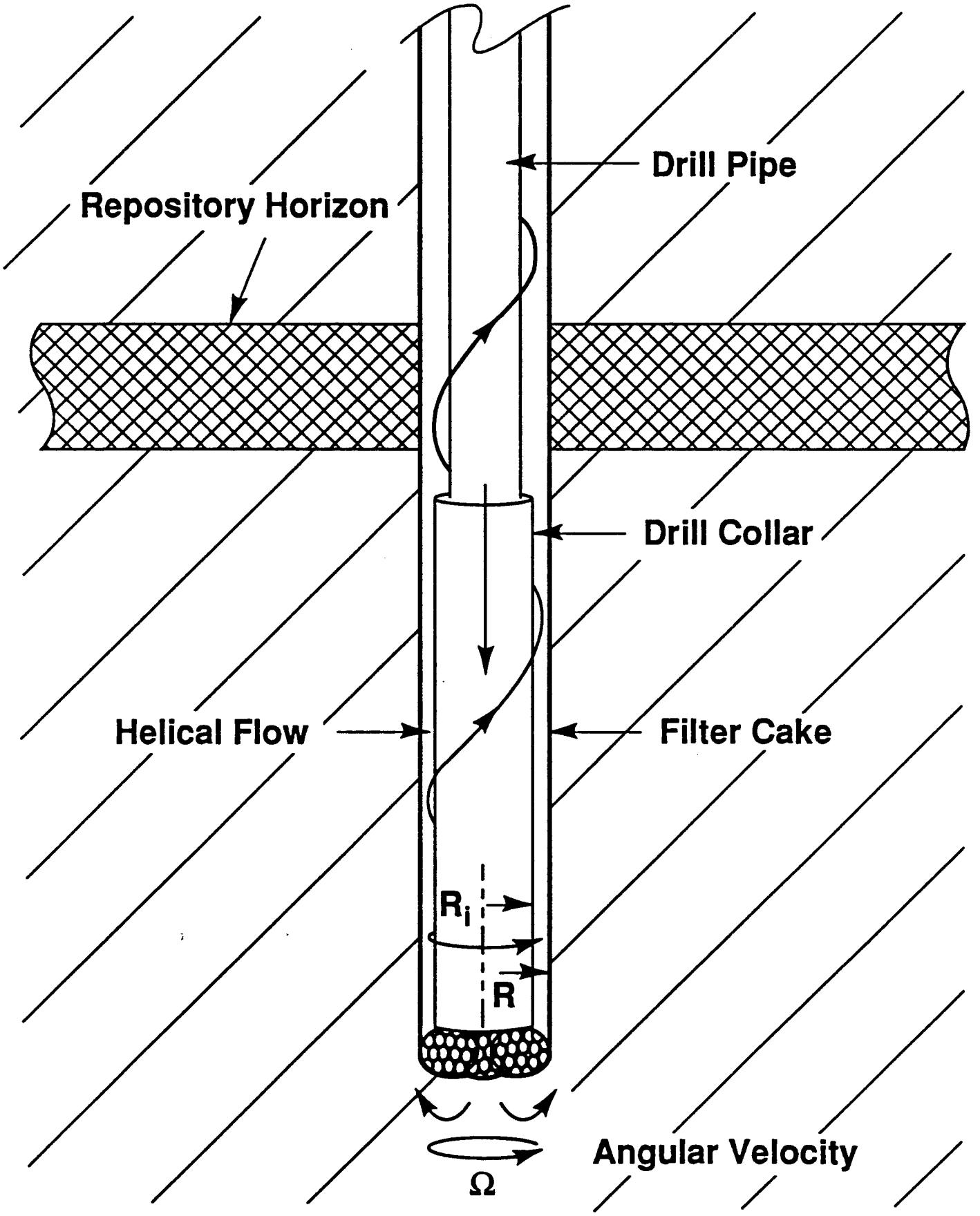
+ Pilot Point

Transmissivities in $m^2/s$

Contour Scale: Logarithmic

Contour Interval: 0.5 log $m^2/s$

TRI-6342-264-0




TRI-6342-400-0

# Helical Flow of a Non-Newtonian Fluid (Laminar Flow)

$$F_1 = \int_{\alpha}^{1} \left(\frac{\rho^2 - \lambda^2}{\rho}\right) \frac{d\rho}{\eta} = 0$$

$$F_2 = C \int_{\alpha}^{1} \frac{d\rho}{\rho^3 \eta} - \Delta\Omega = 0$$

$$\tau^2 = \tau^2_{r\theta} + \tau^2_{rz}$$

$$\tau_{r\theta} = \frac{C}{\rho^2}$$

$$\tau_{rz} = \frac{RJ}{2} \left(\frac{\rho^2 - \lambda^2}{\rho}\right)$$

| | | |
|---|---|---|
| $J$ | = | pressure gradient |
| $\Omega, \Omega_1$ | = | angular velocity of outer and inner cylinders, respectively |
| $\Delta\Omega$ | = | $\Omega - \Omega_1$ |
| $r$ | = | radial coordinate |
| $R, R_1$ | = | radius of outer and inner cylinders, respectively |
| $\alpha$ | = | $R_1/R$ |
| $\rho$ | = | reduced radial coordinate, equal to r/R |
| $\eta$ | = | shear-dependent viscosity function |
| $\tau, \tau_{21}, \tau_{r\theta}, \tau_{rz}$ | = | shear stress |
| $\lambda$ | = | helical flow parameter |

TRI-6342-380-0

$$F_3 = \frac{4Q}{\pi R^3} + 4\left(\frac{RJ}{2}\right)\int_{\infty}^{1}\left(\frac{\alpha^2-\rho^2}{\eta}\right)\left(\frac{\rho^2-\lambda^2}{\rho}\right)d\rho = 0$$

$$F_1 = \int_{\alpha}^{1}\left(\frac{\rho^2-\lambda^2}{\rho}\right)\frac{d\rho}{\eta} = 0$$

$$F_2 = C\int_{\alpha}^{1}\frac{d\rho}{\rho^3\eta} - \Delta\Omega = 0$$

Q = axial discharge rate

TRI-6342-381-0

**Taylor series expansion of each equation up to their linear terms**

$$\frac{\partial F_1}{\partial \lambda^2}\,\delta\lambda^2 + \frac{\partial F_1}{\partial C}\,\delta C + \frac{\partial F_1}{\partial (RJ/2)}\,\delta\left(\frac{RJ}{2}\right) = -F_1$$

$$\frac{\partial F_2}{\partial \lambda^2}\,\delta\lambda^2 + \frac{\partial F_2}{\partial C}\,\delta C + \frac{\partial F_2}{\partial (RJ/2)}\,\delta\left(\frac{RJ}{2}\right) = -F_2$$

$$\frac{\partial F_3}{\partial \lambda^2}\,\delta\lambda^2 + \frac{\partial F_3}{\partial C}\,\delta C + \frac{\partial F_3}{\partial (RJ/2)}\,\delta\left(\frac{RJ}{2}\right) = -F_3$$

**Initial values for $\lambda^2$, C, and RJ/2 are assumed and the three linear equations are solved for the corrections $\delta\lambda^2$, $\delta C$, and $\delta(RJ/2)$. We replace $\lambda^2$ by $\lambda^2 + \delta\lambda^2$, C by $C + \delta C$, and RJ/2 by $RJ/2 + \delta(RJ/2)$. This solution process is repeated until $|\delta\lambda^2|\cdot|\delta C|$ , and $|\delta(RJ/2|$ are all less than some specified limit.**

TRI-6342-382-0

$$\frac{\partial F_1}{\partial \lambda^2} = - \int_{\alpha}^{1} \frac{1}{\eta\rho} \left[ 1 + \frac{\rho^2 - \lambda^2}{\eta} \frac{\partial \eta}{\partial \lambda^2} \right] d\rho$$

**The shear-dependent viscosity function $\eta$ is related to the shear rate function Y ($\Gamma$) by the equation**

$$\eta^2 Y = 2 \left[ \left( \frac{RJ}{2} \right)^2 \left( \frac{\rho^2 - \lambda^2}{\rho} \right)^2 + \frac{C^2}{\rho^4} \right]$$

$$\frac{\partial \eta}{\partial \lambda^2} = \frac{\partial (\eta^2 Y)}{\partial \lambda^2} \frac{\partial \eta}{\partial (\eta^2 Y)} = -4 \left( \frac{RJ}{2} \right)^2 \left( \frac{\rho^2 - \lambda^2}{\rho^2} \right) \frac{\partial \eta}{\partial (\eta^2 Y)}$$

**Y, Y(f) = shear rate function, equal to $2\Gamma^2$**

# Variables

$\Delta\Omega$ - Drillstring angular velocity

$Q$ - Drilling fluid flowrate

$R$ - Drill Radius

$R_1$ - Collar radius

$\eta$ - Drilling fluid viscosity

$\eta_o$
$\sigma_1$
$\sigma_2$

$T_R$ - Respository depth

$\tau_f$ - Failure shear stress of repository material (or filter cake)

TRI-6342-384-0

$$r = \eta \Gamma$$

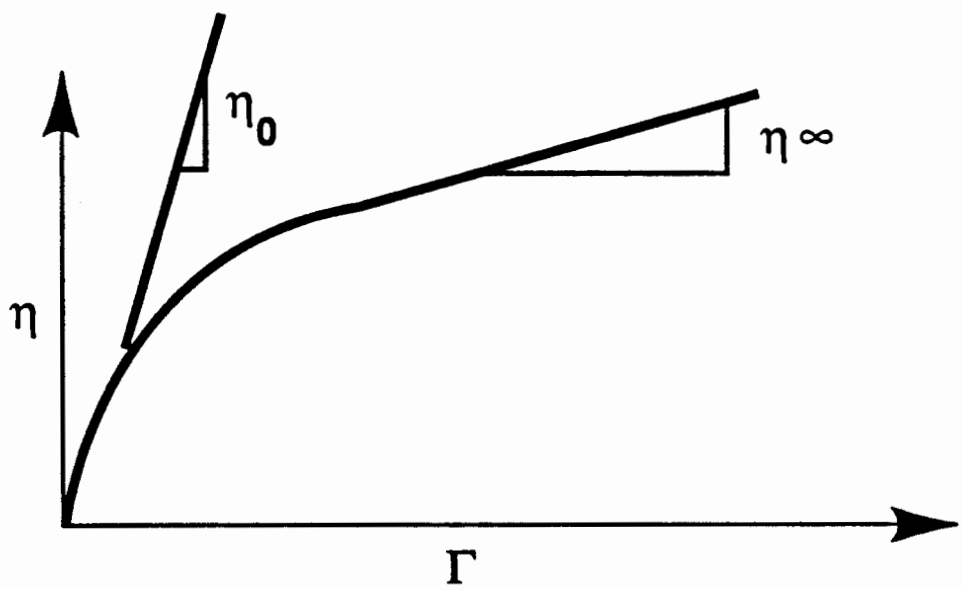
$$\eta = \eta_0 \left[ \frac{1 + \sigma_2 \Gamma^2}{1 + \sigma_2 \Gamma^2} \right]$$

$\Gamma$ = shear rate

$\eta$ = limiting viscosity at infinite rate of shear

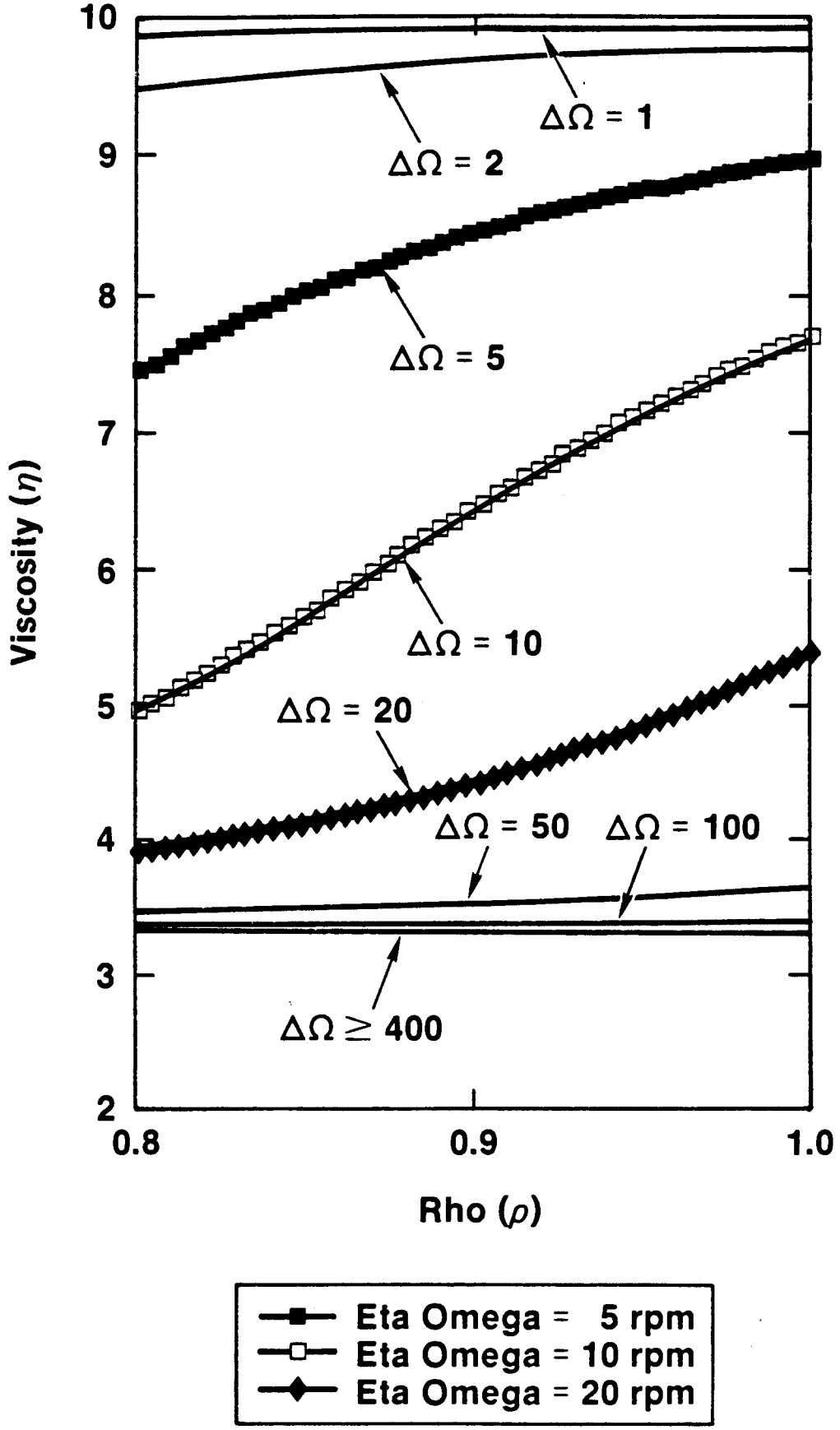
$$\eta = \eta_0 \frac{\sigma_2}{\sigma_1}$$

$\eta_0$ = limiting viscosity at zero rate of shear



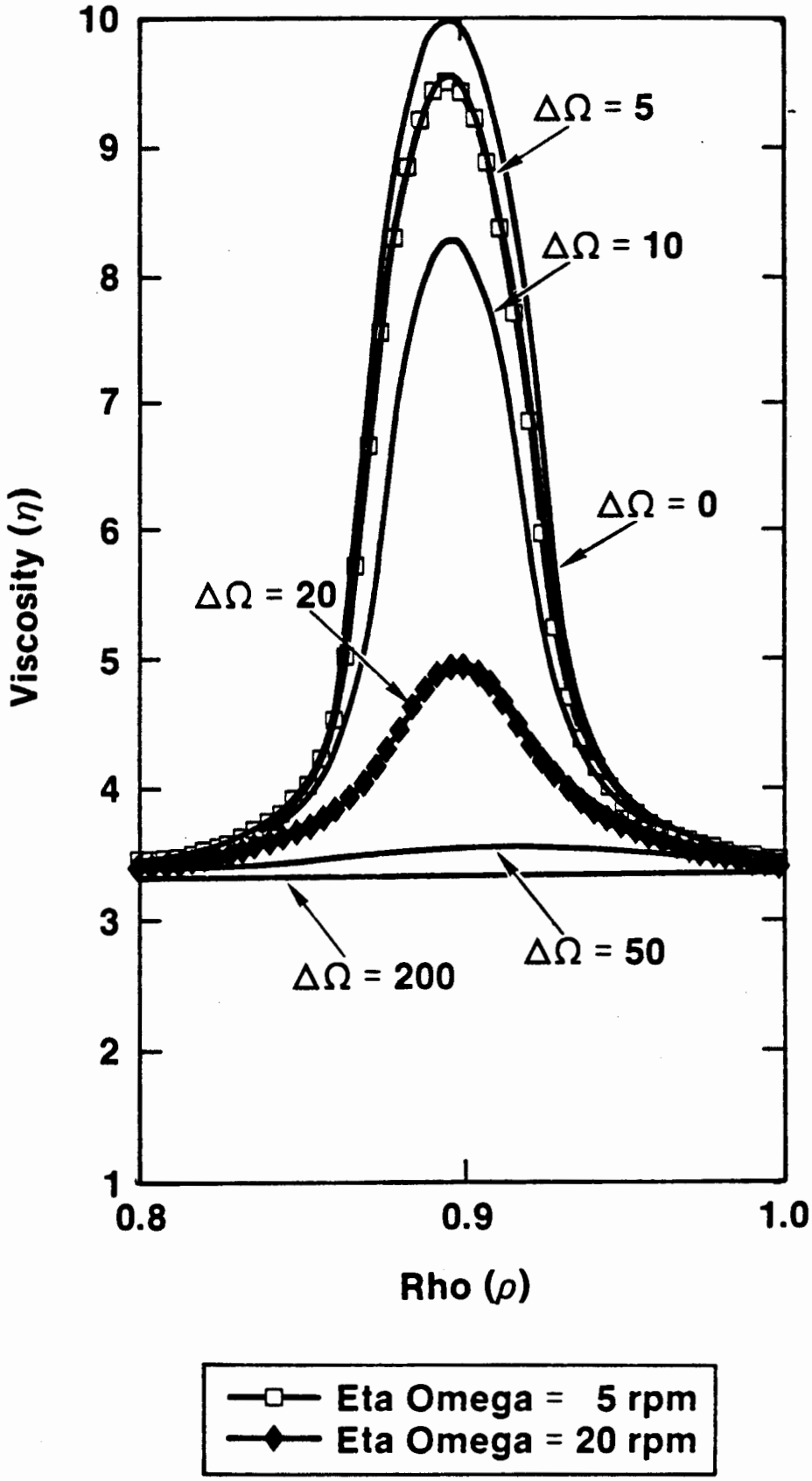

TRI-6342-405-0

# Viscosity Profiles in Couette Flow

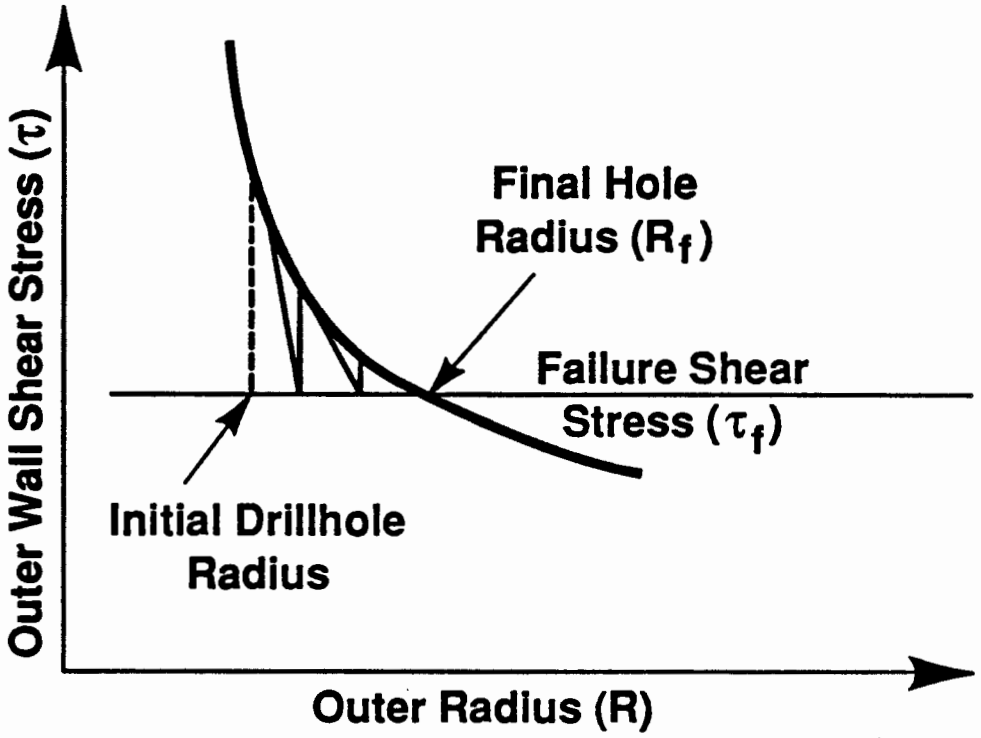


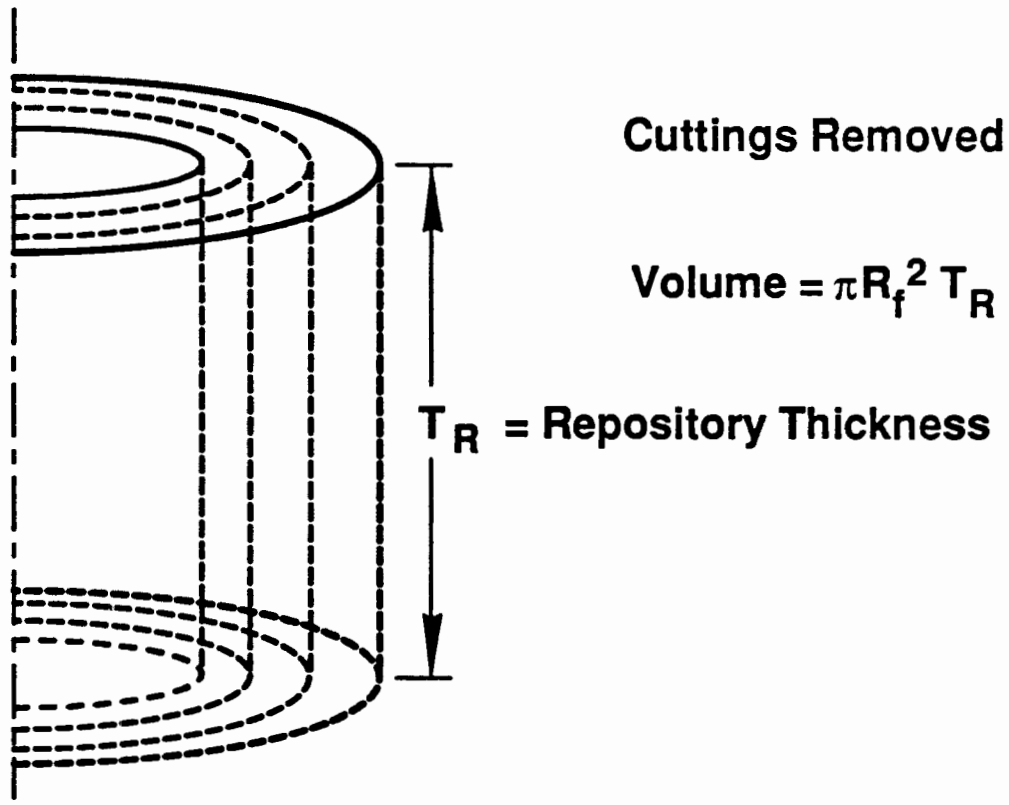

TRI-6342-406-0

# Viscosity Profiles in Helical Flow (RJ/2 = 500)




TRI-6342-407-0




TRI-6342-408-0

# Reference Case
# B. Butcher (Division 6345)

| Component | % Volume | Porosity | Hydraulic Conductivity (m/s) |
|---|---|---|---|
| Combustibles | 41 | 0.10 - 0.176 | $10^{-8}$ |
| Metallics | 40 | 0.464 - 0.516 | $10^{-5}$ |
| Sludges | 19 | 0.10 - 0.219 | $10^{-9}$ |

| | Mean | Coefficient of Variation |
|---|---|---|
| Hydraulic Conductivity | $4 \times 10^{-6}$ | $1.2 \times 10^{-2}$ |
| Porosity | 0.3 | $7 \times 10^{-2}$ |

TRI-6342-412-0

# Modified Case
# B. Butcher (Division 6345)

1) Sludge component is removed and replaced by salt

2) Metallic waste component is ground up and dispersed in salt

3) Metallic barrel component is removed

4) Combustibles are ground up and dispersed in salt

5) Resulting ground up waste-salt mixture is packaged in new containers

# Modified Case
# B. Butcher (Division 6345) (Cont.)

| | |
|---|---|
| 100% Hydraulic Conductivity $< 7 \times 10^{-10}$ m/s | 100% Porosities $< 0.12$ |
| 50% Hydraulic Conductivity $< 7 \times 10^{-13}$ m/s | 50% Porosities $< 0.08$ |
| 0% Hydraulic Conductivity $< 7 \times 10^{-15}$ m/s | 0% Porosities $< 0.06$ |

| | Mean | Coefficient of Variation |
|---|---|---|
| Hydraulic Conductivity | $2 \times 10^{-10}$ m/s | $1.2 \times 10^{-2}$ |
| Porosity | 0.085 | $2.5 \times 10^{-2}$ |

TRI-6342-411-0

# Uncertainty/Sensitivity Analysis for Human Intrusion Scenarios

| Sampled Parameter | Number Zones or Chains |
|---|---|
| Time of intrusion (exponential) | (1) |
| Intrusion borehole conductivity (lognormal) | (1) |
| Intrusion borehole porosity (normal) | (1) |
| Intrusion borehole diameter (empirical) | (1) |
| Intrusion borehole flow/Castile (triangular) | (1)* |
| Brine pocket volume (lognormal) | (1)* |
| Panel brine inflow (uniform) | (1)* |
| Radionuclide solubility (loguniform) | (1)* |
| Culebra zone hydraulic conductivity (empirical) | (8) |
| Culebra retardation/clay (empirical) | (3) |
| Culebra retardation/matrix (empirical) | (4) |
| Culebra matrix diffusivity (lognormal) | (1)* |
| Culebra block size (uniform) | (1) |
| Climate variability/precipitation (uniform) | (2) |
| | (27) |

TRI-6342-418-0

# Probability Distribution Functions for $K_d$ Values (ml/g) for Fracture Clays of the Culebra Dolomite
## M. Siegel (Division 6344)

| Percentile | Pu[Th] | Am | U, Np [Ra, Pb] |
|---|---|---|---|
| 100% | 40,000 | 4100 | 50 |
| 75% | 2300 | 500 | 20 |
| 50% | 300 | 300 | 10 |
| 25% | 100 | 200 | (1) |
| 0% | 0 | 0 | 0 |

( ) = Value poorly constrained by available data; estimated by assumption of similar behavior to homolog element.

[ ] = Radionuclide grouping added later following Lappin et al., 1989.

TRI-6342-414-0

# Probability Distribution Functions for $K_d$ Values (ml/g) for Culebra Dolomite Matrix
## M. Siegel (Division 6344)

| Percentile | Pu[Th] | Am | U[Ra, Pb] | Np |
|---|---|---|---|---|
| 100% | 1050 | 380 | 7.5 | (10) |
| 75% | 100 | 200 | 1 | (1) |
| 50% | 80 | 110 | 0.6 | (0.6) |
| 25% | 25 | 100 | ng | ng |
| 0% | 0 | 0 | 0 | 0 |

( ) = Value poorly constrained by available data; estimated by assumption of similar behavior to homolog element.

[ ] = Radionuclide grouping added later following Lappin et al., 1989.

TRI-6342-413-0

# Culebra Conductivity Zones for SECO2D

| Zone | Min | Max | Wells | Distribution |
|---|---|---|---|---|
| LND | $10^{-4}$ | $10^{-3}$ | 0 | Uniform |
| A | $10^{-4}$ | $2 \times 10^{-3}$ | 3 | Empirical |
| B | $2 \times 10^{-5}$ | $10^{-4}$ | 5 | Empirical |
| C | $6 \times 10^{-6}$ | $10^{-5}$ | 4 | Empirical |
| D | $10^{-7}$ | $4 \times 10^{-6}$ | 8 | Empirical |
| E | $4 \times 10^{-8}$ | $10^{-7}$ | 10 | Empirical |
| F | $2 \times 10^{-8}$ | $3 \times 10^{-8}$ | 4 | Empirical |
| G | $10^{-9}$ | $10^{-8}$ | 3 | Empirical |

TRI-6342-419-0

# Estimated Scenario Probabilities

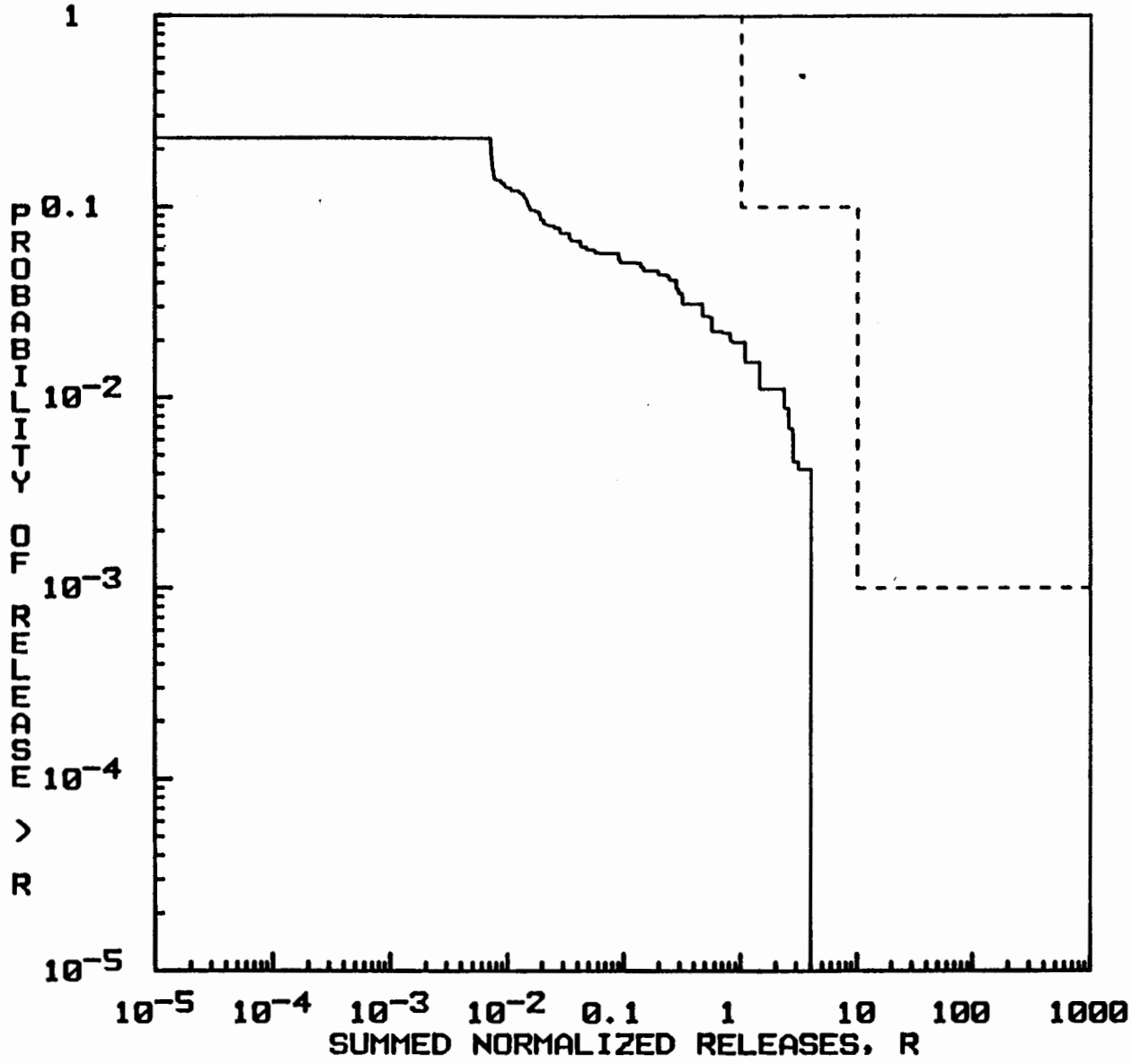
| | |
|---|---|
| BC | 0.7215 |
| E2 | 0.1478 |
| E1 | 0.0670 |
| E1E2 | 0.0137 |
| TS | 0.0380 |
| TSE2 | 0.0078 |
| TSE1 | 0.0035 |
| TSE1E2 | 0.0007 |
| | 1.0000 |

CASES: UNDISTURBED, E1, E2, AND E1E2, FOR REF WASTE

CCDPLT VERSION: 2.0 VAX DATE: 3-JUN-90 TIME: 19:41:33

WITH DRILL CUTTINGS

DASHED LINE IS EPA CONTAINMENT REQUIREMENT

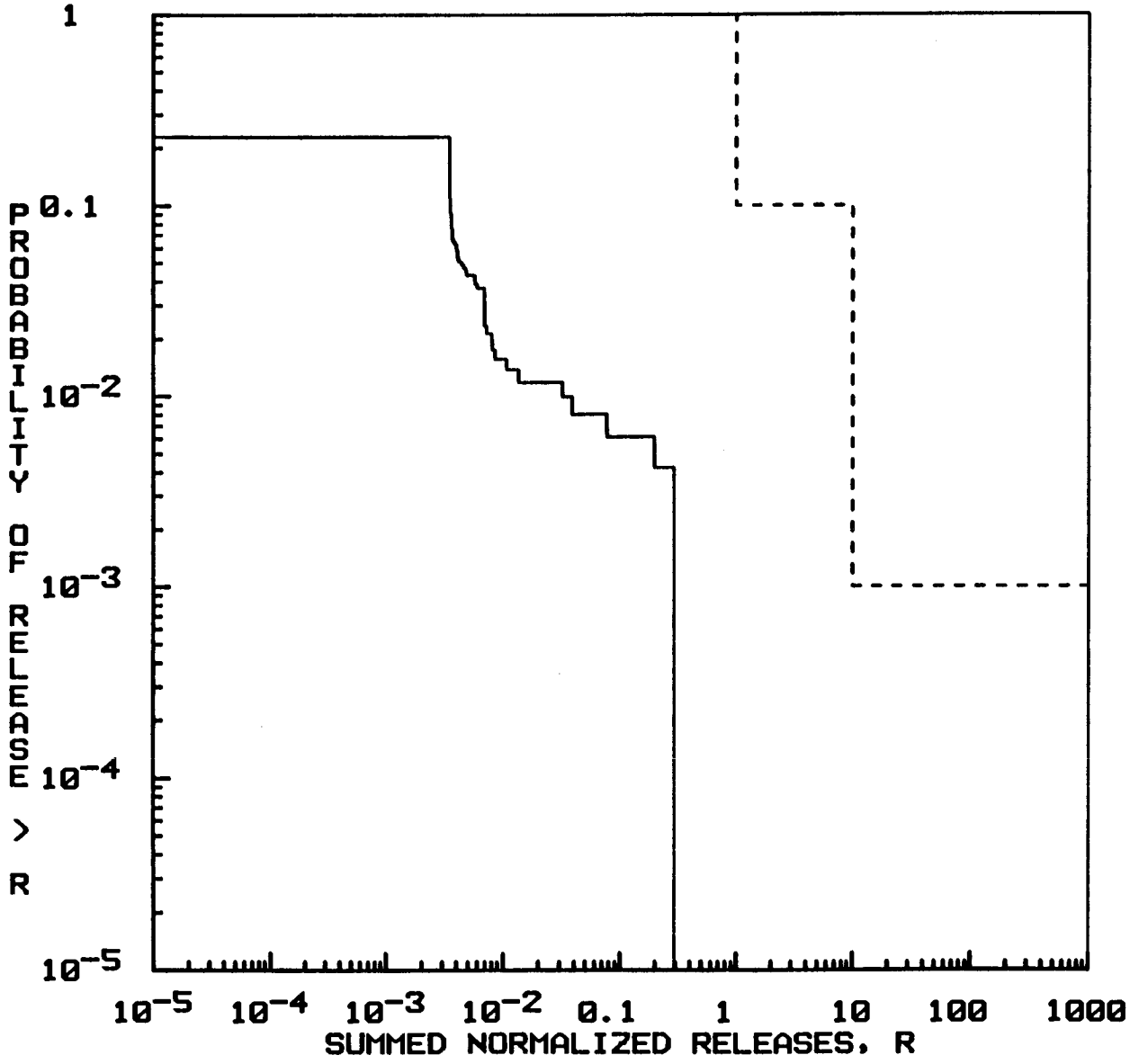


CASES: UNDISTURBED, E1, E2, AND E1E2, FOR MOD WASTE

CCDPLT VERSION: 2.0 VAX DATE: 3-JUN-90 TIME: 19:21:09

WITH DRILL CUTTINGS

DASHED LINE IS EPA CONTAINMENT REQUIREMENT



ICRP recommended risk limit is $10^{-5}$

Risk factor is $10^{-4}$/rem

Weighted mean risk of cancers for a typical individual in the critical group is the mean total dose multiplied by the risk factor

- Reference case is 10 mrem x $10^{-4}$ $rem^{-1}$ = $10^{-6}$
- Modified case is 5 mrem x $10^{-4}$ $rem^{-1}$ = 5 x $10^{-7}$
- Main contributors are U-233, Pb-210, Th-229

**A probability versus risk curve can be constructed as a ccdf that includes scenario probabilities using the previous procedure for probability versus release curves.**

# Effect of Gas Generation on the ccdf

**Question: Does gas generation increase or decrease the integrated flux of brine into an intrusion borehole?**

**(1) 1-D, 2-phase case**

**(2) 2-D, 2-phase, cylindrical geometry case with BOAST**

# 1-D Case

- Solve saturation and pressure equations
- Borehole, room, and infinite Salado
- Capillary pressure is zero or gas pressure equals brine pressure
- Gas generates for 600 years
- Borehole pressure is hydrostatic
- Salado pressure is lithostatic

# Relative Integrated Flux into Borehole at $10^4$ years

| | No gas generation | With gas generation |
|---|---|---|
| Ideal gas law | 1.00 | 0.94 |
| Redlich - Kwong (Gas Equation of State) | 1.00 | 0.94 |

TRI-6342-448-0

# BOAST II
# DOE (Bartlesville)
# J.R. Fanchi et al.

(1) 3-Phase, isothermal Darcy Flow "black oil" simulator

(2) 3-D finite difference

(3) Implicit pressure-explicit saturation formation

(4) Direct and iterative equation solvers

(5) Automatic time step control

(6) Well models: rate or pressure control

(7) Pressure-dependent physical properties

(8) Developed under contract to Department of Energy by K&A Associates of Tulsa, Oklahoma

# December Performance Assessment Studies

- Empirical distributions will be used where data are available
- Principle of maximum entropy will be used otherwise
- Failure rate function including passive marker time scales will be used for time of first intrusion
- Multiple intrusion scenarios will be included
- Both dual-porosity and discrete-fracture, clay-skin submodels will be included
- Zone sampling for including uncertainty in Culebra flow and transport will be used
- Sampling will include important CUTTER, BPCKT, GENII, and BOAST (gas effects) parameters

# December Performance Assessment Studies

- TS scenarios will be included in ccdf
- Climate variability and boundary-condition uncertainty included
- HIs will be located randomly in waste panels
- HI borehole closure effect will be included
- Crude room model using BOAST (two-phase) will be included
- Separate parallel assessment of gas effects using a more sophisticated two-phase room model
- Separate parallel assessment of uncertainty in Culebra using geostatistics

6/7/90

# Uncertainty/Sensitivity Analysis Techniques

- Differential Analysis
- Monte Carlo Analysis
- Response Surface Methodology
- Fourier Amplitude Sensitivity Test

# Steps in Differential Analysis

A differential analysis for a model given by

$$y = F(X_1, X_2, \ldots, X_m) = F(X)$$

involves the following steps:

- Select base values, ranges and distributions for the $X_j$
- Develop Taylor series for y

$$\hat{y}(X) = F(X_0) + \sum_j \frac{\partial F(X_0)}{\partial X_j} (X_j - X_{j0})$$

# Steps in Differential Analysis (Cont.)

- Evaluate uncertainty with expected value and variance

$$\hat{E}(y) = F(X_0) + \sum_j \frac{\partial F(X_0)}{\partial X_j} E(X_j - X_{j0})$$

$$\hat{V}(y) = \sum_j \left[ \frac{\partial F(X_0)}{\partial X_j} \right]^2 V(X_j)$$

- Evaluate sensitivity with normalized derivatives

$$\frac{y(X) - F(X_0)}{F(X_0)} = \sum_j \left[ \frac{\partial F(X_0)}{\partial X_j} \frac{X_{j0}}{F(X_0)} \right] \left[ \frac{X_j - X_{j0}}{X_{j0}} \right]$$

$$\frac{y(X) - F(X_0)}{\hat{SD}(y)} = \sum_j \left[ \frac{\partial F(X_0)}{\partial X_j} \frac{SD(X_j)}{\hat{SD}(y)} \right] \left[ \frac{X_j - X_{j0}}{SD(X_j)} \right]$$

TRI-6342-361-0

# Example References on Differential Analysis


R. Tomovic and M. Vukobratovic, General Sensitivity Theory, Elsevier, New York, NY, 1972.

R. P. Dickinson and R. J. Gelinas, "Sensitivity Analysis of Ordinary Differential Equations - A Direct Method," J. Comp. Phys., 21, 123-143 (1976).

P. M. Frank, Introduction to System Sensitivity Theory, Academic Press, New York, NY, 1978.

D. G. Cacuci, "Sensitivity Theory for Nonlinear Systems, Parts I and II," J. Math. Phys., 22, 2794-2802 and 2803-2812 (1981).

E. M. Oblow et al., "Sensitivity Analysis Using Computer Calculus: A Nuclear Waste Isolation Example," Nucl. Sci Eng., 94, 46-65 (1986).

Y. Ronen (Ed.), Uncertainty Analysis, CRC Press, Boca Raton, FL, 1988.

# Steps in Monte Carlo Analysis

A Monte Carlo analysis for a model given by

$$y = F(X_1, X_2, \ldots, X_m) = F(\mathbf{X})$$

involves the following steps:

- Select ranges and distributions for the $X_j$
- Generate sample

$$\mathbf{X}_i = (X_{i1}, X_{i2}, \ldots, X_{im}), \; i = 1, 2, \ldots, n$$

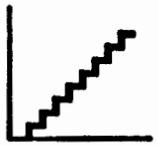
- Evaluate model

$$y_i = F(X_{i1}, X_{i2}, \ldots, X_{im}) = F(\mathbf{X}_i), \; i = 1, 2, \ldots, n$$

TRI-6342-366-0

# Steps in Monte Carlo Analysis (Cont.)

- Perform uncertainty analysis
  - expected value: $\hat{E}(y) = (\sum_i y_i)/n$
  - variance: $\hat{V}(y) = \sum_i \left[y_i - \hat{E}(y)\right]^2/n$
  - distribution function:

    $(y_i, 1/n),\ i = 1, 2, \ldots, n \Rightarrow$ 

- Perform sensitivity analysis
  - scatterplots
  - stepwise regression
  - partial correlations

TRI-6342-367-0

# Example References on Monte Carlo Analysis


N. Metropolis and S. Ulam, "The Monte Carlo Method," J. Amer. Stat. Assoc., 44, 335-341 (1949).

J. M. Hammersley and D. C. Handscomb, Monte Carlo Methods, Metheun, London, 1964.

M. D. McKay et al., "A Comparison of Three Methods for Selecting Values for Input Variables in the Analysis of Output from a Computer Code," Technometrics, 21, 239-245 (1979).

G. Schwarz and F. O. Hoffman, "Imprecision of Dose Predictions for Radionuclides Released to the Environment: An Application of a Monte Carlo Simulation Technique," Environ. Int., 4, 289-297 (1980).

R. L. Iman and W. J. Conover, "A Distribution-Free Approach to Inducing Rank Correlation Among Input Variables," Commun. Stat., B11, 311-334 (1982).

J. C. Helton et al., "Sensitivity Analysis of the Asymptotic Behavior of a Model for the Environmental Movement of Radionuclides," Ecol. Modelling, 28, 243-278 (1985).

# Steps in Response Surface Methodology

A response surface methodology analysis for a model given by

$$y = F(X_1, X_2, \ldots, X_m) = F(\mathbf{X})$$

involves the following steps:

- Select ranges and distributions for the $X_j$
- Develop experimental design for input selection

  $$\mathbf{X}_i = (X_{i1}, X_{i2}, \ldots, X_{im}), \quad i = 1, 2, \ldots, n$$

- Evaluate model

  $$y_i = F(X_{i1}, X_{i2}, \ldots, X_{im})\, F(\mathbf{X}_i), \quad i = 1, 2, \ldots, n$$

- Construct response surface

  $$\hat{y} = b_0 + \sum_j b_j X_j$$

TRI-6342-372-0

# Steps in Response Surface Methodology (Cont.)

- Perform uncertainty analysis

$$\hat{E}(y) = b_0 + \sum_j b_j E(X_j)$$

$$\hat{V}(y) = \sum_j b_j^2 V(X_j)$$

Distribution function by Monte Carlo simulation of response surface

- Perform sensitivity analysis

$$\frac{\hat{y} - \hat{E}(y)}{\hat{E}(y)} = \sum_j \left[\frac{b_j E(X_j)}{\hat{E}(y)}\right]\left[\frac{X_j - E(X_j)}{E(X_j)}\right]$$

$$\frac{\hat{y} - \hat{E}(y)}{\hat{SD}(y)} = \sum_j \left[\frac{b_j SD(X_j)}{\hat{SD}(y)}\right]\left[\frac{X_j - E(X_j)}{SD(X_j)}\right]$$

TRI-6342-373-0

# Example References on Response Surface Methodology


G. E. P. Box and K. B. Wilson, "On the Experimental Attainment of Optimum Conditions," J. Roy. Stat. Soc., Ser. B, 13, 1-38 (1951).

R. H. Myers, Response Surface Methodology, Allyn and Bacon, Boston, MA, 1971.

R. H. Morton, "Response Surface Methodology," Math. Scientist, 8, 31-52 (1983).

D. J. Downing et al., "Response Surface Methodologies for Uncertainty Analysis in Assessment Models," Technometrics, 27, 151-163 (1985).

R. Mead and D. J. Pike, "A Review of Response Surface Methodology from a Biometric Viewpoint," Biometrics, 31, 803-851 (1985).

G. E. P. Box and N. R. Draper, Empirical Model-Building and Response Surfaces, Wiley, New York, NY, 1987.

J. P. C. Kleijnen, Statistical Tools for Simulation Practitioners, Marcel Dekker, New York, NY, 1987.

# Steps in Fourier Amplitude Sensitivity Test (FAST)

A FAST analysis for a model given by

$$y = F(X_1, X_2, ..., X_m) = F(\mathbf{X})$$

involves the following steps:

- Select ranges and distributions for the $X_j$ (i.e., construct a density function p for $\mathbf{X}$ on a domain $\Omega$)

- Construct functions $G_j$ and integers $\omega_j$, $j = 1, ..., m$, such that

$$E(y) = \int_{\Omega} y(\mathbf{X})\, p(\mathbf{X})\, d\mathbf{X}$$

$$\doteq \frac{1}{2\pi} \int_{-\pi}^{\pi} y\left[G_1(\sin \omega_1 s), G_2(\sin \omega_2 s), ..., G_m(\sin \omega_m s)\right] ds$$

TRI-6342-389-0

# Steps in Fourier Amplitude Sensitivity Test (FAST) (Cont.)

- Evaluate uncertainty with expected value and variance

$$E(y) \doteq \frac{1}{2\pi} \int_{-\pi}^{\pi} y\left[G_1(\sin \omega_1 s), G_2(\sin \omega_2 s), \ldots, G_m(\sin \omega_m s)\right] ds$$

$$V(y) \doteq \frac{1}{2\pi} \int_{-\pi}^{\pi} \left\{y\left[G_1(\sin \omega_1 s), G_2(\sin \omega_2 s), \ldots, G_m(\sin \omega_m s)\right]\right\}^2 ds - E^2(y)$$

$$= \sum_{n=1}^{\infty} (A_n^2 + B_n^2),$$

TRI-6342-390-0

# Steps in Fourier Amplitude Sensitivity Test (FAST) (Cont.)

where

$$A_n = \frac{1}{\pi} \int_{-\pi}^{\pi} y\left[G_1(\sin \omega_1 s), G_2(\sin \omega_2 s), \ldots, G_m(\sin \omega_m s)\right] \cos(ns)\, ds$$

$$B_n = \frac{1}{\pi} \int_{-\pi}^{\pi} y\left[G_1(\sin \omega_1 s), G_2(\sin \omega_2 s), \ldots, G_m(\sin \omega_m s)\right] \sin(ns)\, ds$$

# Steps in Fourier Amplitude Sensitivity Test (FAST) (Cont.)

- Evaluate sensitivity by fractional contribution to variance.

  Contribution of $X_j$ to the variance V(y) of y:

$$V_j(y) \doteq \sum_{n=1}^{\infty} \left( A^2_{n\omega_j} + B^2_{n\omega_j} \right)$$

  Fractional contribution of $X_j$ to the variance of y:

$$V_j(y) / V(y)$$

# Example References on Fourier Amplitude Sensitivity Test (FAST)


R. I. Cukier et al., "Study of the Sensitivity of Coupled Reaction Systems to Uncertainties in Rate Coefficients. I. Theory," J. Chem. Phys., 59, 3873-3878 (1973).

J. H. Schaibly and K. E. Shuler, "Study of the Sensitivity of Coupled Reaction Systems to Uncertainties in Rate Coefficients. II. Applications," J. Chem. Phys., 59, 3879-3888 (1973).

R. I. Cukier et al., "Nonlinear Sensitivity Analysis of Multiparameter Model Systems," J. Comp. Phys., 26, 1-42 (1978).

G. J. McRae et al., "Global Sensitivity Analysis - A Computational Implementation of the Fourier Amplitude Sensitivity Test (FAST)," Comput. Chem. Eng., 6, 15-25 (1982).

J. W. Tilden and J. H. Seinfeld, "Sensitivity Analysis of a Mathematical Model for Photochemical Air Pollution," Atmospheric Env., 16, 1357-1364 (1982).

D. Liepmann and G. Stephanopoulos, "Development and Global Sensitivity Analysis of a Closed Ecosystem Model," Ecol. Modelling, 30, 13-47 (1985).

# Example Uncertainty/Sensitivity Analysis Based on Monte Carlo Techniques for Brine Pocket Penetration by Borehole (Scenario E1)

TRI-6342-434-0

# Step 1: Select Ranges and Distributions for Variables

**See following table**

# Uncertainty/Sensitivity Analysis for Human Intrusion Scenarios

| Sampled Parameter | Number Zones or Chains |
|---|---|
| Time of intrusion (exponential) | (1) |
| Intrusion borehole conductivity (lognormal) | (1) |
| Intrusion borehole porosity (normal) | (1) |
| Intrusion borehole diameter (empirical) | (1) |
| Intrusion borehole flow/Castile (triangular) | (1)* |
| Brine pocket volume (lognormal) | (1)* |
| Panel brine inflow (uniform) | (1)* |
| Radionuclide solubility (loguniform) | (1)* |
| Culebra zone hydraulic conductivity (empirical) | (8) |
| Culebra retardation/clay (empirical) | (3) |
| Culebra retardation/matrix (empirical) | (4) |
| Culebra matrix diffusivity (lognormal) | (1)* |
| Culebra block size (uniform) | (1) |
| Climate variability/precipitation (uniform) | (2) |
| | (27) |

TRI-6342-418-0

# Step 2: Generate Sample

Possible sampling techniques:

- Random sampling
- Stratified sampling
- Latin hypercube sampling

Technique used: Latin hypercube sampling

# Latin Hypercube Sampling

Generation of a sample of size n from m variables $X_1, X_2, \ldots, X_m$ involves the following steps:

- Divide the range of each variable into n intervals of equal probability
- Select a value at random from each interval
- Randomly pair the values for $X_1$ and $X_2$ to produce n pairs $(X_{i1}, X_{i2})$
- Randomly combine the preceding pairs with the values for $X_3$ to produce n triples $(X_{i1}, X_{i2}, X_{i3})$
- Continue this process until n m-triples

$$\mathbf{X}_i = (X_{i1}, X_{i2}, \ldots, X_{im}),\ i = 1, 2, \ldots, n,$$

are produced

The vectors $\mathbf{X}_i$ constitute the sample

TRI-6342-437-0

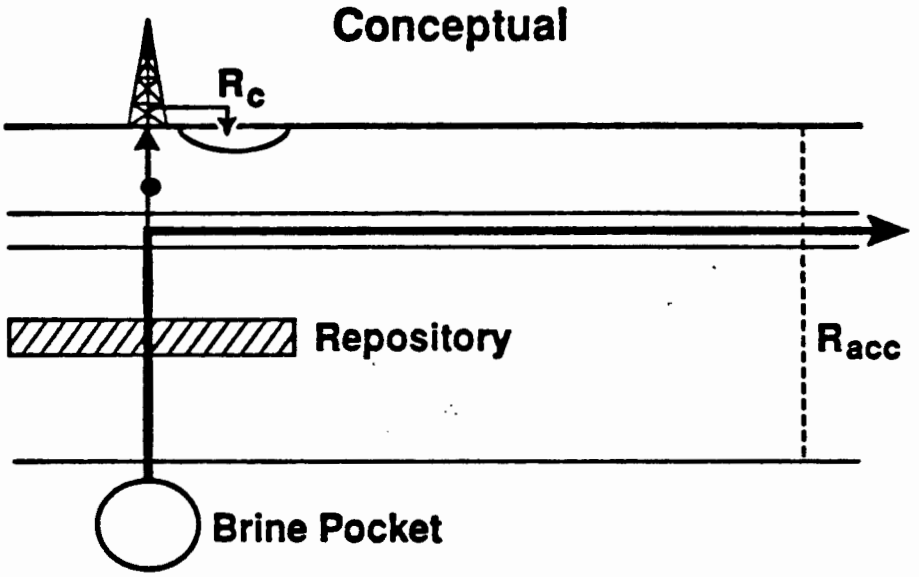
# LHS
# Sandia National Laboratories
# R.L. Iman

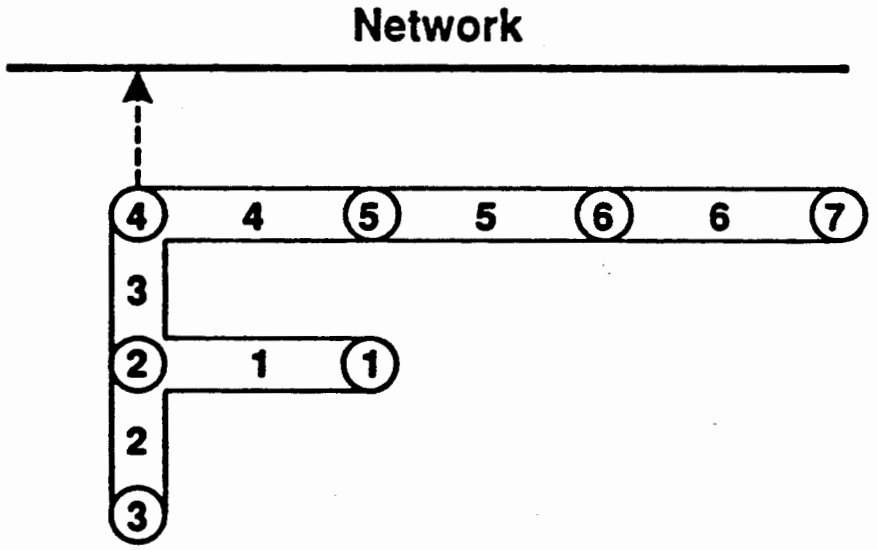
- Random sampling
- Latin hypercube sampling
- Variety of distributions: normal, lognormal, uniform, loguniform, triangular, beta, user-defined (exponential, Rayleigh, and modified Rayleigh have been added)
- Restricted pairing to induce specified rank-correlation structure

Iman, R.L., and M.J. Shortencarier, 1984. A FORTRAN 77 Program and User's Guide for the Generation of Latin Hypercube and Random Samples for Use with Computer Models, SAND83-2365, NUREG/CR-3624. Sandia National Laboratories, Albuquerque, NM.

# Step 3: Evaluate Model

# Conceptual and Network Models for E1

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# Independent Variables in Sensitivity Analysis for Scenario E1

| | | |
|---|---|---|
| SOL | = | Solubility of each nuclide (g/g) |
| BPPRES | = | Average brine pocket pressure (Pa) |
| INTRTM | = | Intrusion time (yr) |
| RMPRES | = | Room (actually, Salado) driving pressure (Pa) |
| BHCOND | = | Borehole hydraulic conductivity (m/s) |
| BHPOR | = | Borehole porosity |
| BHAREA | = | Borehole area ($m^2$) |
| RTPUTH | = | Pu and Th retardation in the Culebra |
| RTAM | = | Am retardation in the Culebra |
| RTU-PB | = | U, Np, Ra, and Pb retardation in the Culebra |
| CULCON4 | = | Culebra hydraulic conductivity in region 4 (m/s) |
| CULCON6 | = | Culebra hydraulic conductivity in region 6 (m/s) |

TRI-6342-439-0

# Dependent Variables in Sensitivity Analysis for Scenario E1

| | |
|---|---|
| Pu-240 | release (Ci) |
| U-236 | release (Ci) |
| Am-241 | release (Ci) |
| Np-237 | release (Ci) |
| U-233 | release (Ci) |
| Th-229 | release (Ci) |
| Pu-238 | release (Ci) |
| U-234 | release (Ci) |
| Th-230 | release (Ci) |
| Ra-226 | release (Ci) |
| Pb-210 | release (Ci) |
| Pu-239 | release (Ci) |
| Total | release (Ci) |

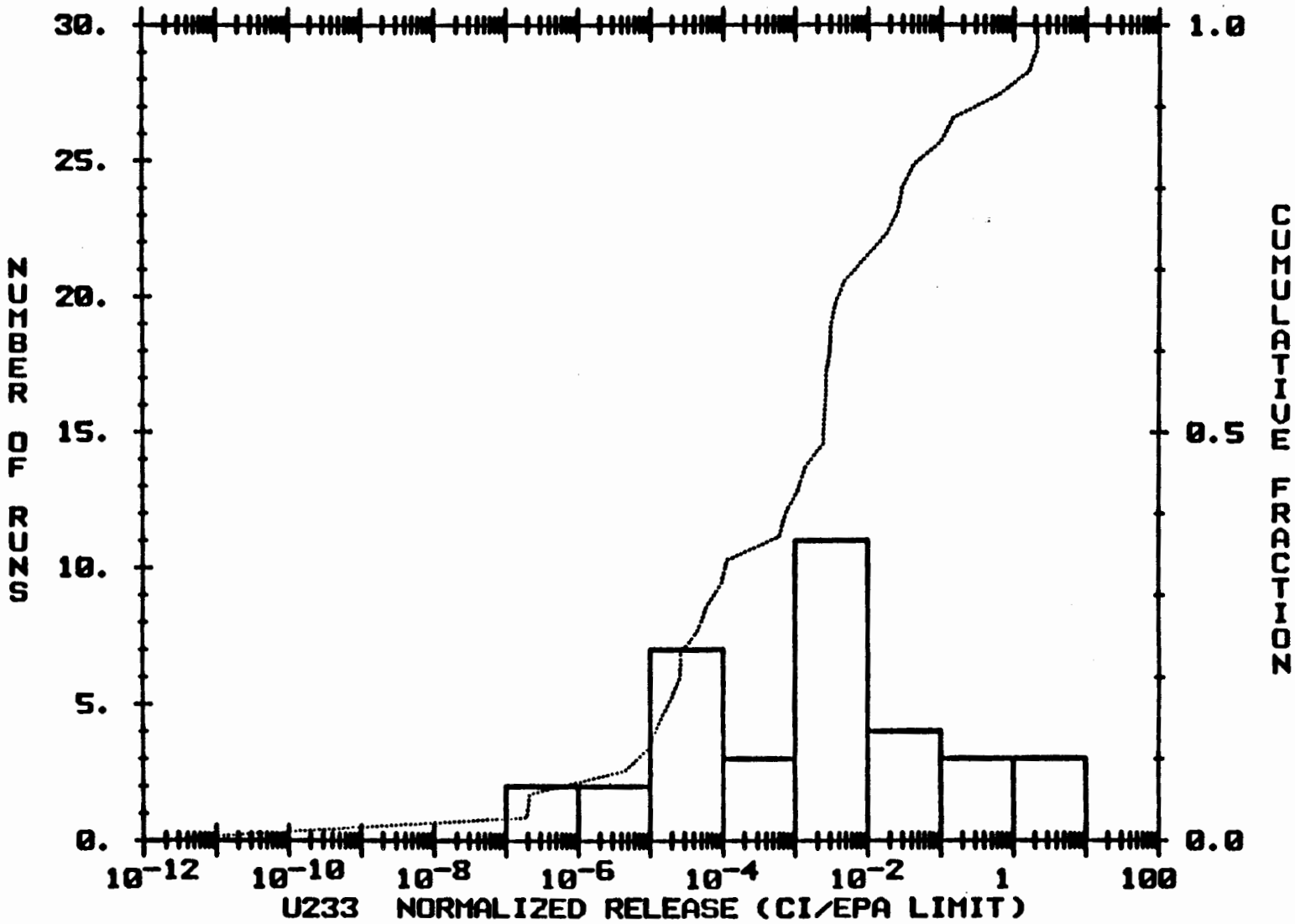
Releases calculated at land withdrawal boundary

- Release occurs at southeast corner of waste panels
- Distance from release point to boundary: 2400 m
- Flowpath from release point to boundary: 2640 m

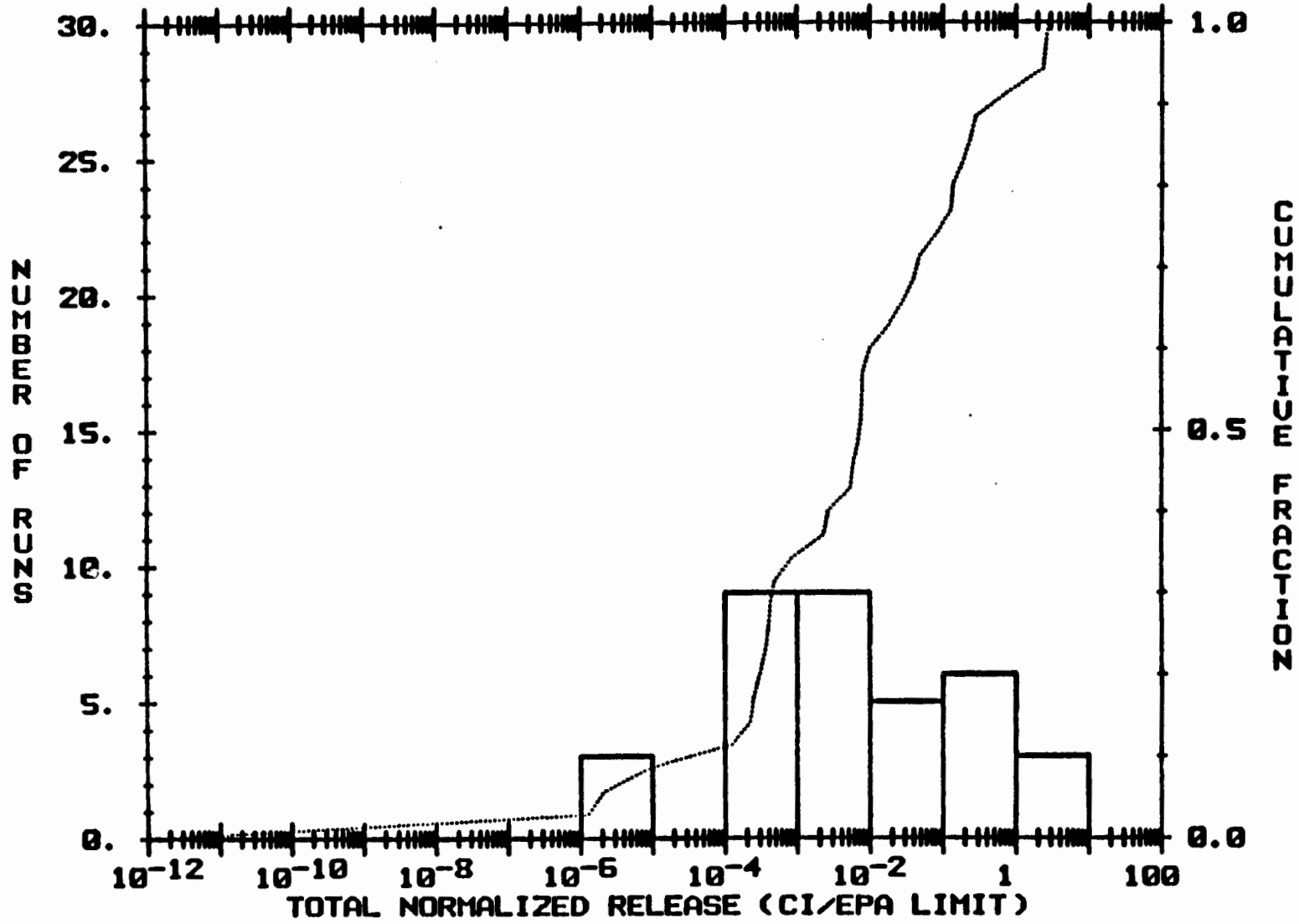
# Step 4: Perform Uncertainty Analysis

**Example distribution functions follow**

00000001LOCAL IN0001TRUSION SCENARIO 01 (CASE E1)
SCENARIO 01 END TIME = 10000 YEARS
SAMPLE SIZE = 35



00000001LOCAL IN0001TRUSION SCENARIO 01 (CASE E1)
SCENARIO 01 END TIME = 10000 YEARS
SAMPLE SIZE = 35



# Step 5: Perform Sensitivity Analysis

**Example sensitivity analyses based on regression techniques follow**

# Example Sensitivity Analysis: U-233 Release

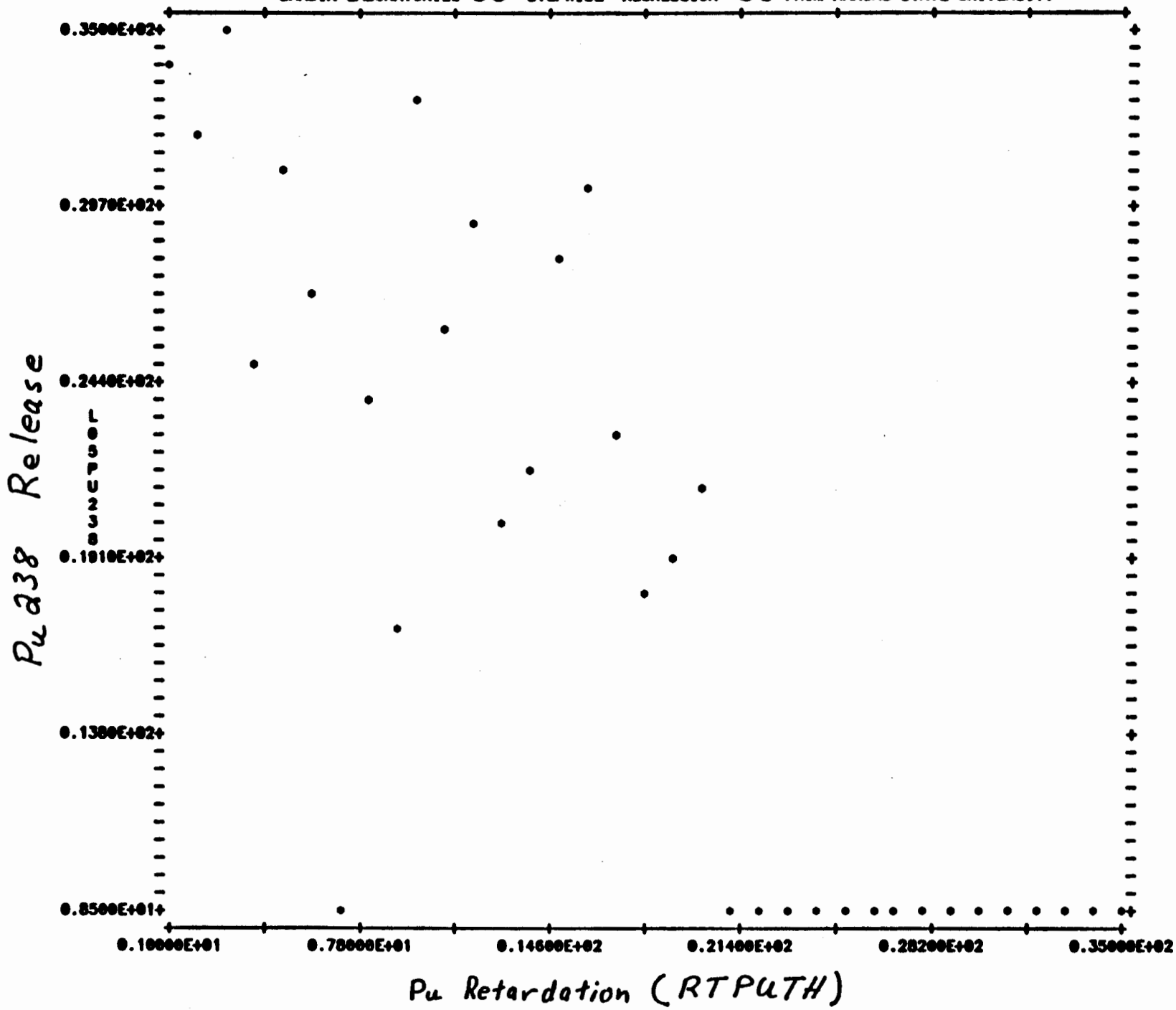
| Step | Reference Waste Variable | Coefficient | $R^2$ | Modified Waste Variable | Coefficient | $R^2$ |
|---|---|---|---|---|---|---|
| 1 | SOL | 0.93 | 0.73 | SOL | 0.82 | 0.58 |
| 2 | RTU-PB | -0.40 | 0.84 | RTU-PB | -0.47 | 0.78 |
| 3 | BHCOND | 0.28 | 0.87 | BHCOND | 0.39 | 0.89 |
| 4 | RMPRES | 0.21 | 0.90 | BPPRES | 0.27 | 0.89 |
| 5 | BPPRES | 0.18 | 0.92 | | | |

**Step:** Step in stepwise regression
**Variable:** Name of selected variable at designated step
**Coefficient:** Standardized regression coefficient for variable in final regression model
**$R^2$:** Cumulative $R^2$ value for entry of successive variables into regression model
**Note:** Regression performed with rank-transformed variables

TRI-6342-443-0

TITLE,CASE E1 REFERENCE WASTE FORM (SCENARIO 1)

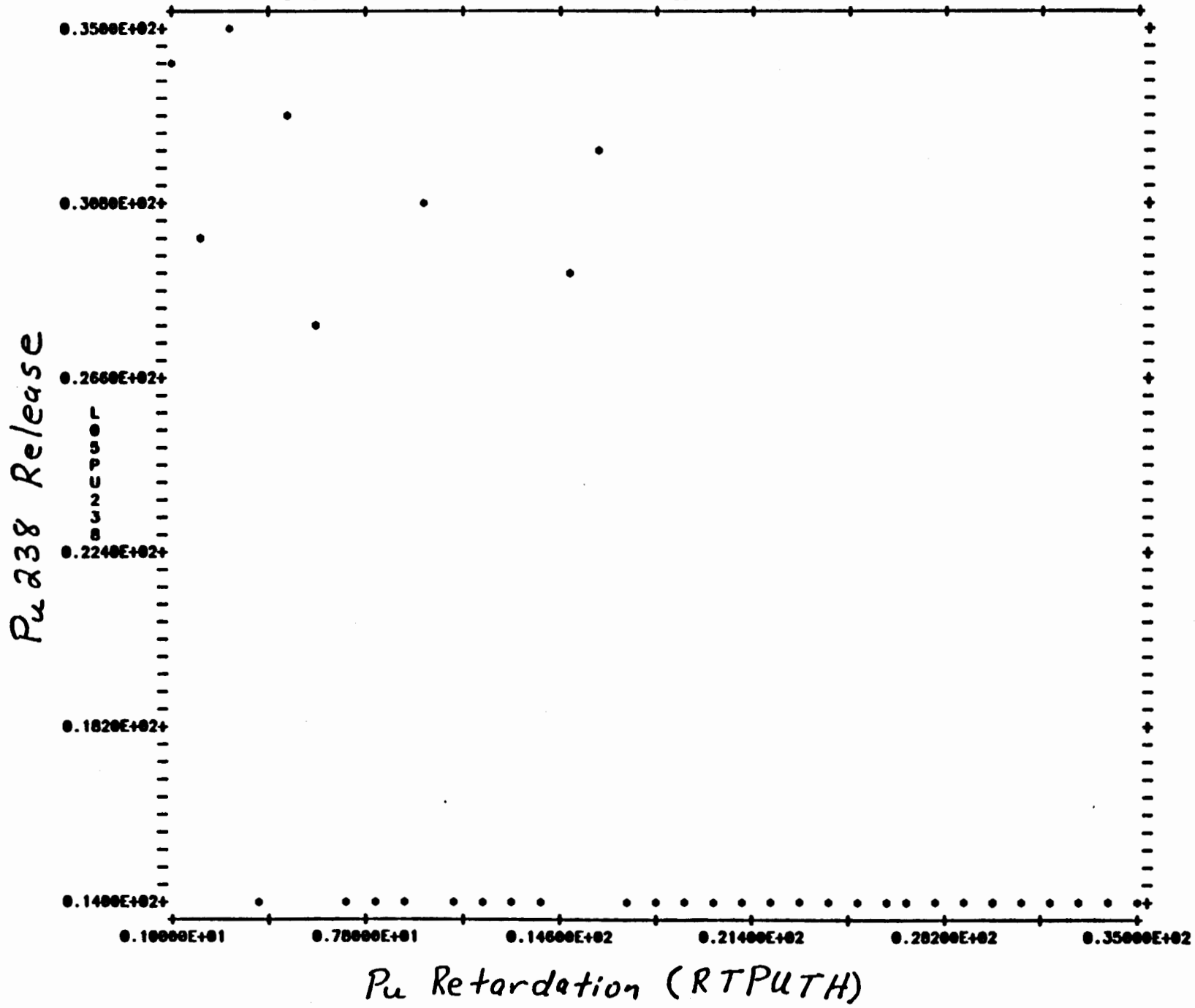
SANDIA LABORATORIES <> STEPWISE REGRESSION <> FROM KANSAS STATE UNIVERSITY



TITLE,CASE E1 MODIFIED WASTE FORM (SCENARIO 11)



SANDIA LABORATORIES <> STEPWISE REGRESSION <> FROM KANSAS STATE UNIVERSITY



# STEPWISE
# Sandia National Laboratories
# R.L. Iman

- Simple and multiple regression models
- Best subset selection by backward elimination
- Best subset selection by stepwise regression
- Rank regression option
- User-defined variable transformations
- Scatter plots, residual plots
- Correlation matrix
- PRESS criterion as a check for overfitting of data

Iman, R.L., J.M. Davenport, E.L. Frost, and M.J. Shortencarier, 1980. Stepwise Regression with PRESS and Rank Regression (Program User's Guide), SAND79-1472. Sandia National Laboratories, Albuquerque, NM.

TRI-6342-426-0

# Example Summary

Variability in radionuclide releases dominated by

- Solubility limit
- Retardation in Culebra

Results conditional on

- Ranges and distributions assigned to variables
- Use of constant hydraulic conductivity and porosity in room model
- Transport from southeast corner of waste panels to land withdrawal boundary (approximately 2400 m)

6/8/90

# UPDATE ON THE ENGINEERED ALTERNATIVES TASK FORCE

## PRESENTATION TO THE

## NATIONAL ACADEMY OF SCIENCES

## JUNE 8, 1990

## IRVINE, CALIFORNIA


## JONATHAN MYERS

## IT CORPORATION

# TOPICS COVERED

- REPORT ON CEMENT EXPERT PANEL
- UPDATED DESIGN ANALYSIS RESULTS

# CEMENT EXPERT PANEL

## MEMBERS

| NAME | ORGANIZATION |
|---|---|
| D. R. (Rip) Anderson | Sandia National Laboratories |
| Ned E. Bibler | Savannah River Site |
| John Boa | US Army Corps of Engineers |
| Barry M. Butcher | Sandia National Laboratories |
| Mark Gardiner | IT Corporation |
| Hamlin Jennings | Northwestern University |
| Lawrence Johnson | AECL Research/Whiteshell |
| Chris Langton | Savannah River Site |
| Ken E. Philipose | AECL Research/Chalk River |
| Jonathan Myers | IT Corporation |
| Lillian Wakeley | US Army Corps of Engineers |

## OBSERVERS

| | |
|---|---|
| Don Blackstone | DOE/WIPP |
| Tod Burrington | Westinghouse/WIPP |
| Andrew Peterson | Sandia National Laboratories |
| John Valdez | IT Corporation |

# REPORT ON CEMENT EXPERT PANEL

**MISSION:**

- **DETERMINE WHETHER CEMENTITOUS MATERIALS SHOULD BE CONSIDERED FURTHER FOR USE AT WIPP TO IMPROVE LONG-TERM PERFORMANCE AND REDUCE UNCERTAINTIES IN KEY PERFORMANCE PARAMETERS.**

**SPECIFIC APPLICATIONS CONSIDERED:**

- **BACKFILL**
- **WASTE FORMS**
- **CONTAINER MATERIAL**

# REPORT ON CEMENT EXPERT PANEL
## (CONTINUED)

**PANEL CONCLUSIONS:**

- THE PANEL IS CONFIDENT THAT METHODOLOGY CAN BE DEVELOPED TO EVALUATE LONG-TERM PERFORMANCE OF CEMENTITOUS MATERIAL FORMULATIONS FOR USE AT THE WIPP.

- PANEL AGREES THAT PROPERLY FORMULATED CEMENT-BASED MATERIALS ARE LIKELY TO MEET LONG-TERM PERFORMANCE CRITERIA INCLUDING PERMEABILITY AND SHEAR STRENGTH.

- PANEL AGREES THAT SPECIFIC FORMULATIONS WILL DEPEND ON THE SPECIFIC ENVIRONMENT AND MUST TAKE INTO ACCOUNT WASTE AND REPOSITORY CHARACTERISTICS.

# BACKFILL CONSIDERATIONS

**REQUIREMENTS:**

- MAINTAIN PERMEABILITY WITHIN 5 ORDERS OF MAGNITUDE OF INTACT HOST ROCK
- FILL VOIDS
- MAINTAIN ACCEPTABLE SHEAR STRENGTH
- MINIMIZE RESIDUAL FREE WATER

# BACKFILL CONSIDERATIONS
## (CONTINUED)

**RECOMMENDATIONS:**

- USE CEMENT WITH HIGH PERCENTAGE OF SALT AGGREGATE TO PROVIDE DEFORMABILITY AND MAINTAIN LOW PERMEABILITY.
- USE BRINE AS MAKEUP WATER.
- ADD MINIMUM AMOUNT OF REACTIVE COMPONENT TO ABSORB MOST OF THE FREE WATER WHEN SET.
- REACTIVE COMPONENTS THAT SHOULD BE CONSIDERED:
  - REACTIVE ALKALIS SUCH AS CaO OR MgO
  - HYDROSCOPIC GLASS
  - PORTLAND CEMENT
  - ZEOLITE
  - EXPANSIVE CLAYS
  - ALUMINATE CEMENTS

# BACKFILL CONSIDERATIONS
## (CONTINUED)

**ANTICIPATED PERFORMANCE OF RECOMMENDED FORMULATION:**

- CEMENT-BASED GROUTS CAN BE FORMULATED TO HAVE PLASTIC PROPERTIES THAT WILL SELF-SEAL AND MAINTAIN ACCEPTABLY LOW PERMEABILITIES UNDER A 2,000 PSI CONFINING STRESS.

- PERMEABILITY AND CREEP PROPERTIES WILL BE SIMILAR TO SALT.

- NO MECHANISM ANTICIPATED THAT MAY DEGRADE PERMEABILITY UNDER LITHOSTATIC CONFINING STRESS.

- CONVENTIONAL DURABILITY CONCERNS DO NOT APPLY.

  - CONSTANT TEMPERATURE
  - NO FREEZE/THAW
  - NO DIRECTED STRESS
  - ISOSTATIC CONFINING STRESS
  - NO GROUND WATER FLOW

- FORMULATION AND AGING EXPERIMENTS ARE REQUIRED TO VERIFY ANTICIPATED PERFORMANCE.

# BACKFILL CONSIDERATIONS
## (CONTINUED)

**EXPERIMENTAL OBJECTIVES:**

- HYDRATION CAPACITY
- CHARACTERIZE HYDRATED PHASES
- OPTIMAL EMPLACEMENT TECHNIQUE
- VOLUME OF RESIDUAL FREE BRINE
- PERMEABILITY UNDER CONFINING STRESS
- SET TIME
- SHEAR STRENGTH
- OPTIMAL GRAIN SIZE OF DRY MIX
- INITIAL VISCOSITY
- OPTIMAL SALT/BRINE/REACTIVE COMPONENT PROPORTIONS

# WASTE FORM CONSIDERATIONS

**REQUIREMENTS:**

- REDUCE PERMEABILITY OF WASTE FORM
- REDUCE INITIAL VOID VOLUME
- MAINTAIN ACCEPTABLE SHEAR STRENGTH
- BUFFER BRINE AT HIGH pH (OPTIONAL)

# WASTE FORM CONSIDERATIONS

## (CONTINUED)

**RECOMMENDATIONS:**

- GROUT PROBABLY CAN FILL VOIDS MORE EFFECTIVELY THAN DRY GRANULAR MATERIAL, LEADING TO MORE RAPID REPRESSURIZATION.

- FORMULATIONS SIMILAR TO THOSE CONSIDERED FOR BACKFILL SHOULD BE EVALUATED.

- GROUTING OF ALUMINUM WASTE MAY GENERATE HYDROGEN.

- INVESTIGATE METHODS TO REDUCE RADIOLYTIC GAS GENERATION:
  - ADD NITRITE SALTS
  - HEAT TO REMOVE UNBOUND WATER
  - USE SELF-DESICCATING FORMULATION
  - PRESS TO REMOVE WATER
  - INFLUX OF BRINE SHOULD BE AVOIDED

- THERE IS NO ASSURANCE THAT A GROUTED WASTE FORM WILL MAINTAIN LOW PERMEABILITY FOR 10,000 YEARS DUE TO UNKNOWN WASTE DEGRADATION PROCESSES.

# CONTAINER CONSIDERATIONS

**REQUIREMENTS:**

- NO GAS GENERATION
- NO CONTRIBUTION TO ROOM PERMEABILITY
- DEFORMABLE (SELF SEALING) AT LITHOSTATIC STRESS
- COMPATIBLE WITH BACKFILL AND WASTE FORMS

**RECOMMENDATIONS:**

- THE PANEL AGREES THAT CEMENT-BASED CONTAINERS SHOULD BE CONSIDERED ALONG WITH OTHER MATERIALS.
- A WIDE RANGE OF PROPERTIES IS ACHIEVABLE WITH CEMENT-BASED MATERIALS INCLUDING HIGH FLEXURAL AND COMPRESSIVE STRENGTH, AND LOW POROSITY AND PERMEABILITY.

# COMPARTMENTALIZATION CONCEPT

- COMPARTMENTALIZATION OF WASTE SHOULD OCCUR ON SEVERAL SCALES:

  - PIECES OF WASTE WITHIN CONTAINERS EMBEDDED IN CEMENT
  - WASTE CONTAINERS EMBEDDED IN BACKFILL
  - WASTE COMPARTMENTS WITHIN ROOMS SEPARATED BY BACKFILL
  - PANELS ISOLATED BY SEALS

- LONGEVITY OF CEMENTED WASTE FORMS IS LESS CERTAIN THAN LONGEVITY OF RECOMMENDED BACKFILL FORMULATIONS, BUT MAINTAINING LOW PERMEABILITY OF WASTE FORMS IS NOT ESSENTIAL IF COMPARTMENTALIZATION APPROACH IS ADOPTED.

# UPDATED DESIGN ANALYSIS RESULTS

## RECENT MODIFICATIONS TO DESIGN ANALYSIS MODEL

- INCORPORATION OF DRILL CUTTINGS CONTRIBUTION
  - VOLUMETRIC WASTE LOADING CALCULATED FOR EACH ALTERNATIVE
  - BOREHOLE RADIUS = 0.14 m (DIAMETER = 11 INCHES)
  - EFFECTIVE RADIUS FACTOR
    - CEMENTED AND VITRIFIED WASTE FORMS = 1
    - ALL OTHERS = 2

- ADVECTION OF GAS/BRINE INTO INTACT MARKER BED
  - TWO-PHASE FLOW ASSUMED
  - MARKER BED INITIALLY BRINE SATURATED
  - MARKER BED PERMEABILITY = $10^{-18}$ $m^2$
  - THRESHOLD PRESSURE = 0.9 MPa
  - FAR-FIELD MARKER BED PRESSURE = 70% LITHOSTATIC
  - DISTURBED MARKER BED MODELED AS 1 m x 400 m DISK
  - GAS PROPERTIES = HYDROGEN

# UPDATED DESIGN ANALYSIS RESULTS
## (CONTINUED)

- ADVECTION OF BRINE/GAS THROUGH SHAFT SEALS
  - TEMPORARY AND LONG-TERM SEALS CONSIDERED
- REVISED PHYSICAL PROPERTIES OF WASTE FORMS
  - BASED ON RECENT SNL COMPACTION EXPERIMENTS

# PROCESSES CONSIDERED IN ROOM SCALE MODEL

- GAS GENERATION AND CONSUMPTION
  - MICROBIAL
  - RADIOLYTIC
  - CHEMICAL
- CREEP CLOSURE
- BRINE INFLOW
- COMPACTION OF WASTE
- LEAKAGE OF GAS THROUGH PANEL SEALS
- LEAKAGE OF GAS UP SHAFT
- COMPRESSIBILITY OF GAS MIXTURES (REAL GAS MIXING)
- DIFFUSION OF GASES INTO THE HOST FORMATION
- ADVECTION OF GAS MIXTURES INTO THE HOST FORMATION
- ADVECTION OF GAS MIXTURES INTO THE UNDISTURBED MARKER BED
- GAS/BRINE INTERACTIONS

# VENTING REPOSITORY FOR 100 YEARS

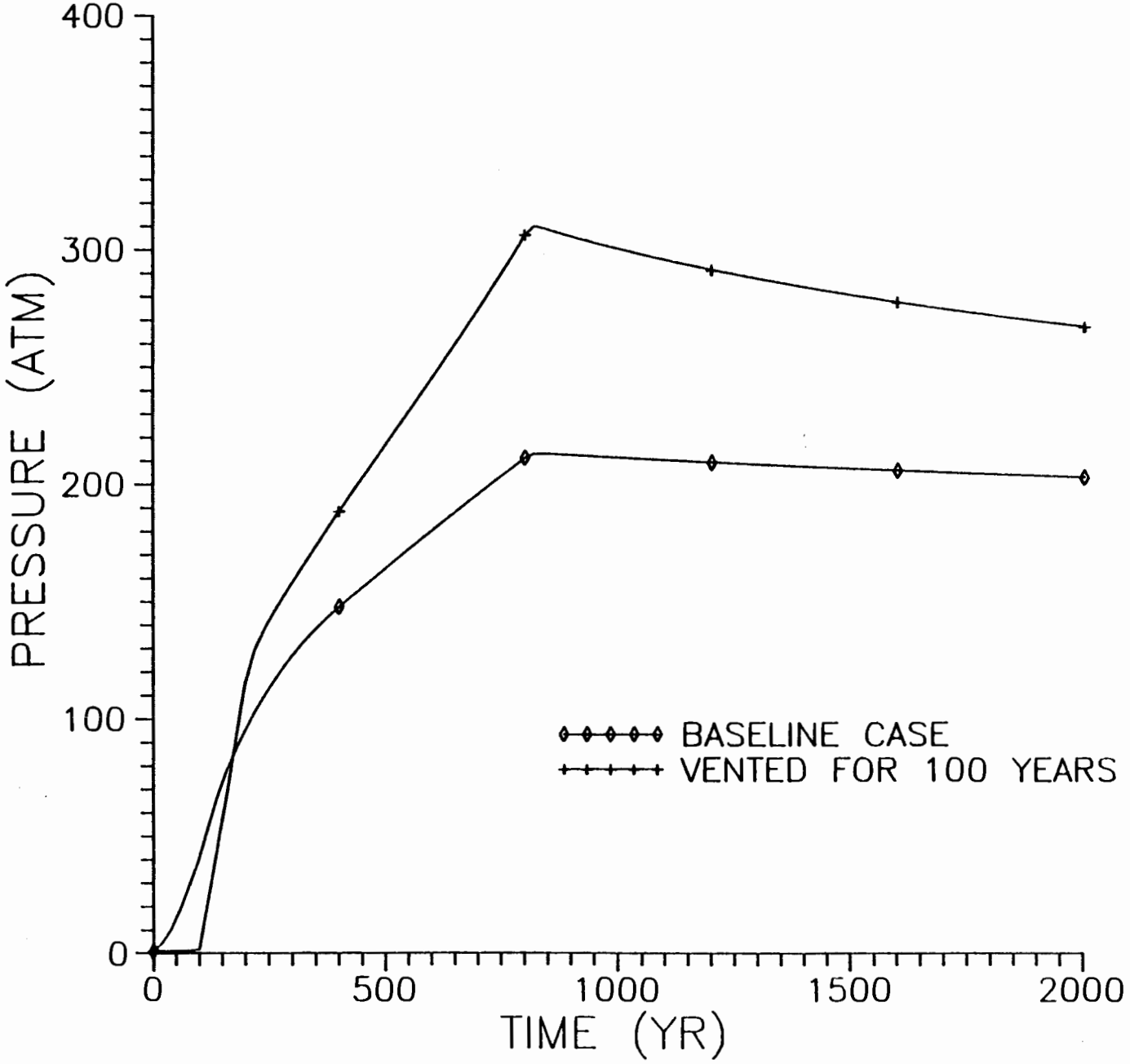
## REPOSITORY VENTED FOR 100 YEARS

- VENTING ALLOWS GREAT REDUCTION OF VOID VOLUME AT 100 YEARS
- PEAK PRESSURES AT 800 YEARS ARE 46% HIGHER THAN UNVENTED DESIGN DUE TO LOWER VOID VOLUME.

## CONCLUSION:

- VENTING INEFFECTIVE UNLESS VENT REMAINS OPEN FOR ENTIRE GAS GENERATION PERIOD (800 YEARS).

# PRESSURE VERSUS TIME PLOTS



# SCENARIOS ANALYZED

| | |
|---|---|
| E1 | CONNECTION OF ROOM WITH CASTILE BRINE RESERVOIR |
| E2 | PENETRATION OF ROOM WITH BOREHOLE |
| E1E2 | DUAL BOREHOLE |

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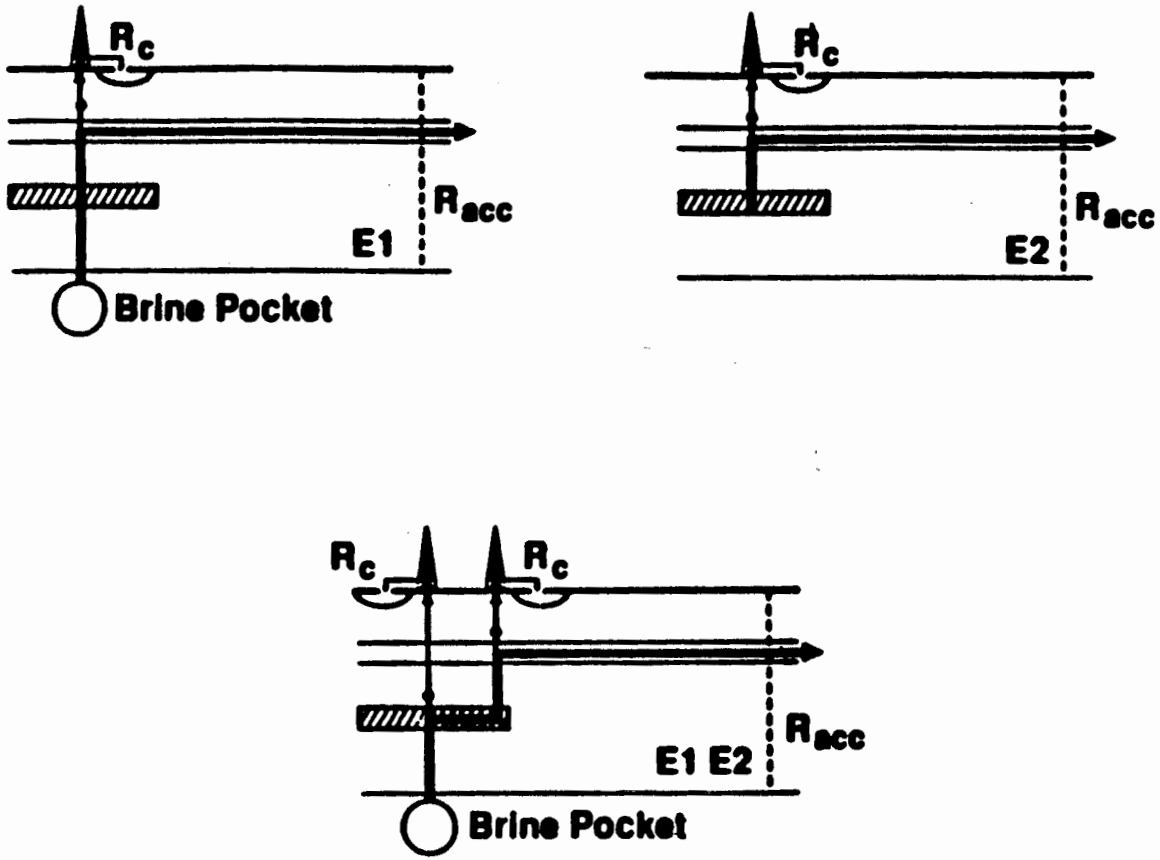
SCENARIOS ANALYZED



# CALCULATION OF EFFECTIVENESS MEASURE

$$EM = \frac{Q_a}{RL_a} + \frac{Q_b}{RL_b} + \frac{Q_c}{RL_c} + \ldots$$

**WHERE:**

| | | |
|---|---|---|
| $EM$ | = | Effectiveness Measure |
| $Q_i$ | = | Cumulative Release of Isotope i into the Culebra |
| $RL_i$ | = | Allowed Release of Isotope i |

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# RELATIVE EFFECTIVENESS MEASURE

$$\text{REM} = \frac{\text{EM OF ALTERNATIVE DESIGN}}{\text{EM OF BASELINE DESIGN}}$$

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# DESIGNS ANALYZED

| DESIGN | SLUDGES | COMBUSTIBLES | GLASS+METALS | BACKFILL |
|---|---|---|---|---|
| B.L. | A.R. | A.R. | A.R. | SALT |
| ALT 1 | CEMENT | INCIN/CEMENT | INCIN/CEMENT | SALT |
| ALT 2 | CEMENT | INCIN/CEMENT | INCIN/CEMENT | GROUT |
| ALT 3 | A.R. | SHRED/CEMENT | SHRED/CEMENT | SALT |
| ALT 4 | CEMENT | SHRED/CEMENT | SHRED/CEMENT | SALT |
| ALT 5 | CEMENT | SHRED/CEMENT | SHRED/CEMENT | GROUT |
| ALT 6 | VITRIFY | INCIN/VITRIFY | INCIN/VITRIFY | SALT |
| ALT 7 | VITRIFY | INCIN/VITRIFY | INCIN/VITRIFY | GROUT |

A.R. = AS RECEIVED (UNPROCESSED)

B.L. = BASELINE CASE (CURRENT DESIGN)

# MAXIMUM GAS PRESSURE AND RELATIVE PRESSURE RESULTS

| DESIGN | $P_{MAX}$ (atm) | $P_{REL}$* |
|---|---|---|
| B.L. | 213 | 1.00 |
| ALT 1 (ICCSB) | 146 | 0.68 |
| ALT 2 (ICCGB) | 146 | 0.68 |
| ALT 3 (SHREDCMT) | 241 | 1.13 |
| ALT 4 (SCCSB) | 224 | 1.05 |
| ALT 5 (SCCGB) | 175 | 0.82 |
| ALT 6 (VITSB) | 146 | 0.68 |
| ALT 7 (VITGB) | 146 | 0.68 |

$$*P_{REL} = \frac{P_{MAX}^{ALT}}{P_{MAX}^{BL}}$$

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# RELATIVE EFFECTIVENESS MEASURE RESULTS WITHOUT CUTTINGS AND RELATIVE EFFECTIVENESS MEASURE RESULTS WITH CUTTINGS

| DESIGN | E1 | E2 | E1E2 |
|---|---|---|---|
| B.L. | 1.00 | 1.00 | 1.00 |
| | 1.00 | 1.00 | 1.00 |
| ALT1 (ICCSB) | 0.31 | 0.57 | $2.13 \times 10^{-3}$ |
| | 0.31 | 0.53 | $3.80 \times 10^{-3}$ |
| ALT2 (ICCGB) | 0.26 | $5.40 \times 10^{-2}$ | $4.10 \times 10^{-4}$ |
| | 0.26 | 0.13 | $1.93 \times 10^{-3}$ |
| ALT3 (SHREDCMT) | 0.20 | 0.79 | $2.08 \times 10^{-4}$ |
| | 0.20 | 0.66 | $1.25 \times 10^{-3}$ |
| ALT4 (SCCSB) | 0.20 | 0.51 | $1.63 \times 10^{-4}$ |
| | 0.20 | 0.45 | $1.18 \times 10^{-3}$ |
| ALT5 (SCCGB) | 0.18 | $3.29 \times 10^{-2}$ | $2.77 \times 10^{-5}$ |
| | 0.18 | $7.66 \times 10^{-2}$ | $9.49 \times 10^{-4}$ |
| ALT6 (VITSB) | 0.12 | $6.16 \times 10^{-2}$ | $3.19 \times 10^{-5}$ |
| | 0.12 | 0.19 | $2.53 \times 10^{-3}$ |
| ALT7 (VITGB) | $9.94 \times 10^{-3}$ | $3.66 \times 10^{-2}$ | $2.48 \times 10^{-6}$ |
| | $1.07 \times 10^{-2}$ | 0.16 | $2.29 \times 10^{-3}$ |

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# SUMMARY OF MODELING RESULTS

**UNDISTURBED SCENARIO:**

- VENTING REPOSITORY FOR 100 YEARS RESULTS IN HIGHER PEAK GAS PRESSURES AT 800 YEARS DUE TO REDUCTION IN VOID VOLUME.
- HYDROGEN GENERATION FROM ANOXIC CORROSION APPEARS TO BE SELF-LIMITING. DATA NEEDED ON BRINE AVAILABILITY AND CORROSION RATE IN HUMID ENVIRONMENT TO VERIFY ASSUMPTIONS.
- OVERPRESSURIZATION IS DUE TO MICROBIAL GAS GENERATION. DATA NEEDED ON ACTUAL MICROBIAL GAS GENERATION RATES.

# SUMMARY OF MODELING RESULTS
## (CONTINUED)

**HUMAN INTRUSION SCENARIOS:**

- RELEASE FROM CUTTINGS IS MAJOR CONTRIBUTOR FOR ALTERNATIVES WITH LOW STORAGE ROOM CONDUCTIVITIES.
- STACK HEIGHT MAY HAVE TO BE REDUCED FOR CONCENTRATED WASTE FORMS TO LIMIT RELEASE FROM CUTTINGS.
- CASTILE BRINE SCENARIO (E1) HAS GREATEST CONSEQUENCE.
- RELATIVE IMPROVEMENTS OF UP TO TWO ORDERS OF MAGNITUDE POSSIBLE FOR E1 SCENARIO WITH ALTERNATIVE WASTE FORMS AND BACKFILL.

6/8/90

# ENGINEERED ALTERNATIVES EVALUATION UPDATE

PRESENTATION TO THE

NATIONAL ACADEMY OF SCIENCES

JUNE 8, 1990

IRVINE, CALIFORNIA

JOHN MCFEE

IT CORPORATION

# RECOMMENDED ALTERNATIVE WASTE FORMS

# FOR INCORPORATION INTO

# WIPP EXPERIMENTAL PROGRAM

# PARAMETERS THAT AFFECT PERFORMANCE

- BIOLOGICAL GAS GENERATION
- CORROSION GAS GENERATION
- RADIOLYTIC GAS GENERATION
- WASTE FORM PERMEABILITY
- WASTE ELEMENT SOLUBILITY

# TYPES OF WASTE FORM MODIFICATIONS TO ADDRESS GAS GENERATION

**LEVEL I** "AS RECEIVED" WASTE FORMS

**LEVEL II*** PROCESSED TO REDUCE GAS GENERATION RATES, PERMEABILITY, AND SOLUBILITY

**LEVEL III*** PROCESSED TO ELIMINATE GAS GENERATION POTENTIAL AND SIGNIFICANTLY LOWER PERMEABILITY AND SOLUBILITY

* STEEL DRUMS WILL PROBABLY HAVE TO BE ELIMINATED FROM AT LEAST NEWLY-GENERATED WASTE

# EATF RECOMMENDED WASTE FORMS FOR INCLUSION IN THE WIPP EXPERIMENTAL PROGRAM

| BASIC WASTE FORMS | ADDITIONAL VARIATIONS |
|---|---|
| VITRIFIED (COMBUSTIBLES)* | VITRIFIED (SLUDGE) * |
| CEMENTED (SLUDGE) | SHRED AND CEMENT (COMBUSTIBLES) |
| | SHRED AND CEMENT (GLASS/METAL) |
| | INCINERATE AND CEMENT (COMBUSTIBLE) |

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* LABORATORY STUDIES ONLY

# ENGINEERING CRITERIA WILL DIRECT WHICH ALTERNATIVES ARE RECOMMENDED FOR FURTHER EVALUATION

FEE056-3

# EATF RECOMMENDED WASTE FORMS FOR INCLUSION IN THE WIPP EXPERIMENTAL PROGRAM (CONTINUED)

| BASIC WASTE FORMS | ADDITIONAL VARIATIONS |
|---|---|
| COMPACTED (COMBUSTIBLES) | SHRED AND COMPACT (GLASS/METAL) |
| | SHRED, ADD SALT AND COMPACT (GLASS/METAL) |
| | SHRED, ADD SALT AND COMPACT (COMBUSTIBLES) |
| SHRED AND ADD BENTONITE FILLER | -- |
| METAL INGOTS * | -- |
| pH BUFFERED (LIME) | pH BUFFERED (CEMENT) |
| | pH BUFFERED (ALUMINA) |

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* LABORATORY STUDIES ONLY

# THE CRITERIA FOR EVALUATION OF ALTERNATIVES RECOMMENDED FOR PERFORMANCE ASSESSMENT ARE:

- COST
- IMPLEMENTATION SCHEDULE (INCLUDING REGULATORY/INSTITUTIONAL)
- TECHNOLOGY STATUS
- SAFETY
  - OPERATIONAL
  - TRANSPORTATION
- EFFECTIVENESS

# THE TECHNOLOGY STATUS OF WASTE COMPACTORS INCLUDES:

- DOE HAS TWO LLW COMPACTORS
- DOE HAS PROCURED ONE TRU COMPACTOR
- ONE COMMERCIAL FIXED BASE COMPACTOR FOR LLW IS IN OPERATION

FEE056

# THE TECHNOLOGY STATUS FOR WASTE CEMENTATION IS:

- DOE HAS 15 CEMENT SYSTEMS IN OPERATION
- SEVERAL COMMERCIAL SUPPLIERS OF CEMENT SYSTEMS EXIST
- COMMERCIAL CEMENTATION SERVICES ARE AVAILABLE

FEE056

# THE TECHNOLOGY STATUS OF RADIOACTIVE WASTE INCINERATION INCLUDES:

- OVER 90 RADIOACTIVE WASTE INCINERATORS HAVE BEEN OPERATED
- DOE HAS OPERATED ONE TRU WASTE INCINERATOR
- REGULATORY ISSUES ARE CURRENTLY IMPEDING SOME APPLICATIONS
- RADIOACTIVE WASTE INCINERATORS ARE OPERATED IN GERMANY, FRANCE, CANADA AND JAPAN
- TWO COMMERCIAL LLW WASTE INCINERATORS HAVE BEEN RECENTLY OPERATED IN THE UNITED STATES

FEE056

# THE TECHNOLOGY STATUS OF PLASMA HEATED THERMAL TREATMENT SYSTEMS INCLUDES NONRADIOACTIVE DEVELOPMENT TESTING

FEE056-10

# THE TECHNOLOGY STATUS OF MICROWAVE MELTING (GLASSIFICATION) SYSTEMS INCLUDES DEVELOPMENT SYSTEMS IN THE U.S. AND JAPAN

FEE056-1

## EXISTING AND PLANNED DOE SUPER COMPACTORS

| DOE FACILITY/REF | STATUS | TONNAGE | CAPACITY | REFERENCES |
|---|---|---|---|---|
| Idaho National Engineering Lab (WERF) | Existing | 200 T box | 1,400 $m^3$/yr uncompted | Gillins, 1989; Gillins and Larsen, 1987 |
| Rocky Flats Plant (SRF) | 1990 | 2,200 T drum | 1,400 $m^3$/yr uncomptd | Barthel, 1988; Barthel, 1989 |
| West Valley (WVDP) | Existing | 1,000 T drum | 4,600 $m^3$/yr | Frank et al., 1988 |

## DOE FACILITY CEMENTATION SYSTEMS

| DOE FACILITY | TREATMENT | UNIT NAME | WASTE TREATMENT CAPACITY[1] | RCRA PERMIT STATUS | SOLID'N AGENT(S) | REFERENCE |
|---|---|---|---|---|---|---|
| **TRU-Waste Treatment Systems** | | | | | | |
| Los Alamos National Lab, NM | ID Solid'n. | TA-50 Vacuum Filter Operation | 1500 l/d | None | Portland Cement/ Diatomaceous Earth | Warren, 1988; Warren, 1989 |
| | ID Solid'n. | Pretreatment Plant | 1900 l/yr | | Portland Cement | |
| | ID Solid'n. | TA-55 Plutonium Facility | 40 l/d | | Envirostone | |
| Rocky Flats Plant, CO | ID Solid'n. | 374 Vacuum Filter Operation | 270 kg/hr | IS | Portland Cement/ Diatomaceous Earth | McMenus, 1989; Fox et al., 1988; DOE, 1988 |
| | ID Solid'n. | 774 Vacuum Filter Operation | 600 kg/d | IS | Portland Cement/ Diatomaceous Earth | |
| | ID Solid'n. | 774 OASIS System | 450 l/shift | IS | Envirostone | |
| | ID Solid'n. | 774 Special Setups Operation | 80 l/d | IS | Portland Cement/ RAMCOTE | |
| **Low-Level Waste Treatment Systems** | | | | | | |
| West Valley, NY | ID Solid'n. | Cement Solidification System | 8860 l/d | None | Portland Cement plus Additives | Gessner, 1988; Cwynar et al., 1984, Weingart et al., 1987 |
| Mound, OH | ID Solid'n. | Alpha-Contaminated Water Processing Facility | 3800 l/mo | None | Portland Cement | Mills, 1989; Fox, 1986 |
| | ID Solid'n. | Tritiated Water Solidification Facility | 9500 l/mo | None | Portland Cement/ Clay | Mills, 1989 |
| Idaho National Eng'g Lab, ID | ID Solid'n. | Waste Experimental Reduction Facility | 450 kg/d | IS | Portland Cement | Larsen, 1989; Larsen et al., 1988; Boehmer et al., 1987 |
| | ID Solid'n. | Waste Engineering Development Facility | 450 kg/d | IS | Portland Cement | |
| Savannah River Plant, SC | Solid'n. | Z Area Saltstone | 600 l/min | | Portland Cement/ Slag/Flyash | Harley, 1989, Dole, 1985, Wilhite et al., 1988, Sturm, 1987 |
| | ID Solid'n. | Naval Fuels Saltcrete | 870 kg/d | None | Portland Cement | |

DOE FACILITY CEMENTATION SYSTEMS
(CONTINUED)

| DOE FACILITY | TREATMENT | UNIT NAME | WASTE TREATMENT CAPACITY[1] | RCA PERMIT STATUS | SOLID'N AGENT(S) | REFERENCE |
|---|---|---|---|---|---|---|
| Hanford Operations, WA | Solid'n. | Grout Treatment Facility | 160 l/min | IS | Portland Cement/ Flyash/Clay | Nevarez, 1988; DOE, 1988; Guymon et al., 1988; Lokken and Mitchell, 1988 |
| Lawrence Livermore Nat'l Lab, CA | ID Solid'n. | Bldg. 513 Solidification Unit | 950 l/d | IS | Various | Aycock, 1988; DOE, 1988 |
| Oak Ridge Gaseous Diffusion Plant, TN | Solid'n. | Hydrofracture Grout Facility | NIO | IS | | Vaughn, 1988; Fox et al., 1986 |
| | Solid'n. | Sludge Treatment Facility | 120 $m^3$/wk | IS | Portland Cement/ Flyash | |
| Oak Ridge Gaseous Diffusion Plant, TN | Solid'n. | Concrete Fixation Facility | | IS | Portland Cement/ Flyash/Slag | Gilliam et al., 1988 |
| Rocky Flats Plant, CO | Solid'n. | 788 Pondcrete Operation | 20 kg/min | IS | Portland Cement | McMenus, 1989; Fox et al., 1988; DOE, 1988 |
| | Solid'n. | Bldg. 374 Saltcrete Operation | 730 kg/hr | IS | Portland Cement | |

[1]Waste treatment capacity figures are rounded to the nearest 10.
ID = In drum; final product drummed.
NIO = Not in operation.
IS = Interim Status

## SUMMARY OF RADIOACTIVE WASTE INCINERATORS[1]

| INSTALLATION | LOCATION | BUILT[1] | STATUS[2] | TYPE | CAPACITY | TYPE[3] | TYPE[4] | REFERENCE |
|---|---|---|---|---|---|---|---|---|
| U.S. Low Activity Incinerators | | | | | | | | |
| Knolls Atomic Power Laboratory | NY | 1949 | N | EA | | | Wet Scrubber | Farinoso and Wilson, 1983 |
| Argonne National Laboratory | IL | 1951 | N | EA | | | Wet Scrubber | Farinoso and Wilson, 1983 |
| Los Alamos Scientific Laboratory | NM | 1951 | N | EA | 90 kg/hr | C | Wet Scrubber | Perkins, 1976 |
| Bettis Atomic Power Laboratory | PA | 1953 | N | | | | Wet Scrubber | Farinoso and Wilson, 1983 |
| Shippingport Atomic Power Station | PA | | N | EA | | | | Farinoso and Wilson, 1983 |
| U.S. Nuclear Defense Laboratory | MD | 1963 | N | CA | | | | Farinoso and Wilson, 1983 |
| Douglas United Nuclear | WA | 1967 | N | EA | | C, P, R | None | Farinoso and Wilson, 1983 |
| Yankee Atomic Electric Co. | MA | 1968 | N | EA | | C | Wet Scrubber | Farinoso and Wilson, 1983 |
| Lawrence Livermore National Laboratory | CA | 1978 | 0 | CA | S 0.4 $m^3$/hr<br>L 110 l/hr | | None | Fox et al., 1986;<br>Jackson, 1988 |
| CECo - Byron Nuclear Station | IL | 1983 | AS | FB | | C, P, R | Wet Scrubber | Farinoso and Wilson, 1983;<br>Terrell, 1989 |
| CECo - Braidwood Nuclear Station | IL | | AS | FB | | C, P, R | Wet Scrubber | Farinoso and Wilson, 1983;<br>Terrell, 1989 |
| Duke Power - Oconee Nuclear Station | SC | 1983 | in Test | FB | | C, P, R | Wet Scrubber | Farinoso and Wilson, 1983;<br>Terrell, 1986;<br>Terrell, 1989 |
| Savannah River Plant (BGI) | SC | 1983 | Hold | CA | 180 kg/hr | C, FCW, P, R | Dry | Friedline, 1988, Irujo and Bucci, 1987 |
| Idaho National Engineering Lab - WERF | ID | 1984 | O | CA | 180 kg/hr | C, P, R | Dry | McFee and Gillins, 1986 |
| Georgia Power - Vogtle Nuclear Station | GA | 1985 | AS | FB | | C, P, R | Wet Scrubber | Farinoso and Wilson, 1983;<br>Terrell, 1989 |
| Babcock and Wilcox | PA | 1985 | AS | CA | | | Wet Scrubber | Bowles et al., 1986,<br>Smith, 1989 |
| Oak Ridge Gaseous Diffusion Plant (K-25) | TN | 1987 | 0 | RK | S 330 kg/hr<br>L 680 l/hr | C, S, N | Wet Scrubber | Fox et al., 1986;<br>DOE, undated |
| Savannah River Plant (CIF) | SC | (1991) | UC | RK | 470 kg/hr | C, FCW, P, R | Wet Scrubber | Friedline, 1988; Weber, 1987 |
| Los Alamos National Laboratory | NM | (1991) | | CA | | | Wet Scrubber | DOE, 1988; Warren, 1989 |
| Lawrence Livermore National Laboratory | CA | (1992) | | RK | | | Wet Scrubber | DOE, 1988; Jackson, 1988 |
| Pantex | TX | (1994) | | CA | | | | Stockton and Burkhard, 1988; DOE, 1988 |

## SUMMARY OF RADIOACTIVE WASTE INCINERATORS[1]
## (CONTINUED)

| INSTALLATION | LOCATION | BUILT[1] | STATUS[2] | TYPE | CAPACITY | TYPE[3] | TYPE[4] | REFERENCE |
|---|---|---|---|---|---|---|---|---|
| Non-U.S. Low Activity Incinerators | | | | | | | | |
| Chalk River Nuclear Laboratory | Canada | 1960 | N | CA | | C, P, R | Dry | Farinoso and Wilson, 1983 |
| Belgian Nuclear Center - Mol | Belgium | 1960 | N | CA | | C, P, R | Wet Scrubber | Farinoso and Wilson, 1983 |
| Harwell Nuclear Research Center | U.K. | 1962 | | CA | | C, P, R | Dry | Farinoso and Wilson, 1983 |
| Nuclear Research Center - Karlsruhe | Germany | 1963 | N | EA | | C, FCW, P, R | Dry | Farinoso and Wilson, 1983 |
| Berkeley Nuclear Laboratory | U.K. | 1965 | | CA | | C, P, R | Wet Scrubber | Farinoso and Wilson, 1983 |
| JAERI - Tokai Research Establish. | Japan | 1966 | N | EA | | C, P, R | Wet Scrubber | Farinoso and Wilson, 1983 |
| CEBG - Bradwell Power Station | U.K. | 1967 | | EA | | C, P, R | Wet Scrubber | Farinoso and Wilson, 1983 |
| Hunterston "A" Station | U.K. | 1967 | | EA | | C, P, R | Wet Scrubber | Farinoso and Wilson, 1983 |
| Cadrache Nuclear Study Center | France | | 0 | EA | | C, FCW, P, R | | Farinoso and Wilson, 1983 |
| Fontenay-Aux-Roses Center | France | 1967 | 0 | EA | | C, P, R | Dry | Farinoso and Wilson, 1983 |
| Grenoble Nuclear Study Center | France | 1970 | 0 | EA | | C, P, R | Dry | Farinoso and Wilson, 1983 |
| National Center of Scientific Research - Strasbourg | France | 1970 | 0 | EA | | C, P, R | Dry | Farinoso and Wilson, 1983 |
| Belgian Nuclear Center - Mol | Belgium | 1970 | 0 | Slag Pyr | | C, P, R | Wet Scrubber | Farinoso and Wilson, 1983 |
| Nuclear Research Center - Karlsruhe | Germany | 1971 | 0 | EA | | C, FCW, P, R | Dry | Farinoso and Wilson, 1983 |
| JAERI - Tokai Research Establish. | Japan | 1972 | N | EA | | | Dry | Farinoso and Wilson, 1983 |
| JAERI - Oharai Research Establish. | Japan | 1973 | 0 | CA | | C, P | Wet Scrubber | Farinoso and Wilson, 1983 |
| Nuclear Research Center - Juelich (Pilot Plant) | Germany | 1975 | 0 | CP | | C, FCW, P, R | Dry | Farinoso and Wilson, 1983 |
| Wuerenlingen Research Center | Switz. | 1975 | O | EA | | C, FCW, P, R | Dry | Farinoso and Wilson, 1983 |
| Studsvik Research Facilities | Sweden | 1976 | O | EA | | C, FCW, P, R | Wet Scrubber | Farinoso and Wilson, 1983 |
| JAERI - Oharai Research Establish. | Japan | 1972 | N | EA | | | Dry | Farinoso and Wilson, 1983 |
| PNC - Oharai Research Establish. | Japan | 1976 | O | EA | | C, FCW, P, R | Wet Scrubber | Farinoso and Wilson, 1983 |
| Japan Atomic Power Co. - Tsuruga Plant | Japan | 1977 | O | EA | | C, P, R | Dry | Farinoso and Wilson, 1983 |
| PNC - Tokai Research Establish. | Japan | 1977 | O | CA | | C, P, R | Wet Scrubber | Farinoso and Wilson, 1983 |
| Bruce Nuclear Complex | Canada | 1977 | O | CP | | C, P, R | Dry | Farinoso and Wilson, 1983 |
| Kansai Electric Power Co - Mihama Plant | Japan | 1978 | O | EA | | C, P, R | Dry | Farinoso and Wilson, 1983 |
| Seiberdorf Research Center | Austria | 1978 | O | EA | | C, FCW, P, R | Dry | Farinoso and Wilson, 1983 |
| CEBG - Hinkley Point Station | U.K. | 1978 | O | EA | | C, P, R | Wet Scrubber | Farinoso and Wilson, 1983 |
| CEBG - Hinkley Point Station | U.K. | | O | EA | | C, P, R | Dry | Farinoso and Wilson, 1983 |
| CEBG - Wylfa Power Station | U.K. | | UC | EA | | C, P, R | Wet Scrubber | Farinoso and Wilson, 1983 |
| JAERI - Tokai Research Establish. | Japan | 1979 | O | EA | | C, P, R | Dry | Farinoso and Wilson, 1983 |
| Chalk River Nuclear Laboratory | Canada | 1980 | O | CP | | C, P, R | Dry | Farinoso and Wilson, 1983 |
| Chubu Electric Power Co. - Hamaoka Plant | Japan | 1981 | O | EA | | C, P, R | Dry | Farinoso and Wilson, 1983 |
| Kyushu Electric Power Co. - Genkai Unit 1 | Japan | 1981 | O | EA | | C, P, R | Dry | Farinoso and Wilson, 1983 |
| Kansai Electric Power Co - Ohi Plant | Japan | 1982 | O | EA | | C, P, R | Dry | Farinoso and Wilson, 1983 |
| Kansai Elec. Power Co. - Takahama Plant | Japan | (1984) | UC | EA | | C, P, R | Dry | Farinoso and Wilson, 1983 |
| Tokyo Elec. Power Co. - Fukushima Plant | Japan | (1984) | UC | EA | | C, P, R | Dry | Farinoso and Wilson, 1983 |
| Chugoku Elec. Power Co - Shimane Plant | Japan | (1984) | UC | EA | | C, P, R | Dry | Farinoso and Wilson, 1983 |
| Kyushu Elec. Power Co - Sendai Plant | Japan | | | EA | | C, P, R | Dry | Farinoso and Wilson, 1983 |

## SUMMARY OF RADIOACTIVE WASTE INCINERATORS[1]
## (CONTINUED)

| INSTALLATION | LOCATION | BUILT[1] | STATUS[2] | TYPE | CAPACITY | TYPE[3] | TYPE[4] | REFERENCE |
|---|---|---|---|---|---|---|---|---|
| **U.S. TRU Waste and U/Pu Recovery Incinerators** | | | | | | | | |
| LANL Pu Recovery Incinerator | NM | 1952 | N | CA | 0.5 kg/hr | C, FCW, P, R | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976 |
| National Lead Co. of Ohio | OH | 1954 | | CA | 1000 kg/hr | C, FCW | None | Farinoso and Wilson, 1983; Perkins, 1976 |
| Union Carbide - ORNL, Y-12 | TN | 1955 | | | 2 kg/hr | C, FCW | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976 |
| Nuclear Fuel Services | TN | | | CA | 270 kg/hr | C, FCW, P | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976 |
| Rocky Flats Plant | CO | 1959 | O | Oxy Enrich | 16 kg/hr | C, P | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976 |
| United Nuclear Corporation | CT | 1960 | N | | 95 kg/hr | FCW | Dry | Farinoso and Wilson, 1983; Perkins, 1976 |
| Metals and Controls | MA | 1960 | N | | 90 kg/hr | FCW | Dry | Farinoso and Wilson, 1983; Perkins, 1976 |
| Pratt and Whitney Aircraft | CT | 1960 | N | | 270 kg/hr | FCW | None | Farinoso and Wilson, 1983; Perkins, 1976 |
| GE Atomic Power Equipment Department | CA | 1960 | N | CA | 45 kg/hr | C, FCW, P, R | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976 |
| Gulf General Atomics | CA | 1960 | N | CA | 10 bbl/da | P, FCW | Dry | Farinoso and Wilson, 1983; Perkins, 1976 |
| ARHCO Pu Recovery Incinerator | WA | 1961 | | CA | 20 kg/8hr | C, FCW, P | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976 |
| United Nuclear Corporation | RI | 1967 | N | | 45 kg/hr | C, FCW, P, R | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976 |
| B and W Nuclear Materials Division | PA | 1969 | N | EA | 9 kg/hr | C, FCW, P | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976 |
| Goodyear Atomic Corporation | OH | 1971 | | CA | 2300 kg/mo | C, FCW, P | None | Farinoso and Wilson, 1983; Perkins, 1976 |
| Babcock and Wilcox | VA | 1972 | | EA | 80 kg/hr | C, FCW, P | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976 |
| Mound Lab. - Pu Recovery Incinerator | OH | 1972 | | CA | 90 l/day | C | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976 |
| Union Carbide, K-25 | TN | 1972 | | CA | | FCW | None | Farinoso and Wilson, 1983; Perkins, 1976 |
| GE Nuclear Fuel Plant | NC | 1972 | N | EA | 1300 kg/hr | C, FCW, P, R | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976 |
| Kerr-McGee Nuclear Corporation | OK | 1972 | | EA | 70 kg/hr | FCW | Dry | Farinoso and Wilson, 1983; Perkins, 1976 |
| Westinghouse Nuclear Fuels Division | SC | 1974 | O | CA | | C, FCW, P, R | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976 |

## SUMMARY OF RADIOACTIVE WASTE INCINERATORS[1]
## (CONTINUED)

| INSTALLATION | LOCATION | BUILT[1] | STATUS[2] | TYPE | CAPACITY | TYPE[3] | TYPE[4] | REFERENCE |
|---|---|---|---|---|---|---|---|---|
| U.S. TRU Waste and U/Pu Recovery Incinerators (Continued) | | | | | | | | |
| Mound Laboratory (Development) | OH | 1975 | | Cyclone | 1 drum | C, FCW, P | Wet Scrubber | Farinoso and Wilson, 1983, Perkins, 1976; Janowiecki, 1989 |
| Los Alamos National Laboratory | NM | 1976 | O | CA | 45 kg/hr | C, FCW, P, R | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976; Varvuska, 1989 |
| Rocky Flats Plant | CO | 1978 | Hold | FB | 75 kg/hr | C, P, R | Dry | Farinoso and Wilson, 1983; Perkins, 1976; Zeigler, 1988 |
| Rocky Flats Plant (Development) | CO | 1980 | N | Agit Hearth | 70 kg/hr | C, FCW, P, R | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976; Ziegler, 1988; Ziegler, 1989 |
| Rocky Flats Plant (Development) | CO | 1980 | N | Rotary Kiln | 40 kg/hr | C, FCW, P, R | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976; Zeigler, 1988 |
| Mound Laboratory | OH | 1981 | Existing, New Task | Glass Melt | 23 kg/hr | C, FCW, P, R | Wet Scrubber | Armstrong and Klingler, 1984; Klingler and Armstrong, 1986; Janowiecki, 1988 |
| Idaho National Engineering Lab. (NWCF) | ID | 1982 | O | FB | | FCW | Wet Scrubber | WINCO, 1987 |
| GE Nuclear Fuel Plant | NC | (1983) | | CA | | C, FCW, P, R | Wet Scrubber | Farinoso and Wilson, 1983 |
| Savannah River Plant (PWI) | SC | 1985 | N | CA | 10 kg/hr | C, FCW, P, R | Dry | Charlesworth and McCampbell, 1985; Meyer, 1989 |
| Idaho National Engineering Lab. (PREPP) | ID | 1987 | In Test | Rotary Kiln | 2300 $m^3$/yr | C, N, P, R, S | Wet Scrubber | McFee and Gale, 1988, Ball, 1988; Stermer, 1989 |
| Advanced Nuclear Fuels, Inc. | WA | 1987 | O | CA | 90 kg/hr | | Wet Scrubber | Francis, 1988 |
| Savannah River Laboratory (PRI) | SC | 1990 | In Design | CA | 0.57 kg/hr | C, FCW, P, R | Dry | Williams and Charlesworth, 1988, Meyer, 1989 |
| Savannah River Laboratory (PRI) (Development) | SC | 1990 | In Design | CA | 200 gm/batch | C, FCW, P, R | Dry | Williams and Charlesworth, 1988, Meyer, 1989; Looper, 1989 |
| Los Alamos National Laboratory | NM | 1991 | Procure | CA | | | Wet Scrubber | Vavruska, 1989 |
| Lawrence Livermore National Lab. | CA | 1991 | Procure | RK | | | | DOE, 1988; Jackson, 1988 |
| Oak Ridge National Laboratory (EURI) | TN | (1991) | Procure | CA | 45 kg/hr | FCW | Dry | Starr, 1989 |

## SUMMARY OF RADIOACTIVE WASTE INCINERATORS[1]
## (CONTINUED)

| INSTALLATION | LOCATION | BUILT[1] | STATUS[2] | TYPE | CAPACITY | TYPE[3] | TYPE[4] | REFERENCE |
|---|---|---|---|---|---|---|---|---|
| Non-U.S. TRU Waste and U-Pu Recovery Incinerators | | | | | | | | |
| Windscale (Pilot Plant) | UK | 1973 | | CP | 5 kg/hr | C, FCW, P, R | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976 |
| Center of Nuclear Studies - Grenoble | France | 1961 | N | CA | 400 kg/yr | C, FCW, P, R | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976 |
| Marcoule Center of Pu Production | France | 1964 | | CA | 90 kg/hr | C, FCW, P, R | Wet Scrubber | Farinoso and Wilson, 1983; Perkins, 1976 |
| Marcoule Center (Pilot Plant) | France | 1970 | | EA | 1 kg/hr | C, FCW, P, R | Dry | Farinoso and Wilson, 1983, Perkins, 1976 |
| PNC - Oharai Research Establish. | Japan | 1983 | | EA | | C, FCW, P, R | Wet Scrubber | Farinoso and Wilson, 1983; |

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(1) Parenthesis around year built indicates actual construction not confirmed for this report.
(2) Status: UC = Under Construction; O = Operational; N = No Longer Operating; AS = Awaiting Start-up.
(3) Type: CA = Controlled Air; FB = Fluidized Bed; EA = Excess Air; CP = Controlled Pyrolysis.
(4) Waste Type: C = Combustibles; FCW = Fuel Cycle Waste; N = Non-Combustibles; P = Plastic; R = Rubber; S = Sludges.

Klingler, L. M., and K. M. Armstrong, 1986, Application of a Glass Furnace System to Low Level Radioactive and Mixed Waste Disposal, MLM-3351-OP, U.S. Department of Energy.

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6/6/20

# Proposed Modifications to WIPP Testing With CH-TRU Wastes

A. R. Lappin
Sandia National Laboratories
Division 6345

Not sample saturated bin test.
Sol data from drum-scale tests - lack tests DOE considering above-ground at WIPP
absent

# Present Conclusions Concerning Modified Approach to Testing

## Level I wastes (existing, as-received) should remain baseline

- Present assumptions reflect uncertainty in gas generation rates/"effective" potentials
  - Microbial activity under "humid" conditions
  - Anoxic corrosion under "humid" conditions
  - Effects of change in container material to non-corroding
- Uncertainty in effective radionuclide solubilities
- Uncertainty in waste/backfill permeability and Salado gas permeability
- Uncertainty in waste/backfill shear strength
- Uncertainty in waste/backfill porosity
- Uncertainty in real safety and economic costs of reprocessing

# Present Conclusions Concerning Modified Approach to Testing

- Given present uncertainties in behavior of Level I wastes, we need data on behavior of Level II modification of LONG/LOOW wastes, Level III modification of HONG/HOOW and PS
- Testing of Levels I, II, III in parallel planned, as available
- Modified approach supports early testing of modified wastes, but also provides scoping/decision-making data on less-modified wastes
- Must recognize possibility of both funding and scheduling constraints

# Objectives of Testing With Real CH-TRU Wastes

- Provide reliable data (in combination with other testing) on behavior of a range of both modified and unmodified waste/filler/backfill
- Identify and test waste form/backfill alternatives for successful regulatory compliance as quickly as possible
- Support evaluation of relative "benefits" and "risks" of both emplacement of both existing wastes and modified wastes and waste treatment at generators

# Implementation of Testing With Real Waste

**Test Level I, II, III wastes in parallel as they become available**

**Although initial testing with Level I Wastes decreased, modified testing approach developed directly from approved bin-scale test plan (Molecke, 1990a)**

- With possible exception of change in container material, Level I wastes should remain baseline ?
- Performance of Level I wastes excellent with <u>expected</u> properties
- No change in approach to alcove testing (Molecke, 1990b)
  - Testing of both treated and untreated wastes
  - Approximately 3850 drum equivalents of waste

# Priorities of Testing With Real Waste

**Obtain "scoping" or "qualifying" data on specific aspects of behavior of less-modified wastes as these are available**

- Untreated LONG/LOOW
- Level II and Level I HONG/HOOW/PS
- Effective gas-generation rates/potentials under realistic conditions
- Effective radionuclide concentrations (especially at high pH)

# Priorities of Testing With Real Waste

- If scoping results with less modified wastes are favorable, develop statistical data base on "representative" wastes at lower degrees of modification
- Combine results with reevaluation of assumed lithostatic limit on allowable gas pressures and assumption of zero far-field gas permeability

# Priorities of Testing With Real Waste

## Develop confidence in performance of selected Level II and Level III wastes

- Effective gas-generation rates (potentials)
- Effective radionuclide concentrations
- Begin testing with existing modified wastes
- Some lab-scale preparation of Level II and Level III wastes anticipated

# Present Assumption of Wastes Providing "High Reliability"

- Require less testing than untreated wastes
- Level II modification of LONG/LOOW
  - Shredding/compaction/salt/grout
- Level III modification of HONG/HOOW/PS
  - Thermally treated
- Change in container to non-corroding materials

# WIPP CH TRU Level II* Test Wastes: TRUCON Codes Cross-Listing

| WIPP Test Type | Waste Type | | TRUCON Designation Content Codes (description) |
|---|---|---|---|
| HONG & HOOW | Solidified Organics | 1. | 116A/216A Combustible Wastes |
| | | 2. | 119A/219A Filters; Mostly Organic |
| | | 3. | 121A/221A Organic Solid Wastes |
| | | 4. | 123A/223A Leaded Rubber Gloves |
| | | 5. | 125A/225A Combustible & Noncombustibles |
| | | 6. | 126A/226A Cemented Organic Process Solids |
| | | | (127/227A Mixed HONG/PS) DELETED |
| LONG | Solidified Inorganics | 7. | 115A/215A Graphite Waste; Equipment |
| | | 8. | 117A/217A Metal Wastes |
| | | 9. | 118A/218A Glass Wastes |
| | | 10. | 122A/222A Inorganic Solid Wastes |
| | | 11. | 124A/224A Pyrochemical Salt Wastes |
| PS | Cemented Sludges & Inorganics | 12. | 111A/211A Cemented/Dewatered Sludges |
| | | 13. | 114A/214A Cemented Inorganic Particulates |

* Shred/Compact/Grout/Salt/Container Change

# Proposed Changes to Plans for WIPP CH-TRU Leach Testing

1. No leachate/solubility sampling from bin tests, but "wet" bins retained
2. Largely separate gas and leach/solubility testing
3. Leach testing can be conducted either at WIPP or off-site
4. Leaching/solubility tests changed to include "drum-scale" and "liter-scale" testing of unmodified and modified wastes
   - Fully saturated conditions
   - Containers to be agitated periodically
   - Containers to be appropriately contained
   - Minimal gas testing in some tests, for comparison with results of bin testing
   - Sampling schedule and data output as in Molecke (1990a)

# Comments on Proposed Changes to Plans for WIPP CH-TRU Leach/Solubility Testing

- Planned modifications should increase technical validity and defensibility of data
- Leach testing of modified wastes can be based, in part, on HLW experience, procedures
- Draft test-plan addendum on modified bin testing and leach/solubility testing submitted to DOE/WPO
- Separate test plan for leach/solubility testing planned

# Proposed Modifications to WIPP CH-TRU Tests

GAS TESTING:

- Level I Existing Wastes
  (Defer Bins with Moist Salado & "Saturated" Castile Brines)

| | |
|---|---|
| HONG | 28 (of orig. 48) |
| HOOW | 16 (of orig. 24) |
| LONG | 14 (of orig. 18) |
| PS | 18 (or orig. 26) |
| Baseline Ref. | 8 |
| Subtotal | 84 bins (+ 40 Deferred) |

- Level II Wastes
  TRUCON Codes: 114, 115, 118, 122, & (part of) 117
  (5 waste cat.) x (2 backfill/fillers) x (2 brine levels)
  x (2 reps) = 40 bins

Total: 124 Bins (+ 40 Deferred)

# Proposed Modifications to WIPP CH-TRU Tests

**LEACH TESTING:**

- **Level I Expected High & Low Gas Generation**
  **TRUCON Codes High 116, 117, 121, Low: 115, 118**
  **(5 waste types) x (2 backfill/fillers) x (3 reps.) = 30 drum-scale**

- **Level II Inorganic Wastes**
  **TRUCON Codes 114, 115, 118, 122, & (part of) 117**
  **(5 waste types) x (2 backfill/fillers) x (3 reps.) = 30 drum-scale**

(cont.)

# Proposed Modifications to WIPP CH-TRU Tests

(cont.)

**LEACH TESTING:**

- Level II High-Organic Wastes and Sludges
  (3 organic wastes) x (2 backfill/fillers) x (3 reps.) = 18 drum-scale
  (2 cemented sludges) x (1 filler) x (3 reps.) = 6 drum-scale

- Level III High-Organic Wastes and Sludges
  (5 cemented incinerator ash types (assumed)) x (1 filler) x (3 reps.) = 15 liter-scale
  (2 melted sludges) x (1 backfill) x (3 reps.) = 6 liter-scale
  (2 glasses (assumed)) x (1 backfill) x (3 nuclide loadings) x (3 reps.) = 18 liter-scale

# Proposed Modifications to WIPP CH-TRU Tests

(cont.)

- Test sequencing based on availability of both untreated and modified wastes
- Selection of waste content codes and test replicates based on ongoing statistical evaluation

# Present Conclusions Concerning Modified Approach to Testing

## Level I wastes (existing, as-received) should remain baseline

- Present assumptions reflect uncertainty in gas generation rates/"effective" potentials
  - Microbial activity under "humid" conditions
  - Anoxic corrosion under "humid" conditions
  - Effects of change in container material to non-corroding
- Uncertainty in effective radionuclide solubilities
- Uncertainty in waste/backfill permeability and Salado gas permeability
- Uncertainty in waste/backfill shear strength
- Uncertainty in waste/backfill porosity
- Uncertainty in real safety and economic costs of reprocessing

# Present Conclusions Concerning Modified Approach to Testing

- Given present uncertainties in behavior of Level I wastes, we need data on behavior of Level II modification of LONG/LOOW wastes, Level III modification of HONG/HOOW and PS
- Testing of Levels I, II, III in parallel planned, as available
- Modified approach supports early testing of modified wastes, but also provides scoping/decision-making data on less-modified wastes
- Must recognize possibility of both funding and scheduling constraints

# Microbial Activity

## Status

- Successfully collected halophilic and halotolerant microorganisms from the WIPP Site and vicinity
  - Salt lakes in Nash Draw
  - Soils adjacent to the WIPP Site
  - WIPP tailings site
  - WIPP underground workings

- Successfully enriched halophilic and halotolerant microorganisms at West Chester University on complex non-cellulosic substrate
  - Aerobes
  - Denitrifiers
  - $SO_4^{2-}$ reducers
  - Fermenters and methanogens

# Microbial Activity

## Status

- Nonhalophilic aerobic and anaerobic mixed sewage-sludge cultures still inhibited by WIPP brine at Stanford University
  - Experiments started 10/89
  - Cultures simulate microorganisms in TRU waste
  - Little or no activity at $\geq$50% brine
- Started similar experiments with microorganisms collected from a Stanford laboratory
  - Experiments started 4/90
  - Cultures also simulate microorganisms in TRU waste
  - No results yet

# Microbial Activity

## Status

- Attempts to use enrichments of halophilic and nonhalophilic microorganisms at Stanford University unsuccessful so far
  - Troubleshooting under way
  - Cellulose substrate
  - Different nutrients
- No doubt that halophiles exist
- Question re use of cellulosic substrate
- Question re available nutrients
- Question re detection limit and acceptable rates

# Anoxic Corrosion

## Status

- Have set up and calibrated equipment at Pacific Northwest Laboratory (PNL)
  - Results will be interpreted by weight loss
- Received and prepared samples
  - Two heats of ASTM A366, a low-C steel (drums)
  - Two heats of ASTM A570, a medium-C steel (boxes and tools)
- Pretest characterization of samples in progress
- Starting 3-month experiments, pH = 6 (pH of Salado brines)
  - Inundated, $N_2$ atmosphere
  - Inundated, $CO_2$ atmosphere
  - Humid, $N_2$ atmosphere
  - Humid, $CO_2$ atmosphere

# Anoxic Corrosion

## Status (cont.)

- Will start 12 - and 24 - month experiments immediately after starting 3-month tests
- Will start 6 - month experiments after completion of 3 - month experiments
- Plan to expand inundated tests to high-pH
- Could expand to include other materials

# Radionuclide Chemistry

## Status

- Solvent-extraction experiments under way at Florida State University to determine stability constants for complexes between Pu, Am, Th, and U; and $Cl^-$, $NO_3^-$, and $OH^-$ in high-ionic-strength solutions

- Planning additional studies at Florida State
  - Carbonate complexing, especially at higher pH
  - Important organic ligands (acetate, ascorbate, citrate, EDTA, lactate, and oxalate)

- Conditions for studies at Florida State
  - Neutral, mildly acidic, and basic
  - All possible oxidation states of redox-sensitive actinide elements

- Starting sorption studies at Oak Ridge National Laboratory

# Log of Measured Stability Constants

## Ionic Strength

| Species | 3M | 5M | 7M |
|---|---|---|---|
| $AmOH^{2+}$ | - | 9.27 | - |
| $EuCl^{2+}$ | 0.022 | 0.11 | 0.20 |
| $EuNO_3^{2+}$ | 0.197 | 0.33 | 0.249 |
| $UO_2Cl^{+}$ | 0.006 | 0.31 | - |
| $UO_2NO_3^{+}$ | 0.39 | 0.069 | - |

---

**Stability constants pertain to reactions such as:**

$$Am^{3+}_{(soln)} + OH^{-} = AmOH^{2+}$$

# Radionuclide Chemistry

## Preliminary Conclusions

- M(III) hydrolysis relatively important
- Complexes between M(III), M(VI) and $Cl^-$, $NO_3^-$ relatively unimportant
- Complexes between antinides and organic ligands expected to be unimportant
  - Small quantities in the inventory
  - Competition from $Mg^{2+}$ in WIPP brines

# Radionuclide Chemistry

## Preliminary Conclusions (cont.)

- Expected solubilities
  - Lowest at pH = 8 to 9
  - Much higher under acidic conditions
  - Somewhat higher if pH > 9

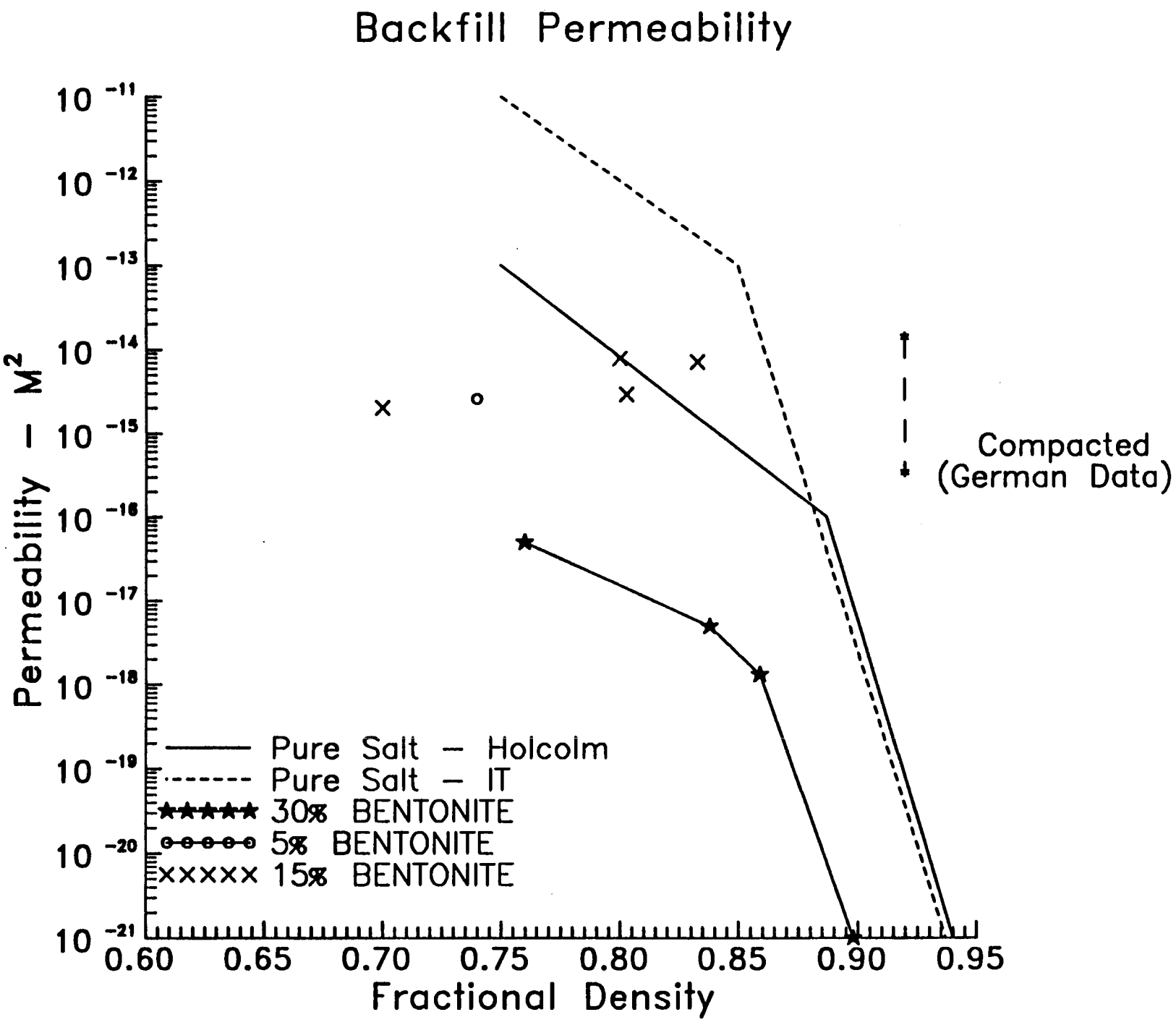
# Empirical Solubility Study

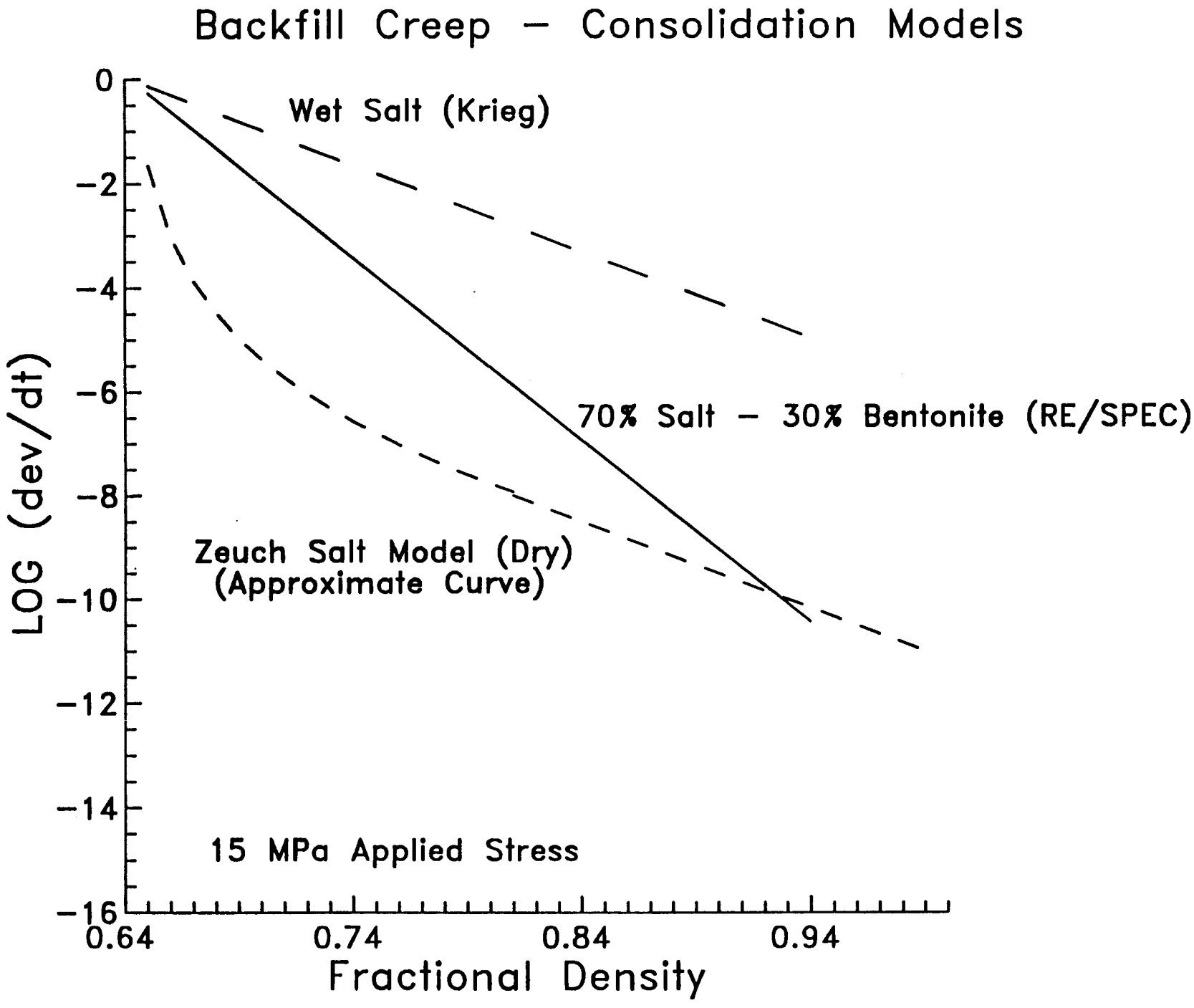
| Oxidation State Analog | pH 6 | 8 | 10 | 12 |
|---|---|---|---|---|
| Eu (III) | 1, 2 | 1, 3 | 1, 3 | 1, 3 |
| Th (IV) | 1, 2 | 1, 3 | 1, 3 | 1, 3 |
| Np (V) | 1, 2 | 1, 3 | 1, 3 | 1, 3 |
| V (VI) | 1, 2 | 1, 3 | 1, 3 | 1, 3 |

1. Both dissolution and precipitation experiments
2. Both with and without organic and inorganic ligands
3. Without organic and inorganic ligands

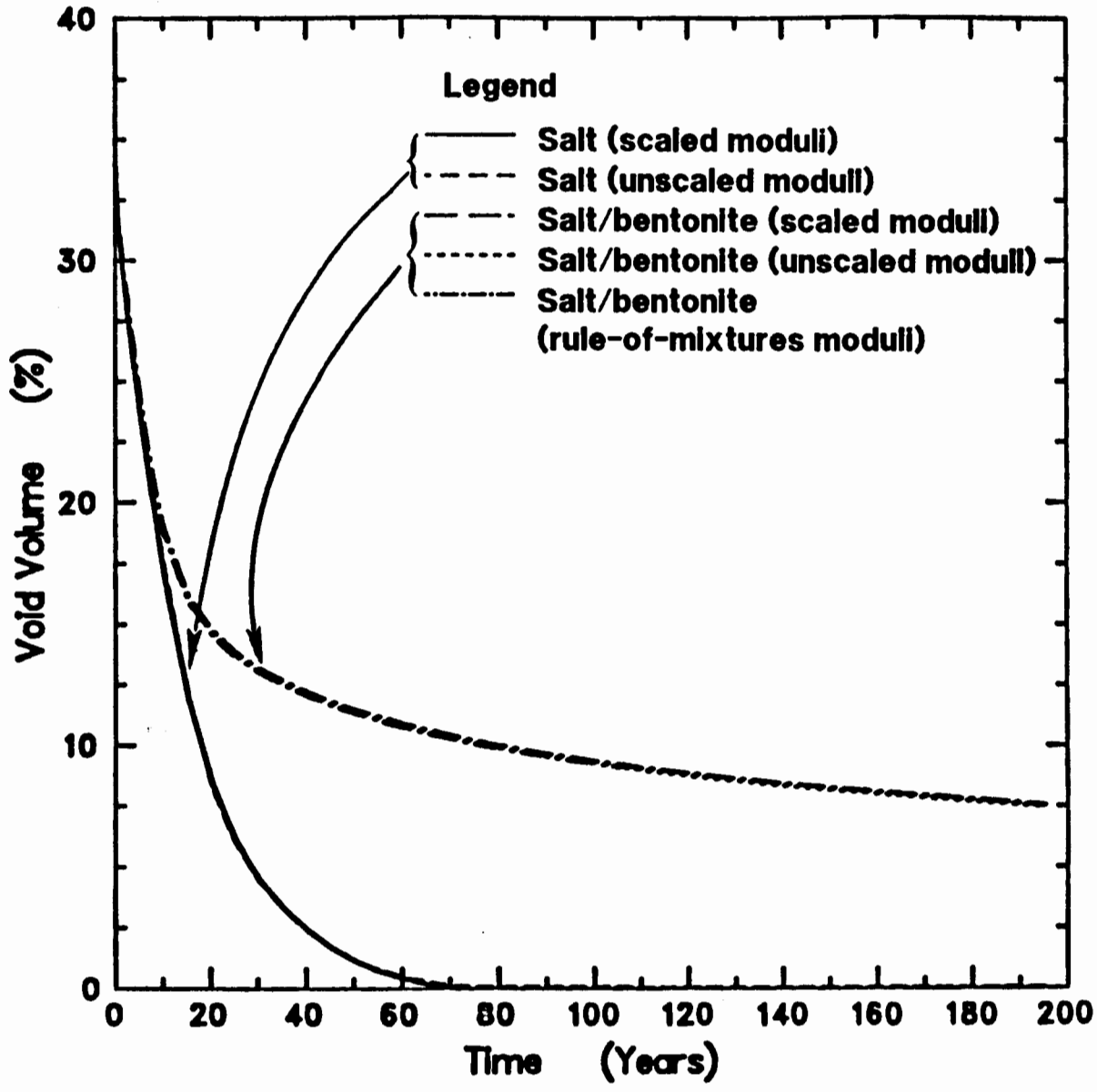
# Waste Material Brine Permeability Values at Full Saturation

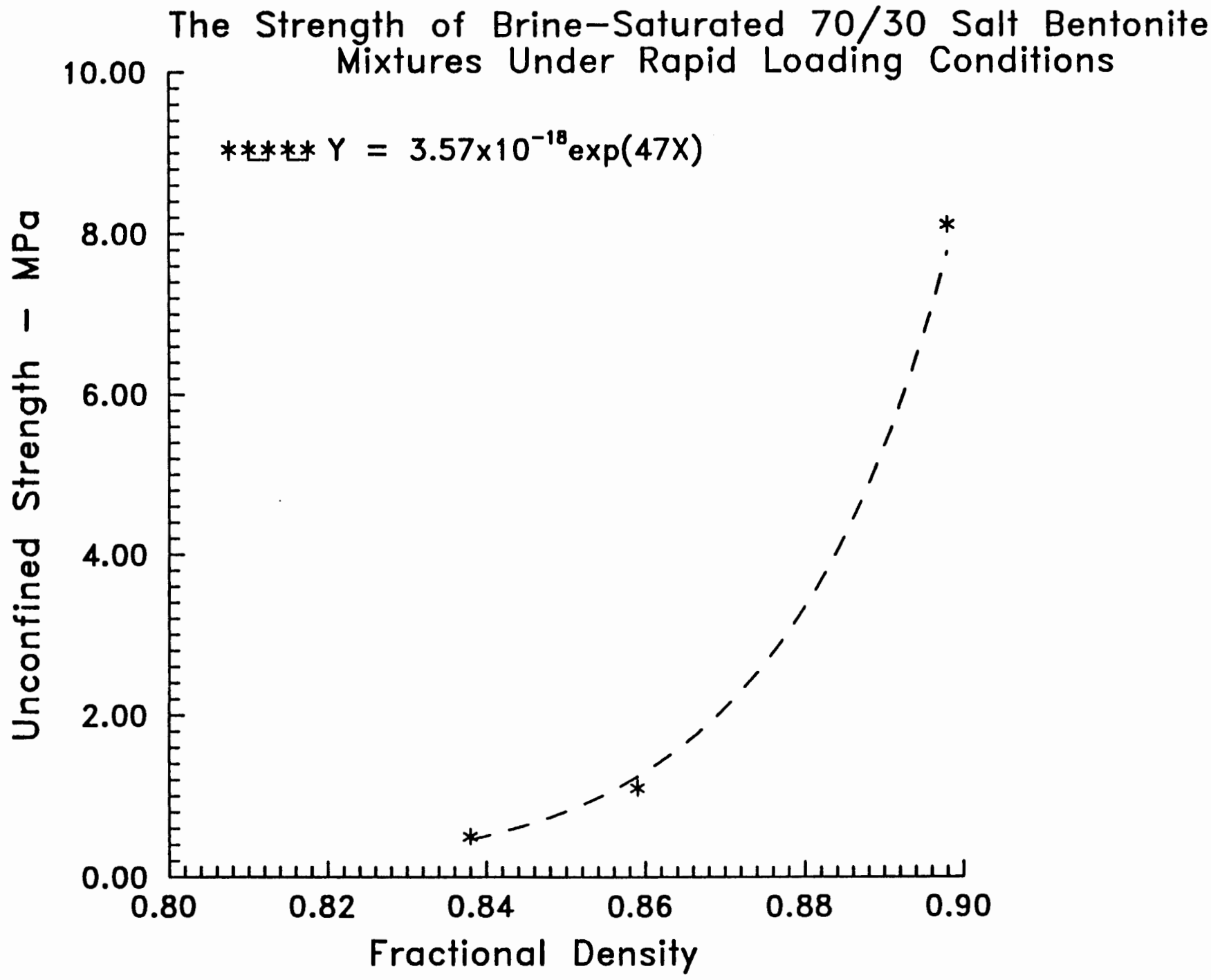
| Material # | Description | Days at 14 MPa (two tests each) | Permeability millidarcy (two tests each) |
|---|---|---|---|
| 1 | 40% PE bottles | 30 | No flow at 1000 psi |
| | 40% PVC Parts | 30 | 25 |
| | 20% Gloves | | |
| 2 | 60% Pine cubes | 30 | 13 |
| | 40% Rags | 30 | 203 dropped to 2 |
| 4 | 45% Matl. #1 | 30 | 19 |
| | 37% Matl. #2 | 30 | 15 |
| | 9% 1" metals | | |
| | 9% Dry Portland | | |
| 7 | 50% Magnetite | 24 hr | 11 |
| | 50% 1" Metals | 24 hr | 500 dropped to 4 |

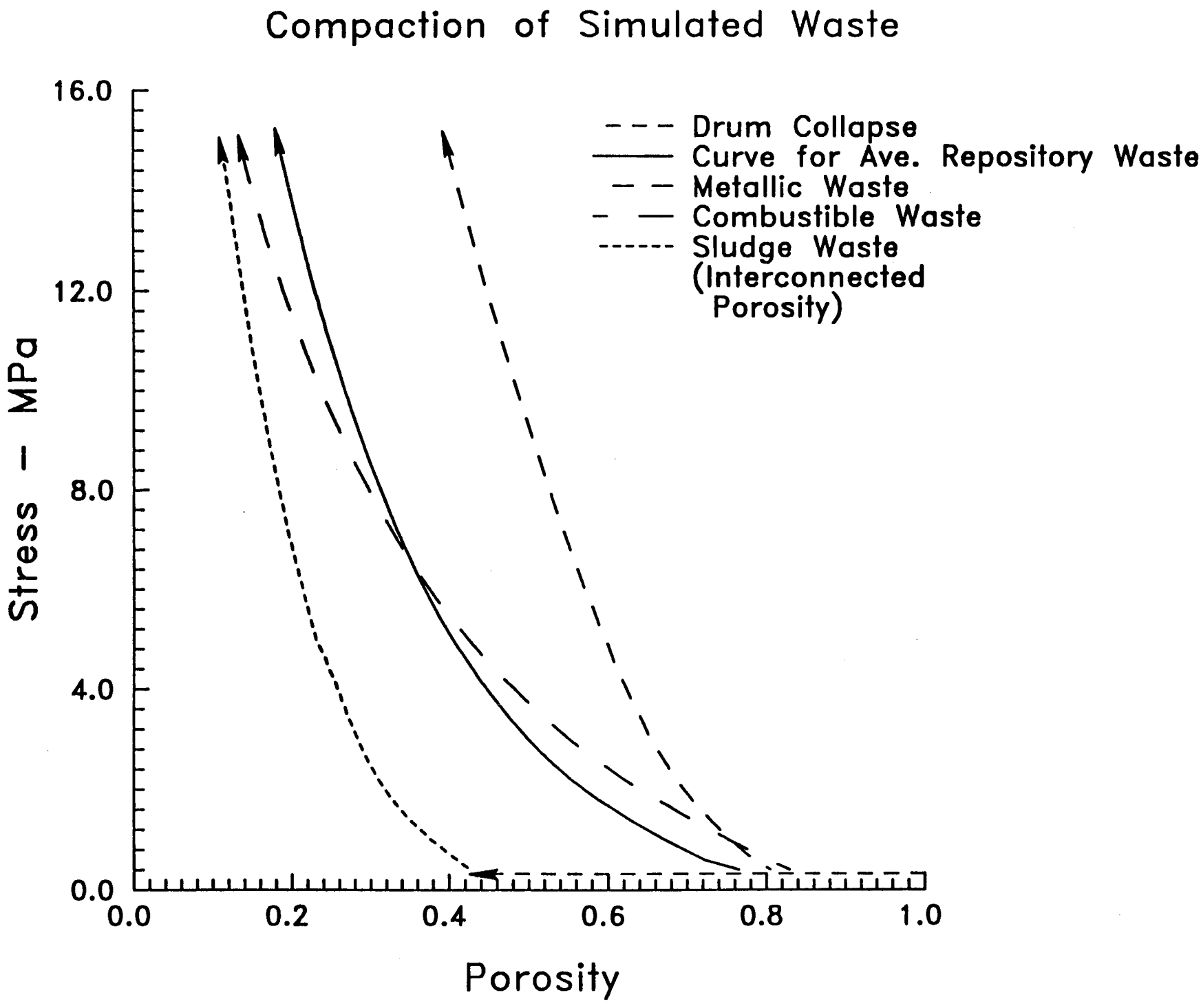

Backfill Permeability
Permeability - M2
10 -11
10 -12
10 -13
10 -14
10 -15
10 -16
10 -17
10 -18
10 -19
10 -20
10 -21
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
Fractional Density
Compacted
(German Data)
Pure Salt - Holcolm
Pure Salt - IT
30% BENTONITE
5% BENTONITE
15% BENTONITE


Backfill Creep – Consolidation Models
Wet Salt (Krieg)
70% Salt – 30% Bentonite (RE/SPEC)
Zeuch Salt Model (Dry)
(Approximate Curve)
15 MPa Applied Stress
LOG (dev/dt)
0
−2
−4
−6
−8
−10
−12
−14
−16
0.64
0.74
0.84
0.94
Fractional Density

# Void Volume in the Disposal Room




The Strength of Brine-Saturated 70/30 Salt Bentonite Mixtures Under Rapid Loading Conditions
***** Y = 3.57x10^-18 exp(47X)
Unconfined Strength - MPa
10.00
8.00
6.00
4.00
2.00
0.00
0.80
0.82
0.84
0.86
0.88
0.90
Fractional Density


Compaction of Simulated Waste
16.0
12.0
8.0
4.0
0.0
Stress - MPa
0.0
0.2
0.4
0.6
0.8
1.0
Porosity
Drum Collapse
Curve for Ave. Repository Waste
Metallic Waste
Combustible Waste
Sludge Waste
(Interconnected
Porosity)

6/7/90

# Proposed Risk-Based Extension of Radiological Criteria

R. D. Klett
Sandia National Laboratories

June 7-8, 1990

# PROPOSED RISK-BASED EXTENSION OF RADIOLOGICAL CRITERIA

Robert D. Klett
Sandia National Laboratories
June 7-8, 1990

Review panels, advisory boards, and individual investigators have recommended numerous modifications to 40 CFR 191. This report suggests two extensions to the existing standards that would maintain the same fundamental safety goal for all repositories and would relate probabilistic release from the controlled region to population risk, without changing the form of the regulations. Now that two very different disposal sites (YMP & WIPP) have been selected, different nuclide transport models could be use to derive separate release limits for each site. These could supplement the existing release limits that were derived with a simplified generic model. Examples are given that show the current method of dealing with probabilistic releases by requiring that summed normalized releases (CCDF) to have a lower value than a stepped limit, does not correspond to population risk. Integration of the CCDF does produce the normalized risk from the repository, provided the release limits for that repository accurately represent the fundamental safety goal.

# Extensions of 40 CFR 191

- Who to protect? (Individuals and/or populations)
- How to protect them? (Dose or Derived Standards)
- Acceptable level (Risk/Benefit or Absolute Value)
- Regulation of probabilistic events (Risk or Prescriptive)
- Assumptions for low probability events
- Minimum probability event to be regulated
- Duration of regulation
- What modifications should be made and how should they be implemented?

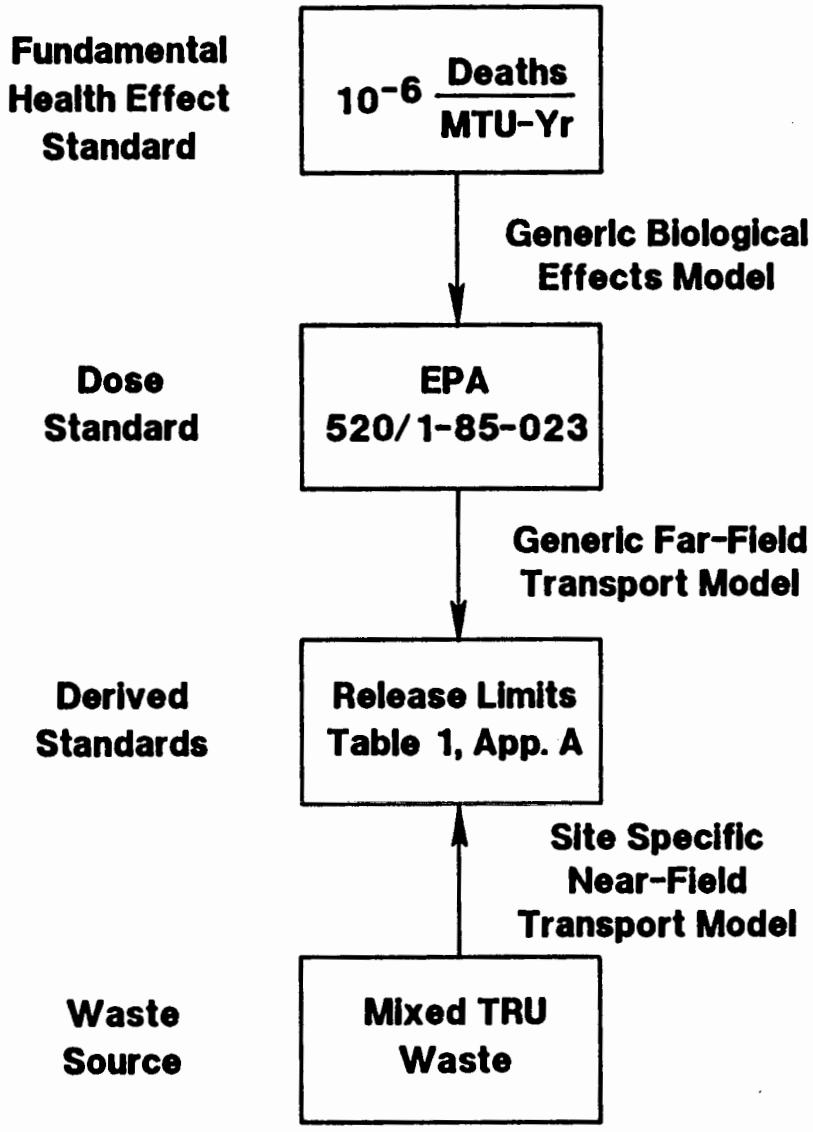
# Current Derived Release Limits

- The release limits were derived using simplified generic nuclide transport models, and generic pathways and usage assumptions
- The limits are not traceable to the fundamental safety criteria when applied to the WIPP and YMP repositories
- Some of the simplified models used to compute the generic release limits are very conservative, and some are non-conservative
- The same limits apply to releases through any surface of the controlled volume

## Example of Criteria Traceability
## (YMP Thermal Design Requirements)

| Criterial Level | Criteria Category | Criteria |
|---|---|---|
| 1 | Fundamental | No unreasonable risk to the populace |
| 2 | Dose | Definition of acceptable dose (ICRP 26 & 46) |
| 3 | Derived | Integrated nuclide flux across repository boundary (US EPA 40 CFR 191) |
| 4 | Prescriptive | Retrieval, containment, and ground water travel time (US NRC 10 CFR 60) |
| 5 | Functional Requirements | Dry canister, no spalling, no phase change, limit on fuel rod failure, limit on surface condition changes, limit on rock thermal fracturing, and human access to drifts |
| 6 | Design Requirements | Temperature limits on canister, bore-hole, drifts, formation, and surface |
| 7 | Secondary Design Requirements | Areal power density, layout, inventory, and ventilation cooling and drying |

# 40 CFR 191 Criteria/Model Path

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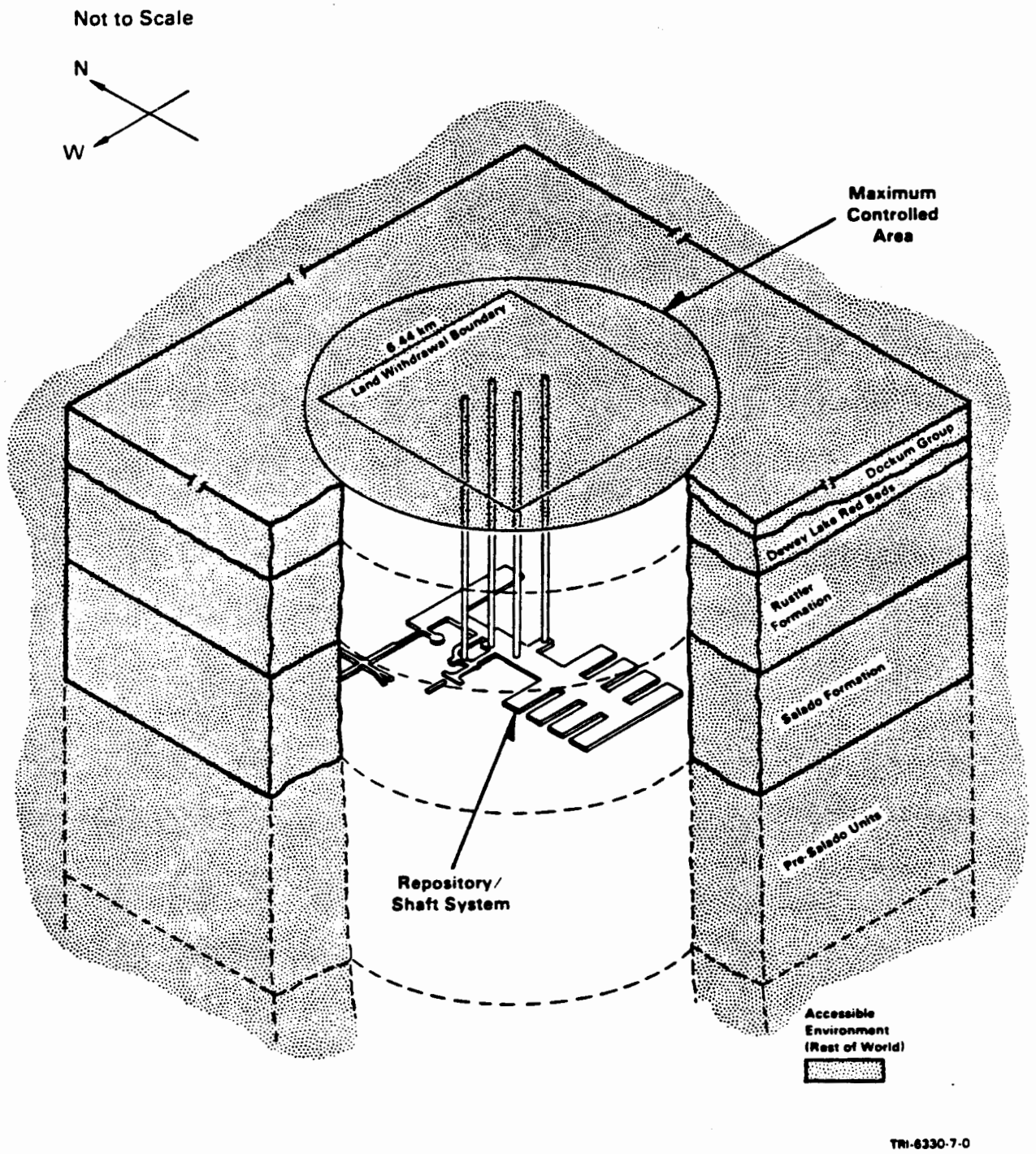
# Differences Between YMP & WIPP That Affect Derived Standards

Pathways from the peripheral boundaries to humans during normal operation are different.

Pathways from the surface or peripheral boundaries to humans following human intrusion or abnormal events are different.

- Local lithology
- Local hydrology
- Waste form
- Repository layout



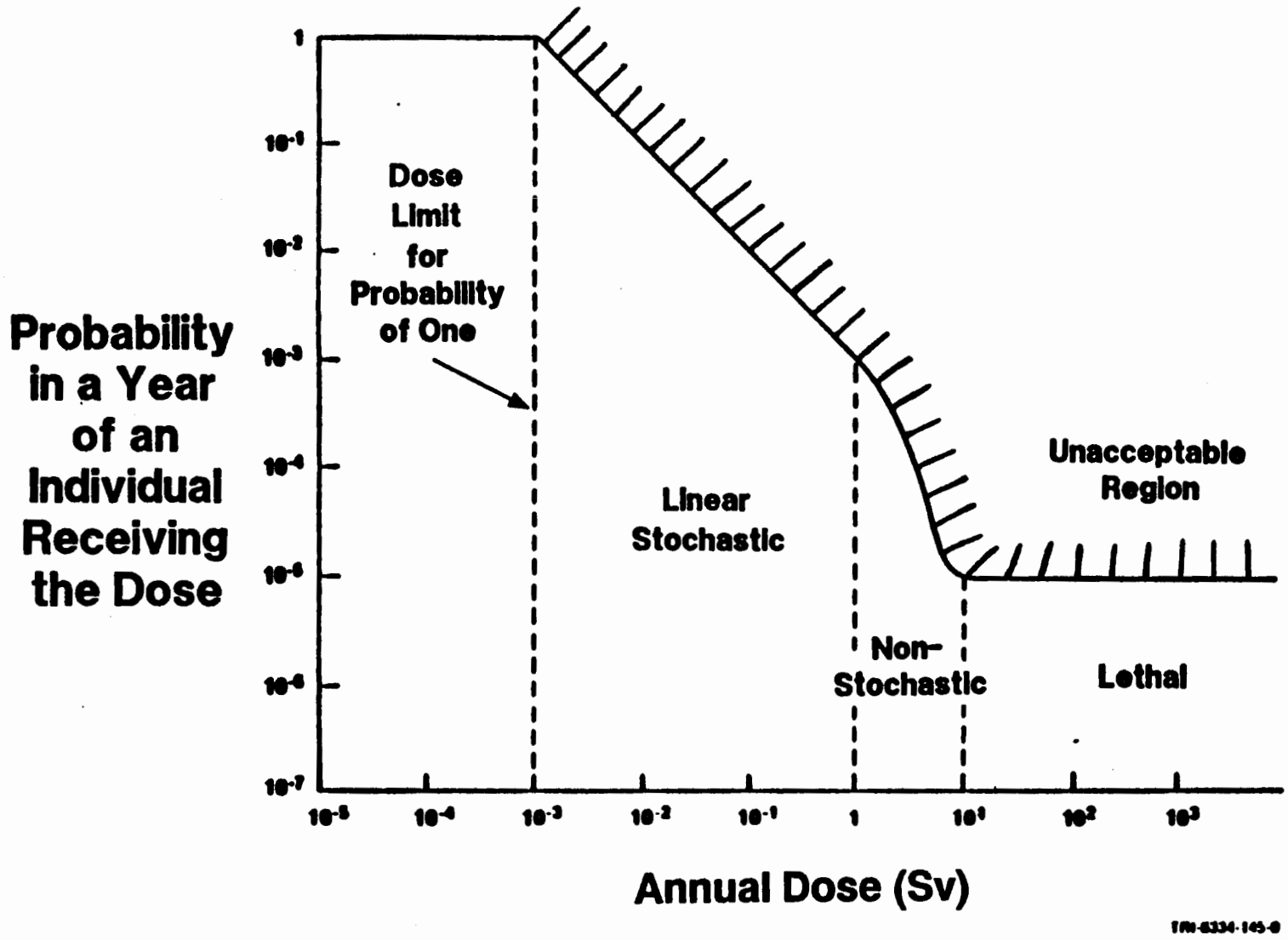

Disposal System: Repository/Shaft System and Controlled Area

TABLE D-1:
Fatal cancers per curie released for different release modes

| Nuclide | Releases to a River | Releases to an Ocean | Releases to Land Surface | Releases due to Violent Interactions* |
|---|---|---|---|---|
| C-14 | 4.58 E- 2 | 1.12 E- 7 | 2.58 E- 5 | 7.65 E- 2 |
| Ni-59 | 6.80 E- 4 | 6.74 E- 5 | 1.10 E- 5 | 1.23 E- 4 |
| Sr-90 | 1.21 E- 1 | 1.91 E- 6 | 9.75 E- 4 | 1.63 E- 2 |
| Zr-93 | 6.94 E- 2 | 5.74 E- 6 | 1.82 E- 1 | 1.55 E- 1 |
| Tc-99 | 2.85 E- 4 | 1.04 E- 6 | 6.03 E- 8 | 3.67 E- 5 |
| Sn-126 | 1.20 E- 1 | 7.86 E- 6 | 4.13 E- 2 | 1.12 E- 1 |
| I-129 | 1.08 E- 2 | 9.62 E- 5 | 2.31 E- 5 | 1.38 E- 3 |
| Cs-135 | 3.81 E- 3 | 1.58 E- 5 | 4.01 E- 4 | 7.36 E- 4 |
| Cs-137 | 1.98 E- 2 | 1.60 E- 5 | 5.62 E- 4 | 6.91 E- 3 |
| Sm-151 | 1.17 E- 4 | 1.38 E- 6 | 2.89 E- 6 | 1.64 E- 5 |
| Ra-226 | 3.16 | 1.49 E- 2 | 8.42 E- 2 | 4.87 E- 1 |
| U-234 | 1.33 | 1.38 E- 3 | 5.70 E- 1 | 6.13 E- 1 |
| Np-237 | 5.96 E- 1 | 2.44 E- 3 | 3.22 E- 3 | 8.03 E- 2 |
| Pu-238 | 2.29 E- 2 | 2.38 E- 5 | 3.21 E- 3 | 1.47 E- 2 |
| Pu-239 | 6.92 E- 2 | 1.31 E- 4 | 5.55 E- 2 | 5.18 E- 2 |
| Pu-240 | 6.53 E- 2 | 1.15 E- 4 | 4.94 E- 2 | 4.76 E- 2 |
| Am-241 | 7.19 E- 1 | 1.19 E- 2 | 8.98 E- 2 | 1.59 E- 1 |
| Pu-242 | 6.76 E- 2 | 1.30 E- 4 | 5.63 E- 2 | 5.13 E- 2 |
| Am-243 | 2.68 E 0 | 8.81 E- 2 | 1.03 E 0 | 1.14 E 0 |

# Evaluation of Probabilistic Events

- The stepped limits in the probability/normalized release plane do not relate to risk.
- Currently 40 CFR 191 can reject repositories with a normalized risk less than one, and accept repositories with a normalized risk greater than one.
- 40 CFR 191 does not <u>regulate</u> high release events with cumulative probabilities less than 0.001. However, these low probability events must be included in performance assessments.

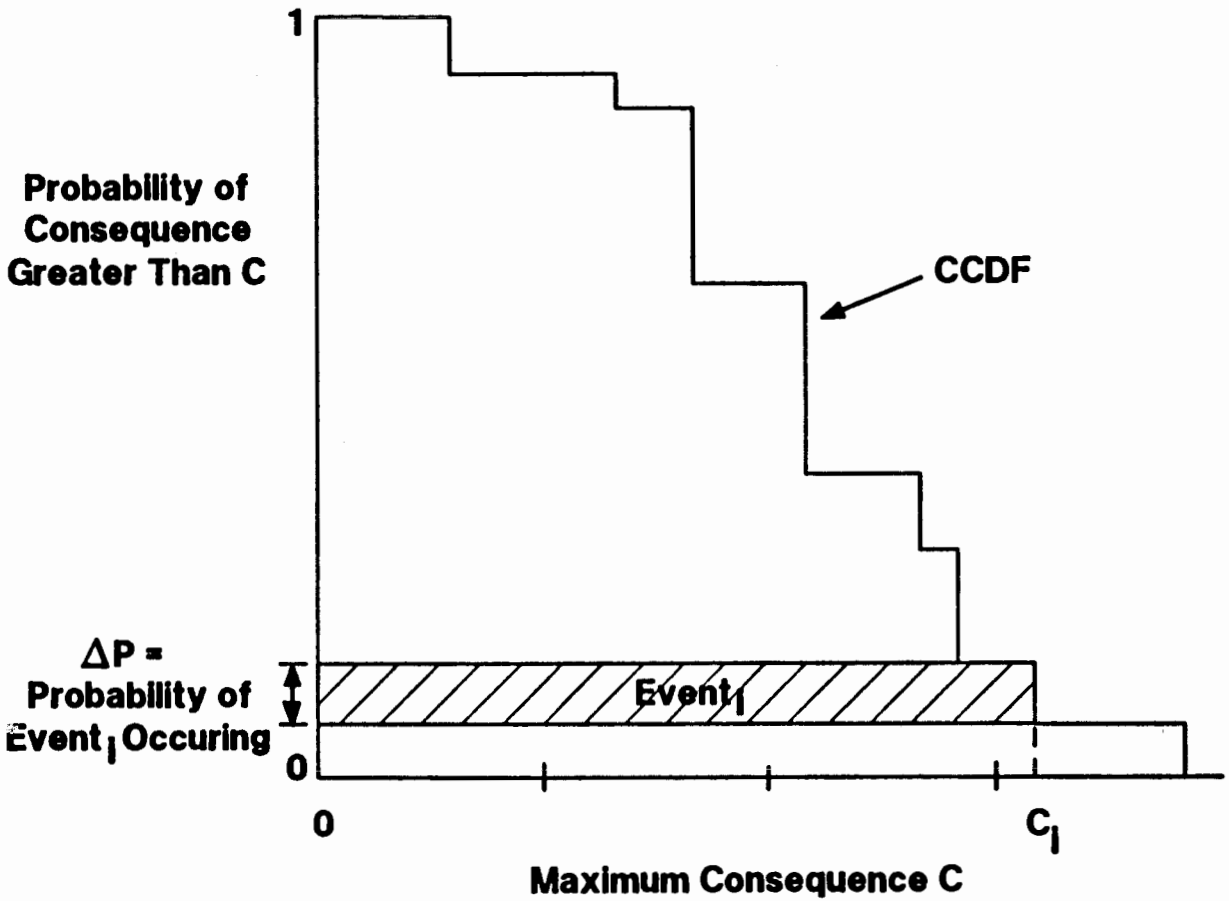



Probability curve for an annual risk of less than $10^{-5}$ from all sources except natural and medical (ICRP 46).

From: "Long-term Radiation Protection Objectives for Radioactive Waste Disposal," Nuclear Energy Agency, 1984

It is the area enclosed by the curve of probabilities of exceeding levels of dose [CCDF] that corresponds to the overall risk. The boundary line [of the dose limit curve] represents only the limit of risk of the risk arises from a single well-defined scenario with its probability of receiving a particular annual dose and is not therefore directly comparable with the [CCDF] curve. It is not a sufficient demonstration of compliance with the maximum risk objective that the whole curve of probabilities exceeding levels of dose [CCDF] lies to the left and below the boundary [of the dose limit curve]. It must be shown that the sum of risks from all exposure scenarios that could affect the same individual is less that the maximum [allowed] value.

# Graphical Representation of Risk




$$\text{Risk} = \sum_{i=1}^{n} \text{Consequence of Event}_i \times \text{Probability of Event}_i$$

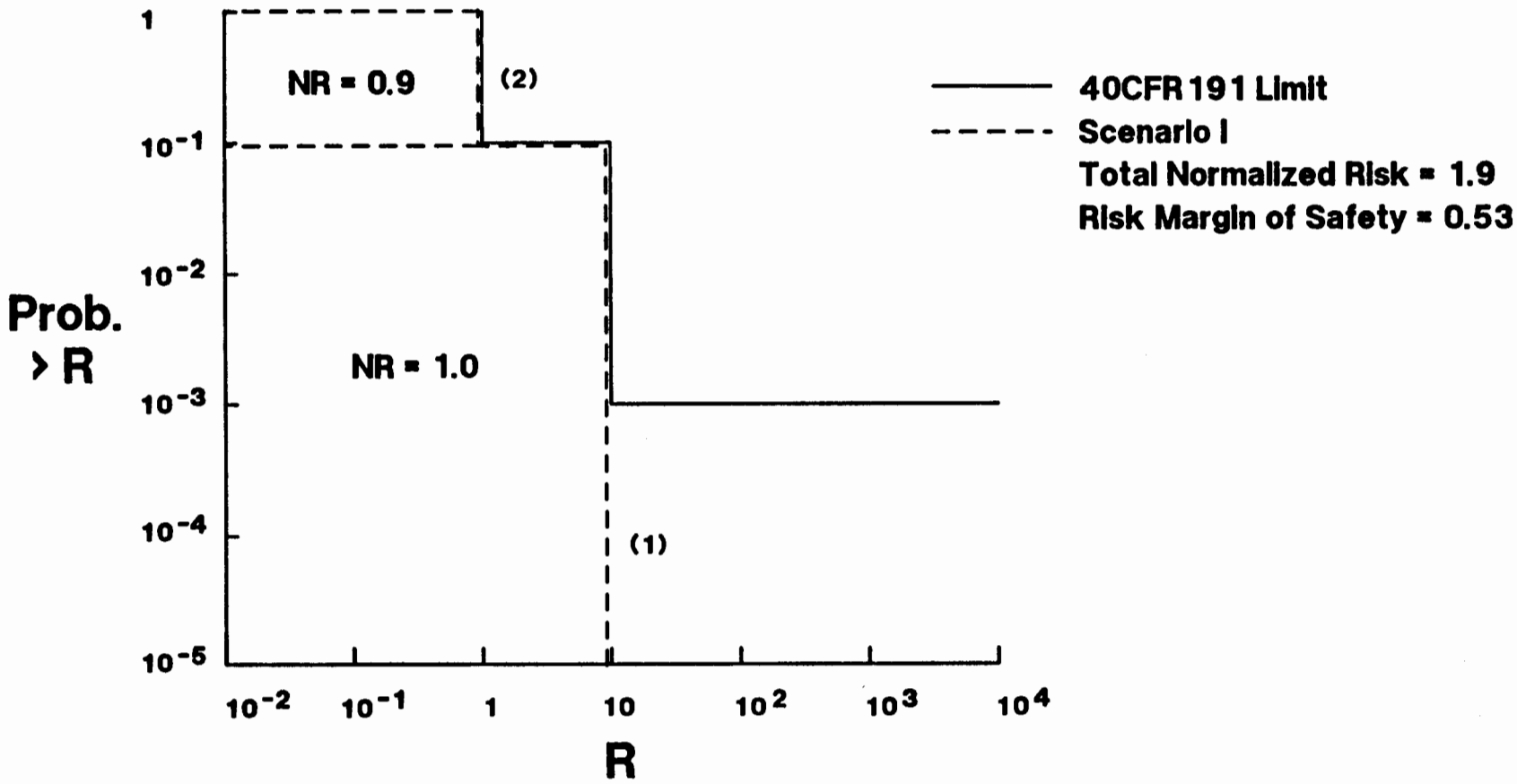
= Integral of CCDF

6341:4/90

# Risk Computations Using Release Limits

- Risk equals the consequence of an event, times the probability of that event, summed over all events
- The normalized releases (R), as defined by the summation rule in Note 6 of Appendix A of 40 CFR 191, corresponds to the consequence of an event
- Therefore, normalized risk equals the R of an event, times the probability of the event, summed over all events

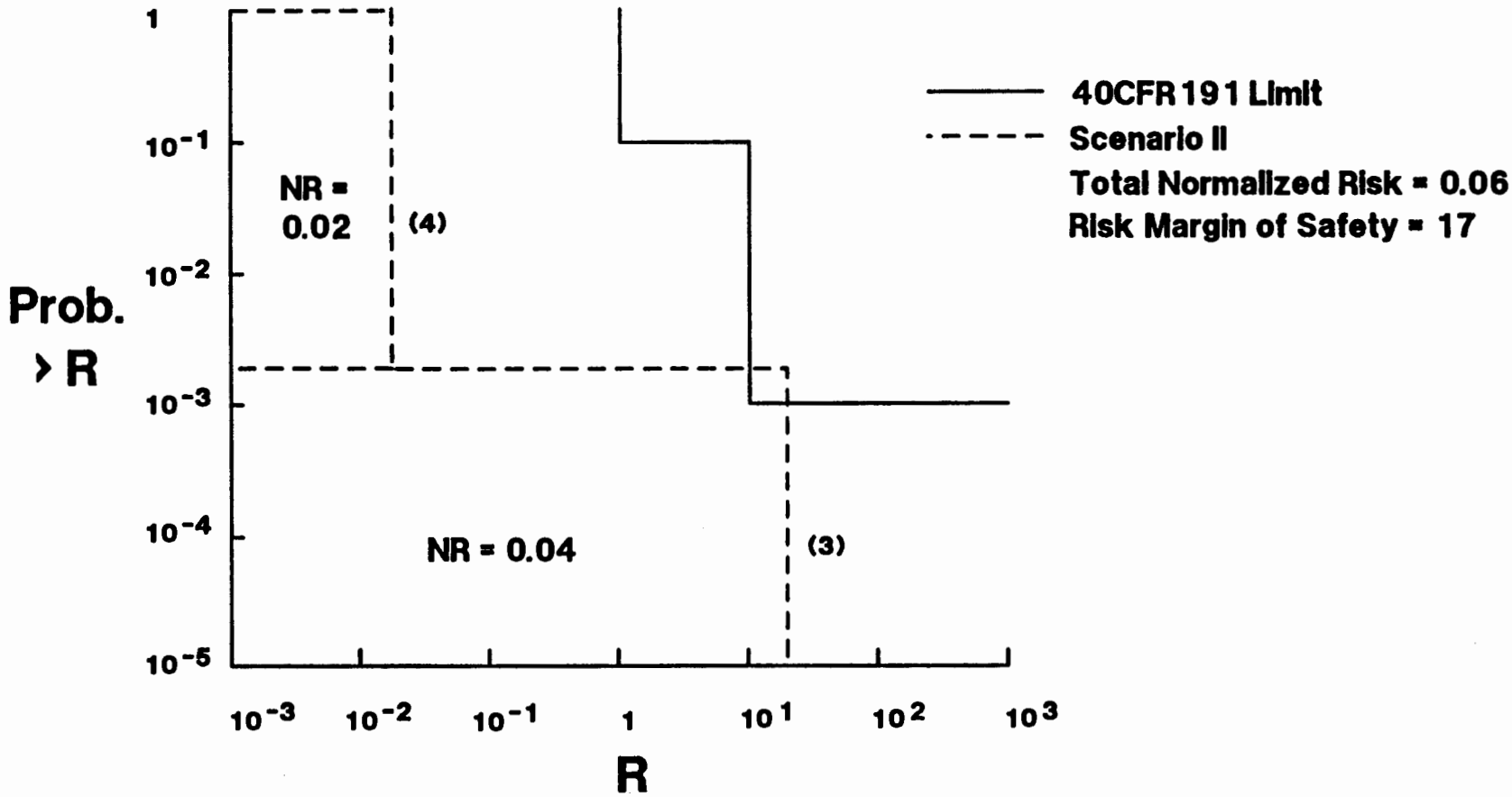
# Scenarios That Are Acceptable With Current CCDF Limits But Unacceptable With Risk Limits




| Event | CCDF (40CFR191) | | | Normalized Risk | |
|---|---|---|---|---|---|
| | R | P | ΣP | R x P | ΣR x P |
| 1 | 10 | .1 | .1 | 1.0 | 1.0 |
| 2 | 1.0 | .9 | 1.0 | .9 | 1.9 |

6341:5/90

# Scenario That Is Unacceptable With Current CCDF Limits But Acceptable With Risk Limits




| Event | CCDF (40CFR191) | | | Normalized Risk | |
|---|---|---|---|---|---|
| | R | P | ΣP | R x P | ΣR x P |
| 3 | 20 | .002 | .002 | .04 | .04 |
| 4 | .02 | .998 | 1.000 | .01996 | .06 |

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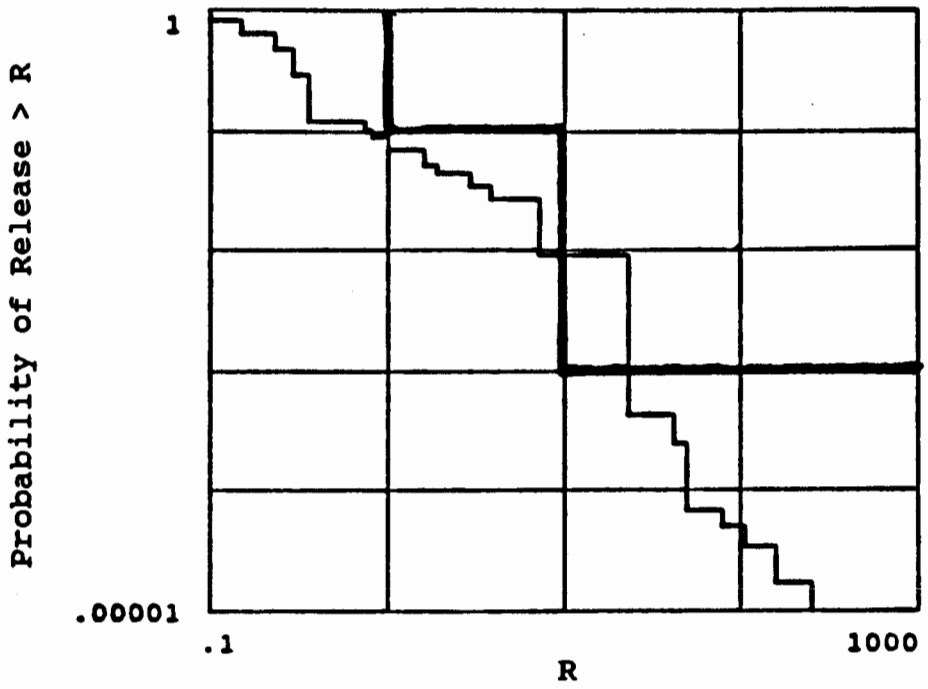
NUREG/CR-4510, SAND86-0121
EXAMPLE

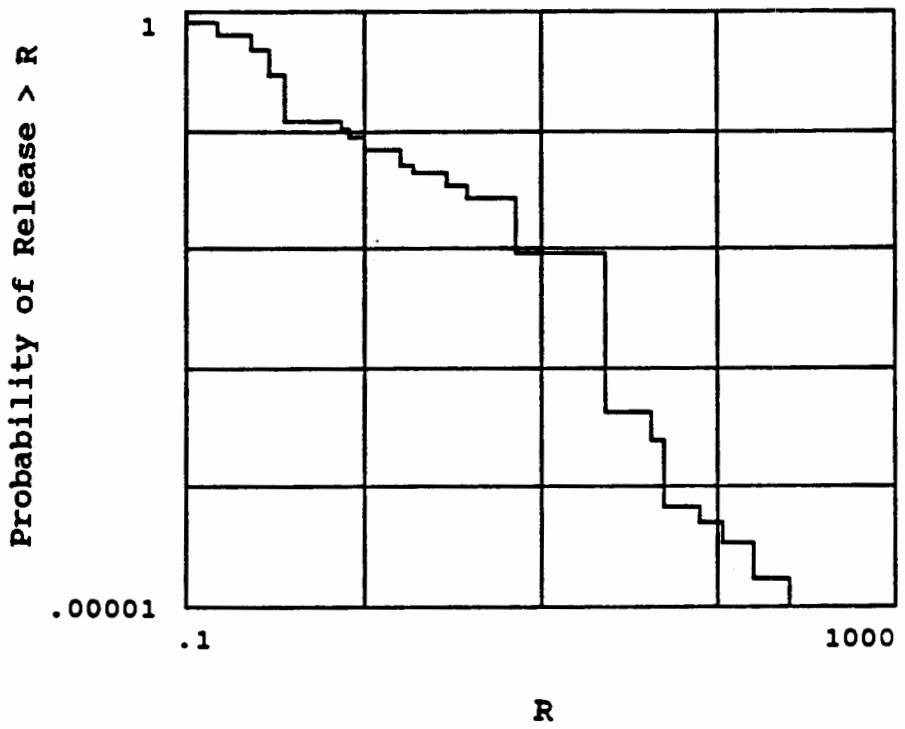
Normalized Risk = 0.695

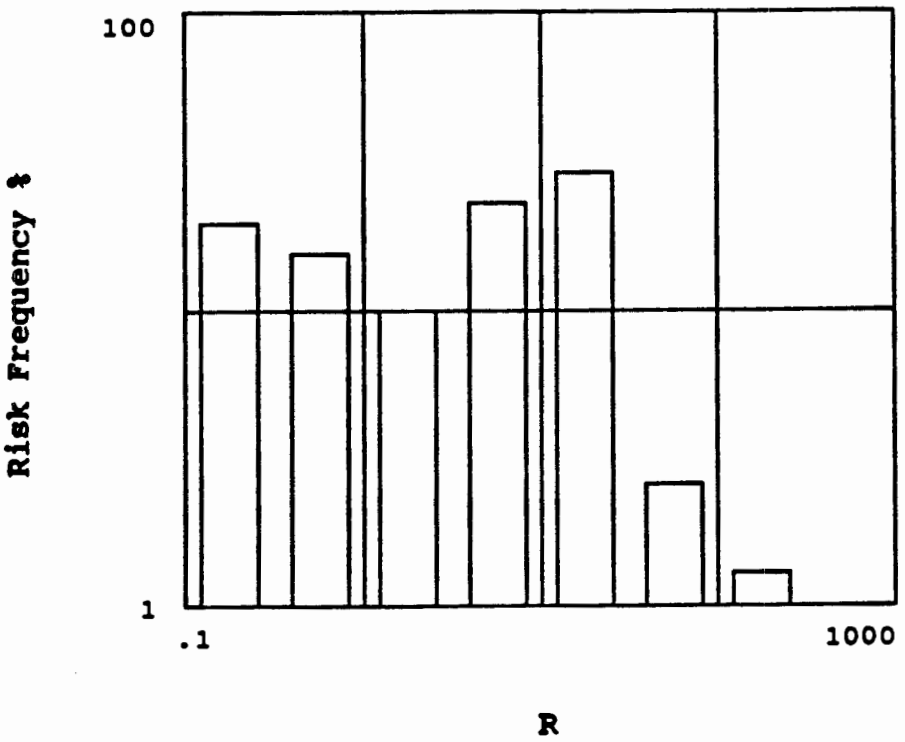


# Factors Affecting Confidence in Predictions of Future Events

- Amount of data (frequency x duration of observations)
- Cyclical or random occurrence of events
- Consistency of occurrence (measured and theoretical)
- Time span of prediction
- Sensitivity to other events

RISK DISTRIBUTIONS



# Conclusions

1. The two recommended extensions to 40 CFR 191 are independent and could be implemented separately.

2. If derived release limit standards are to be used for repository evaluations, they should be based on repository specific far field models that are traceable to the fundamental safety criteria.

3. Risk is a more widely accepted method of regulating probabilistic events than a stepped CCDF limit, and should be used in 40 CFR 191.

4. The proposed extensions would more accurately predict the risks from the WIPP and YMP and would fit in the existing format, but new release limits would have to be derived and some performance assessment procedures would change.

## REFERENCES


1. "A Study of the Isolation System for Geologic Disposaal of Radioactive Wastes," Waste Isolation Systems Panel, Board on Radioactive Waste Management, National Academy Press, Washington, D.C., 1983.

2. "Report on the Review of Proposed Environmental Standards for the Management and Disposal of Spent Fuel, High-Level, and Transuranic Radioactive Wastes (40 CFR 191)," High-Level Radioactive Waste Disposal Subcommittee, Science Advisory Board, U.S. Environmental Protection Agency, January, 1984.

3. "First Report to The U.S. Congress and The U.S. Secretary of Energy," Nuclear Waste Technical Review Board, March, 1990.

4. "Long-Term Radiation Protection Objectives for Radioactive Waste Disposal," Nuclear Energy Agency, OECD/NEA, Paris, 1984.

5. "ICRP Publication 46 - Radiation Protection Principles for the Disposal of Solid Radioactive Waste," Annals of the International Commission on Radiological Protection Volume 15, Number 4, 1985.

6. R. D. Klett, M. F. Kaplan, C. M. Koplik, and D. A. Ensminger, "Subseabed Disposal Project Workshop on Radiological Protection Standards," SAND84-2625, February, 1986.

7. J. M. Smith, T. W. Fowler, and A. S. Goldin, "Environmental Pathway Models for Estimating Population Health Effects from Disposal of High-Level Radioactive Waste in Geologic Repositories," EPA 520/5-80-002, December 1982.

8. J. C. Helton, "Thechnical Assistance for Regulatory Development: Review and Evaluation of the Draft EPA Standard 40CFR191 for Disposal of High-Level Waste - Vol. 5, Health Effects Associated with Unit Radionuclide Releases to the Environment," NUREG/CR-3235, SAND82-1557, April, 1983.

9. C. Starr and C. Whipple, "Risks of Risk Decisions," Science, Vol. 208, June 6, 1980.

# RADIOLOGICAL STANDARDS

1. Contents of 40 CFR 191 should be augmented. (NAS, SAB, NWTRB, & numerous journal articles).

2. Who to protect (Individuals and/or populations)?

3. How to protect them?
   -Dose (ICRP, NAS, SDP/WRPS).
   -Derived, generic far-field model (EPA).
   -Derived, site specific far-field model.
   -Prescriptive (NRC).

4. Acceptable level.
   -Comparable to unmined uranium ore ($10^{-6}$ HE/MTU-Yr).
   -Acceptable dose or release from a single repository.

5. Regulation of probabilistic events.
   -Shape of CCDF curve (EPA).
   -No more than 50% of events above R=1 (SAB).
   -Unacceptable risk/dose region (ICRP).
   -Risk: consequences of an event X probability of the event, summed over all events; or area under the CCDF curve (NEA).
   -Adapt NEA risk definition to release limits.

6. Assumptions for low probability natural events and human intrusion (EPA & NRC).

7. Minimum probability event to be regulated.

8. Duration of regulation.

9. Compatible standards for reprocessing and disposing of TRU waste.

10. What should be changed and what can be done to influence the change?

DIFFERENCES BETWEEN YMP & WIPP THAT AFFECT STANDARDS

1. Pathways from the peripheral boundaries to humans during normal operation are different. Therefore, release limits should be different.

2. Pathways from the surface or peripheral boundaries to humans following human intrusion or abnormal events are different. Therefore, abnormal release limits should be different.

3. Local Lithology
   YMP - Tuff, relatively high permeability, gas permeability high enough to release gaseous radionuclides, igneous with low probability of intrusion but higher probability of seismic activity.
   WIPP - Salt, low permeability, gas permeability too low to relieve gas pressure, sedimentary with higher probability of human intrusion but seismically inactive.

4. Local hydrology
   YMP - Unsaturated, downward flow to acquifer via precipitation, susceptible to climate change.
   WIPP - Saturated, upward flow to region with greater horizontal flow, pressurized brine pocket below repository.

5. Waste form
   YMP - SF and vitrified HLW in long lived canisters, heat generating, short and long half lives, high initial activity.
   WIPP - Mixed TRU in various forms in short lived canisters, gas generating, long half lives, low activity, negligable heat generation.

6. Repository layout
   YMP - Canisters separated enough to be treated independently except for heat transfer.
   WIPP - Contents of canisters can mix in a porous room to create a large mixed effective source.