Rec'd with letter
12/28/94
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SUMMARY OF U.S. NUCLEAR REGULATORY COMMISSION AND U.S. DEPARTMENT OF ENERGY TECHNICAL EXCHANGE ON SUBSTANTIALLY COMPLETE CONTAINMENT AND WASTE PACKAGE DESIGN, DECEMBER 7, 1994

On December 7, 1994, representatives of the U.S. Nuclear Regulatory Commission, the U.S. Department of Energy (DOE), the State of Nevada, and Nye County, Nevada, participated in a technical exchange on substantially complete containment (SCC) and waste package design. The list of attendees and the technical exchange agenda are included as Attachments 1 and 2 to this summary. Copies of presenter's handouts are included as Attachment 3. Technical presenters included representatives from NRC, Center for Nuclear Waste Regulatory Analyses (CNWRA), DOE, DOE's Management and Operations Contractor (M&O), and Lawrence Livermore National Laboratory (LLNL).

Michael Bell (NRC) welcomed the participants. He noted that there were several open items concerning the SCC requirement, but that these could not be resolved solely on the basis of this technical exchange.

Alan Berusch (DOE) presented a brief overview of DOE's objectives for both this technical exchange and the August 1993 technical exchange on SCC. Mr. Berusch also discussed DOE's new SCC performance goal and SCC accomplishments in Fiscal Year 1994.

Hugh Benton (M&O) presented a detailed description of the status of DOE's waste package design program. Specific topics discussed by Mr. Benton included the purpose of the waste package design program, the multi-barrier design concept, the material selection process, thermal considerations, criticality considerations, structural considerations, performance analyses, and Fiscal Year 1995 plans.

R. Daniel McCright (LLNL) presented a detailed description of the waste package materials testing effort. Specific topics discussed by Mr. McCright included the Workshop on Container Materials organized by LLNL, candidate container materials selected by DOE, DOE's short term and long term materials testing plans, results from thermogravimetric analysis testing, results from crack growth testing, and a summary and forecast of the total materials testing effort.

David Stahl (M&O) presented a summary of DOE's model prediction program for containment barrier performance. Specific topics discussed by Dr. Stahl included the purpose of the predictions, the methodology used to calculate the predictions, representative results, and conclusions.

David Stahl (M&O) presented a review of DOE's approach to demonstrating compliance with the SCC requirement. Specific topics discussed by Dr. Stahl included the background of previous DOE efforts to comply with the SCC requirement, DOE's current approach, and the status of open items from NRC's Site Characterization Analysis. Dr. Stahl noted that there was an inadvertent omission in the DOE supplemental response to Question 35. Michael Bell (NRC) and his staff asked several questions on the details of the new DOE approach to complying with the SCC requirement. Dr. Stahl and other DOE representatives emphasized that DOE does not yet have the data and analysis to demonstrate that the waste package will be in compliance with the SCC requirement. The DOE representatives noted, however, that the information

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that has been provided to the NRC during the past year should provide an adequate basis for resolving the NRC's Comment 80, Question 35, and Question 47 on the DOE's 1988 Site Characterization Plan.

Prasad Nair (CNWRA) and Narasi Sridhar (CNWRA) presented a summary of CNWRA's technical assistance efforts related to SCC and waste package design. Specific topics discussed by Dr. Nair and Dr. Sridhar included the SCC Example Problem and the Engineering Experience on Reliability report.

Narasi Sridhar (CNWRA) presented a summary of the status of CNWRA's waste package research efforts. Specific topics discussed by Dr. Sridhar included the use of the License Application Review Plan to identify research needs, the CNWRA's overall approach to waste package performance assessment, specific areas of CNWRA research activities, and future research plans.

There were no closing remarks from the State of Nevada or from Nye County, Nevada. The NRC participants stated that the technical exchange provided an opportunity to understand the status of DOE's waste package design program and DOE's approach to demonstrating compliance with the SCC requirement. As there were many tests being conducted by different groups, NRC staff observed that site visits would be desirable. In closing, the DOE thanked the participants for their input and discussion during the technical exchange.

Michael J Bell for 12/27/94

David M. Dancer, Project Engineer
Engineering and Geosciences Branch
Division of Waste Management
Office of Nuclear Material Safety and Safeguards
U.S. Nuclear Regulatory Commission

Priscilla Bunton 12/22/94

Priscilla Bunton
Regulatory Integration Division
Office of Civilian Radioactive Waste Management
U.S. Department of Energy

December 7, 1994

NRC/DOE TECHNICAL EXCHANGE ON
SUBSTANTIALLY COMPLETE CONTAINMENT

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Steve Nesbit	M&O / Las Vegas	702-794-1910
David Stahl	M&O/LV/BWFC	702-794-7778
Charles Interrante	NRC/DWM/ENGB	301-415-6652
RICK WELLER	"	301-415-7287
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Attachment 1

AGENDA

DOE/NRC Technical Exchange on Substantially Complete Containment and Waste Package Design

December 7, 1994
Two White Flint - Room 7A1
Rockville, MD

Time	Topic	Presenter
8:30	Welcome/Protocol/Opening Remarks	DOE, NRC, Affected Units of Government
9:00	Status of Waste Package Design - Multi-barrier concepts - Thermal considerations - Criticality - Structural considerations	DOE
10:45	Break	
11:00	Status of Waste Package Materials Testing Effort - Candidate materials for container - Plans for short- and long-term testing - Results from thermogravimetric analysis (TGA) testing - Results from crack growth testing	DOE
12:00	Lunch	
1:00	Model Predictions of Containment Barrier Performance	DOE
1:30	Review of DOE's Approach to Demonstrating Compliance with the SCC Requirement - Background - Current approach - Status of SCA Open Items - Supplemental response to Comment 80 - Supplemental response to Question 47 - Supplemental response to Question 35	DOE

Attachment 2

Time	Topic	Presenter
2:15	NRC Comments - Status of SCA Open Items (Comment 80 and Question 47) - DOE's approach to demonstrating compliance with the SCC requirement	NRC
3:00	Break	
3:15	Status of NRC Testing Effort - Corrosion testing - Corrosion modeling - Discussion	NRC
4:15	Closing Comments	DOE, NRC, Affected Units of Government

DOE/NRC Technical Exchange on Substantially Complete Containment and Waste Package Design

Rockville, MD—December 7, 1994

Opening Remarks

Alan Berusch
Senior Engineer

Office of Civilian Radioactive Waste Management
U.S. Department of Energy

Attachment 3

Opening Remarks

- Introduction
  - DOE objectives—August 1993 technical exchange
  - DOE's SCC performance goal
  - FY 1994—a year of SCC progress
  - Key to complying with SCC requirement
- DOE objectives—this technical exchange
- DOE presentations

DOE Objectives—
August 1993 Technical Exchange

- Inform NRC staff about DOE's new SCC performance goal and waste package plans
- Discuss why they are responsive to staff's SCA recommendations

DOE Objectives—
August 1993 Technical Exchange

- Discuss why, when implemented, the plans will provide the information required to satisfy SCC rule

- Establish basis for closing open SCC-related SCA comments/questions

DOE's SCC Performance Goal

- Achieve mean waste package lifetime well in excess of 1,000 years

FY 1994—A Year of SCC Progress

- DOE's SCC Performance Goal
  - Considered by NRC staff to be a reasonable implementation of SCC requirement
- SCA Comment 5 (effects of technological limitations and uncertainties on compliance)
  - Resolved

FY 1994—A Year of SCC Progress

- SCA Question 46 (containment period release rate performance goals)
  - Resolved
- SCA Question 47 (waste package failure criterion) and SCA Comment 80 (consistency between performance goal and SCC requirement)
  - Additional information requested/provided

FY 1994—A Year of SCC Progress

- Waste package design and development
  - In progress

Key to Complying with SCC Requirement

- Successful implementation of DOE waste package plans
  - Waste Package Plan
  - Waste Package Implementation Plan

DOE Objectives— This Technical Exchange

- NRC Feedback
  - Relevance of DOE waste package design/development efforts to compliance with SCC requirement
  - Status of NRC testing program
  - Status of remaining SCC-related open SCA items
- Shared understanding of interpretation and approach to demonstrating compliance with SCC requirement

DOE Presentations

- Hugh Benton—status of waste package design
- Dan McCright—status of waste package materials testing program
- Dave Stahl—model predictions for containment barrier performance
- Dave Stahl—DOE's approach to demonstrating compliance with SCC requirement

DOE Presentations

- **DOE believes these presentations will:**
  - Instill confidence that DOE's waste package program is established on a sound foundation
  - Provide basis for resolving open SCC-related SCA comments and questions

DOE/NRC Technical Exchange on Substantially Complete Containment and Waste Package Design

Status of Waste Package Design

PRESENTED BY

Hugh A. Benton, Manager
Waste Package Development

December 7, 1994

Contents

- **Multi-Barrier Design Concept**
  - Goals and Strategy
  - Design Approach
  - Current Concepts
- **Material Selection Process**
  - Selection Criteria
  - Materials for Testing
- **Thermal Considerations**
  - Thermal Criteria
  - Thermal Performance
  - Thermal Analysis

Contents, continued

Purpose

- Develop waste package designs that will satisfy regulatory requirements with sufficient margin as to be acceptable to the NRC
  - Multi-purpose canister (MPC) waste package
  - Waste package for uncanistered fuel
  - Waste package for high level waste glass canisters

Multi-Barrier Design Concepts

- Goals and Strategy
- Design Approach
- Current Concepts

Waste Package Development Goals

Achieve a design that:

- Meets Quality Assurance requirements
- Can be shown to meet all regulatory requirements with sufficient margin for uncertainty of performance predictability
- Provides mean waste package lifetime well in excess of 1,000 years
- Is compatible with the repository and the rest of waste management system
- Can be deployed at acceptable cost

Waste Package Strategy

- The attainment of the goal using an iterative system engineering approach based on
  - A multibarrier approach
  - The unsaturated nature of the Yucca Mountain site
  - Consideration of technical alternatives
  - Sufficient resolution of technical and regulatory uncertainties
  - Tolerant of broad range of thermal loads and other conditions

NRC REGULATIONS

- Substantially complete containment for 300 to 1,000 years after permanent closure
  10 CFR 60.113 (a)(1)(ii)(A)

- Release rate of any radionuclide from Engineered Barrier System following containment period $\leq$ 1 part in 100,000 per year of inventory at 1,000 years following permanent closure
  10 CFR 60.113(a)(1)(ii)(B)

- Criticality accident not possible without 2 unlikely independent events and $k_{eff} \leq 0.95$ allowing for bias and uncertainty 10 CFR 60.131 (b)(7)

- Retrieval could be accomplished starting any time up to 50 years after initial waste emplacement
  10 CFR 60.111 (b)

- Worker dose in accordance with 10 CFR 20, 10 CFR 60.131(a)

ADVANCED CONCEPTUAL DESIGN WASTE PACKAGE CONCEPTS - FY94

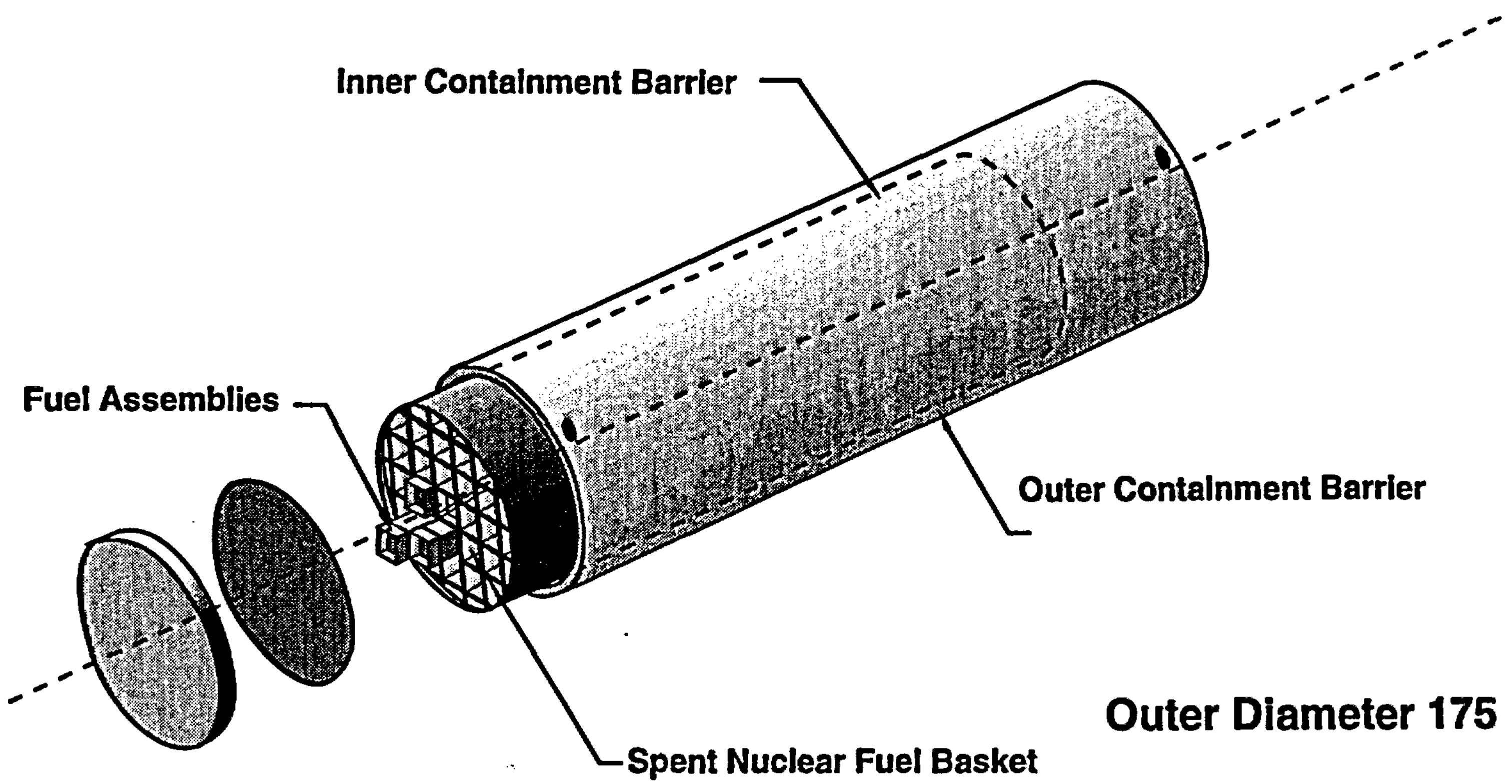
- Multi-Purpose Canister with Disposal Container - 2 sizes
- Defense High Level Waste Container
- Uncanistered Spent Nuclear Fuel Container

Technical Approach for Waste Package Development

Component Functions	→	WP Design
↓		↑
Performance Measures	→	Subsystem Modeling
↓		↑
Degradation Modes	→	Mechanistic Modeling (Scientific Basis)
↓		↑
Performance Parameters	→	Materials Testing

Waste Package Design

Uncanistered Spent Fuel



Outer Diameter 175 cm

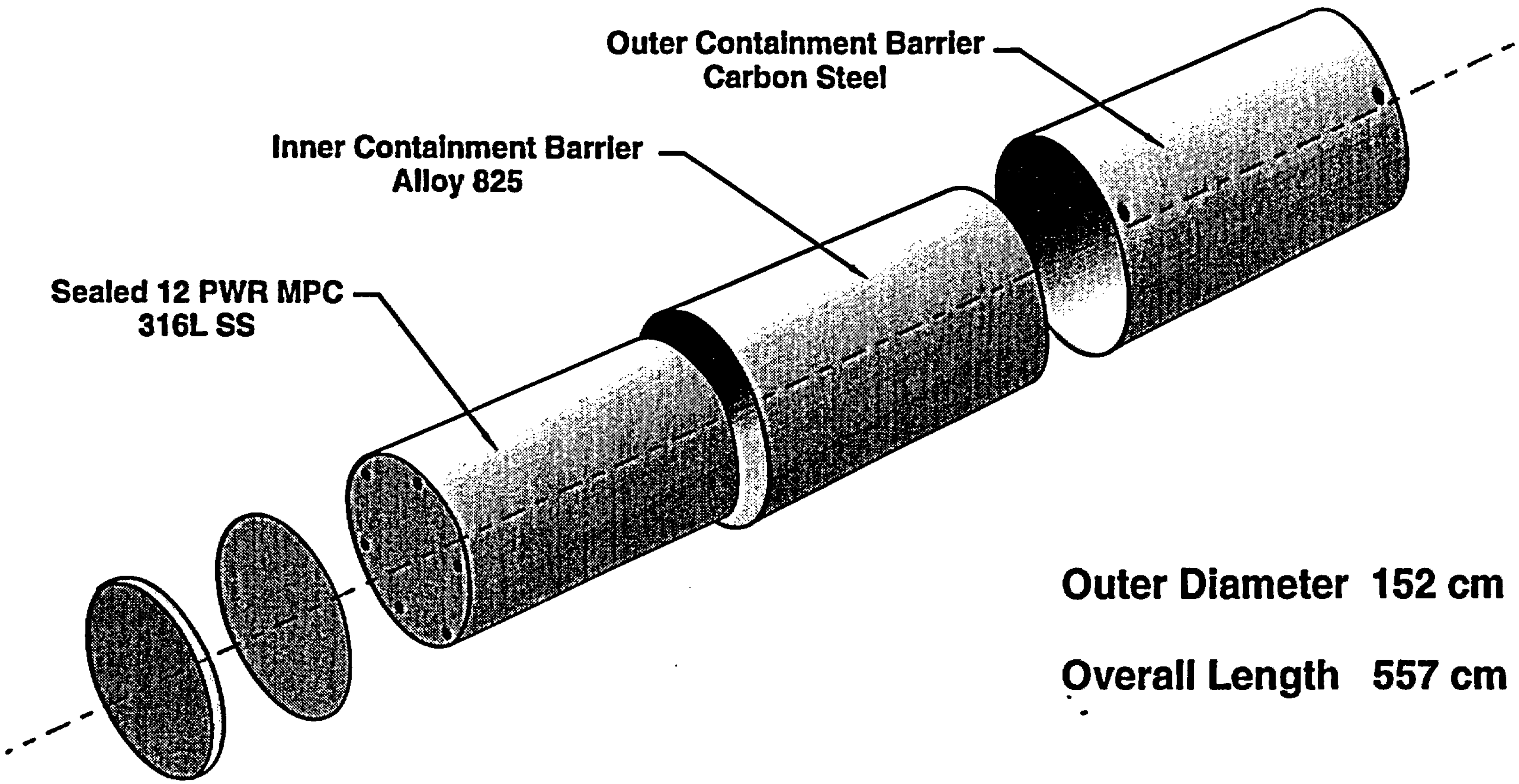
Overall Length 529 cm

PRELIMINARY PREDECISIONAL DRAFT MATERIAL

Waste Package Design

12 PWR Multi-Purpose Canister

Primary Thermal Load Case



Outer Diameter 152 cm

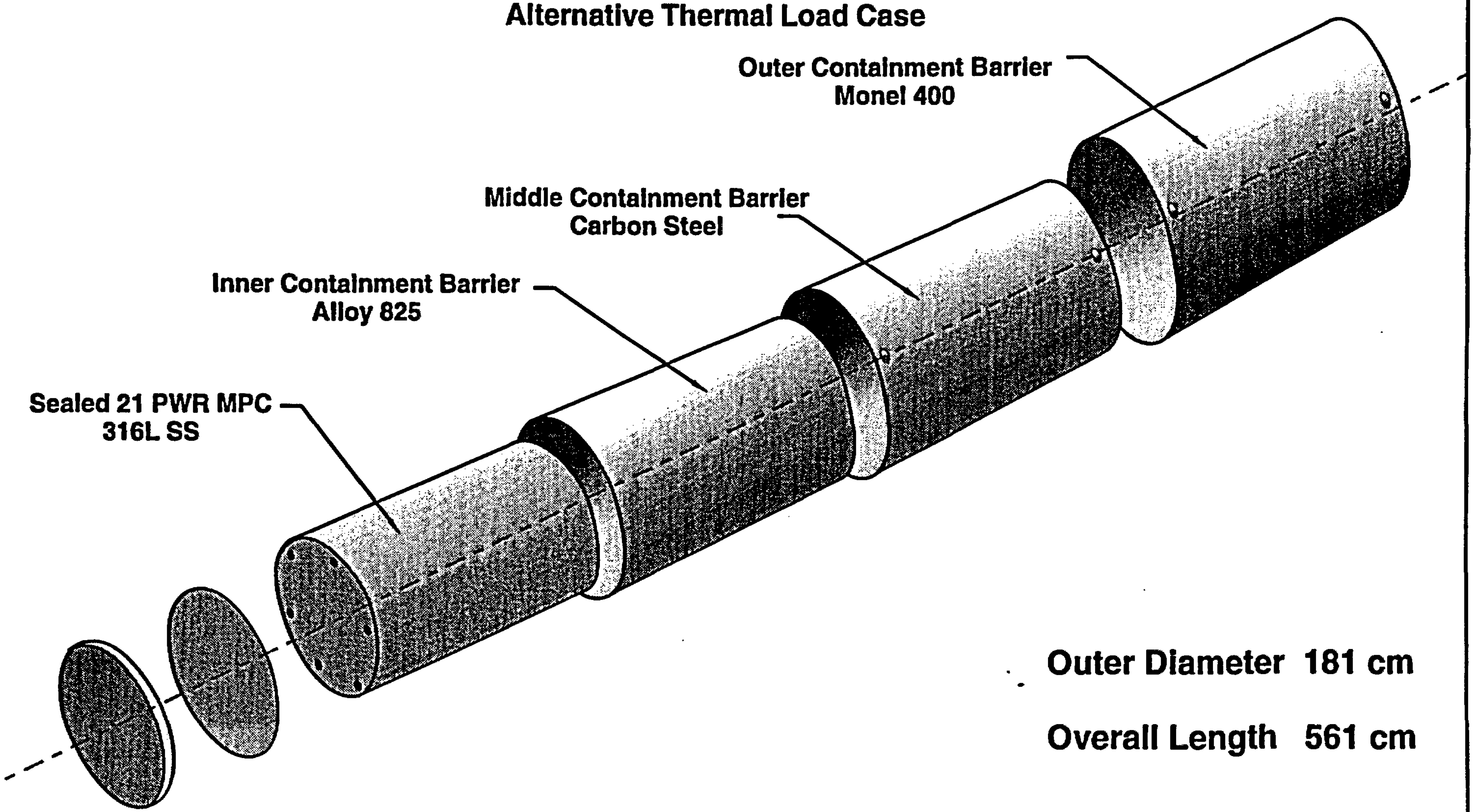
Overall Length 557 cm

PRELIMINARY PREDECISIONAL DRAFT MATERIAL

Waste Package Design

21 PWR Multi-Purpose Canister

Alternative Thermal Load Case



Outer Diameter 181 cm

Overall Length 561 cm

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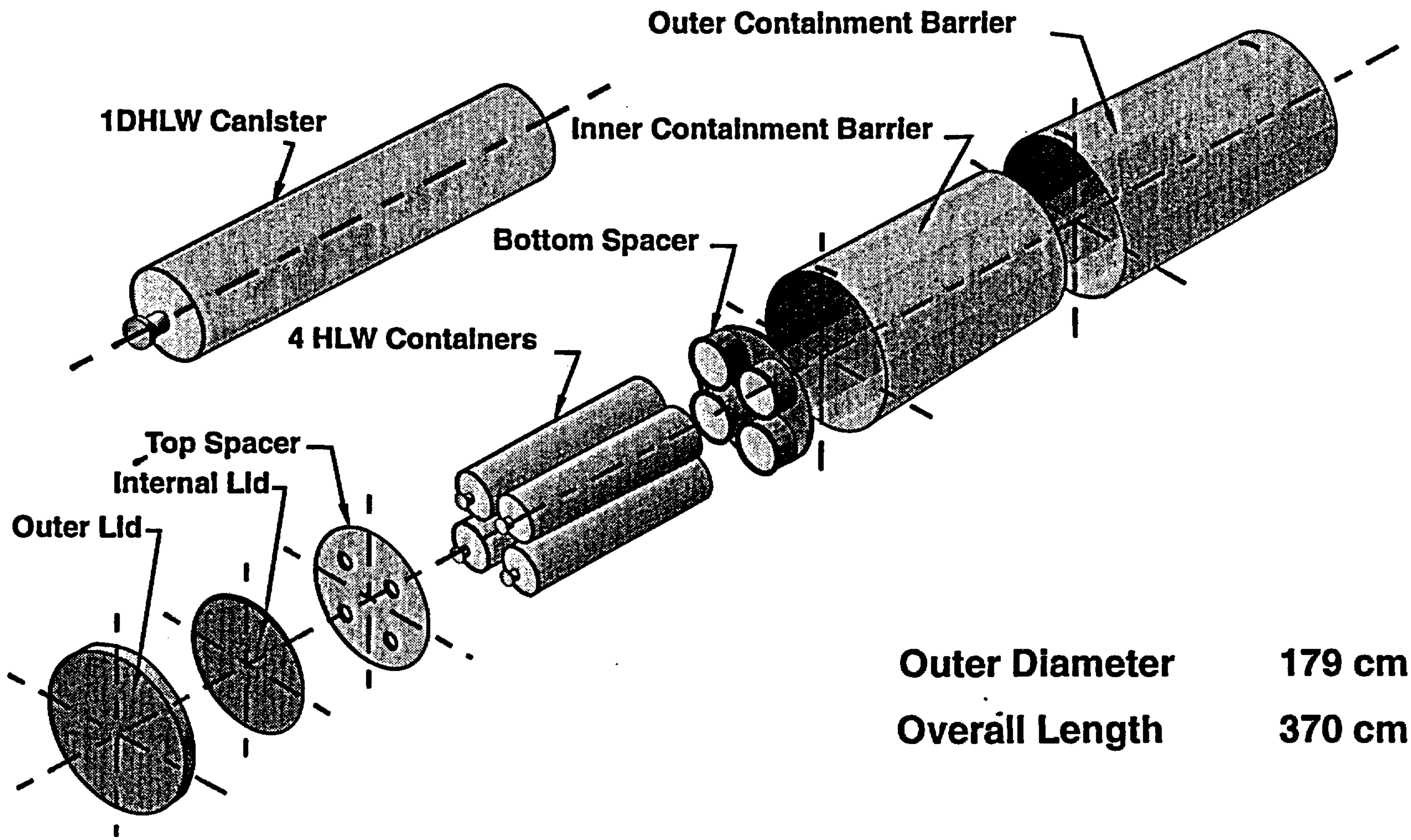
PRELIMINARY PREDECISIONAL DRAFT MATERIAL

High Level Waste Glass Disposal Container

Waste Package Design

High Level Waste Glass Canister

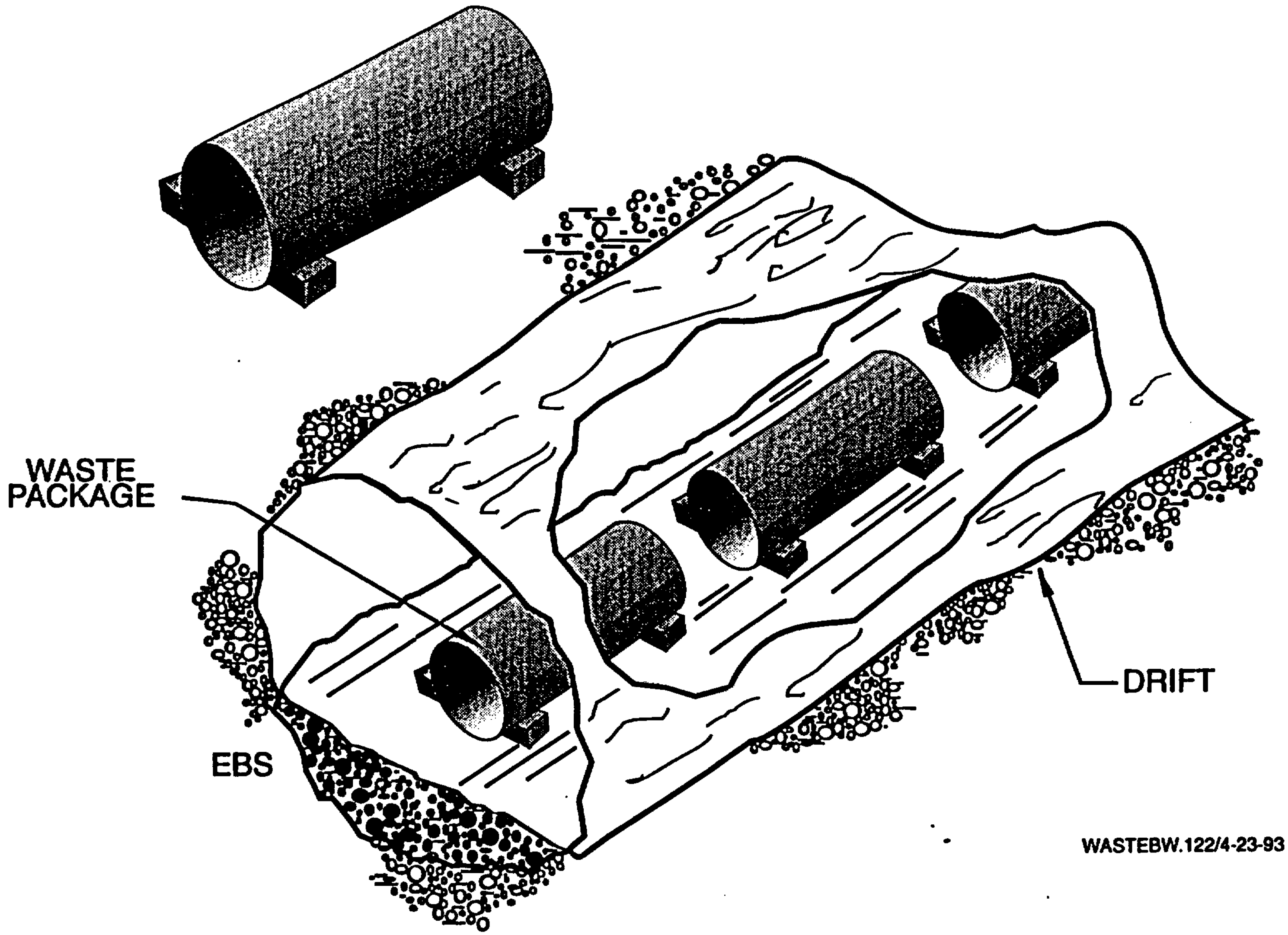
Primary Thermal Load Case



Outer Diameter	179 cm
Overall Length	370 cm

PRELIMINARY PREDECISIONAL DRAFT MATERIAL

WASTE PACKAGE DRIFT EMPLACEMENT

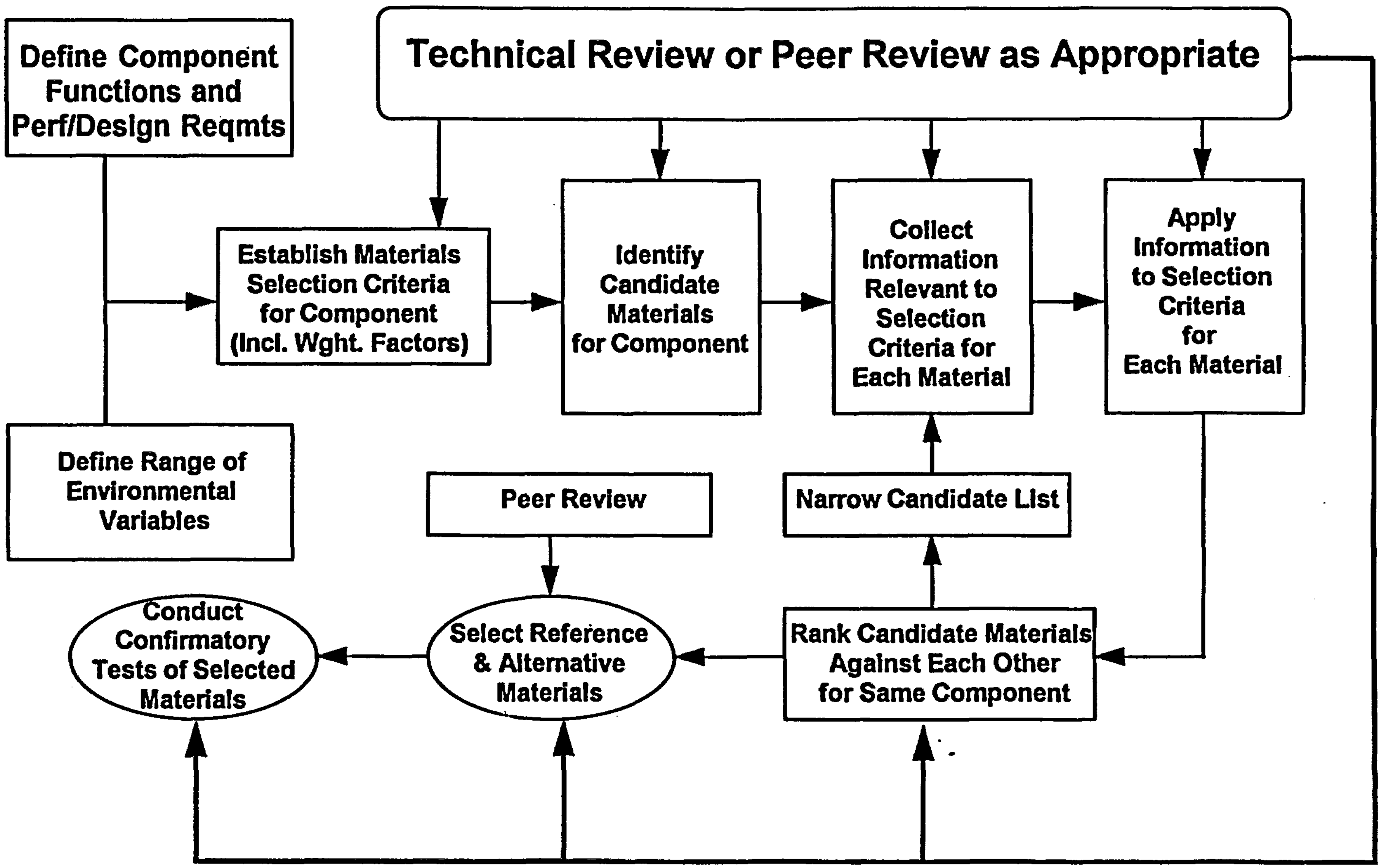


PRELIMINARY PREDECISIONAL DRAFT MATERIAL

Material Selection Process

- Selection Criteria
- Materials for Testing

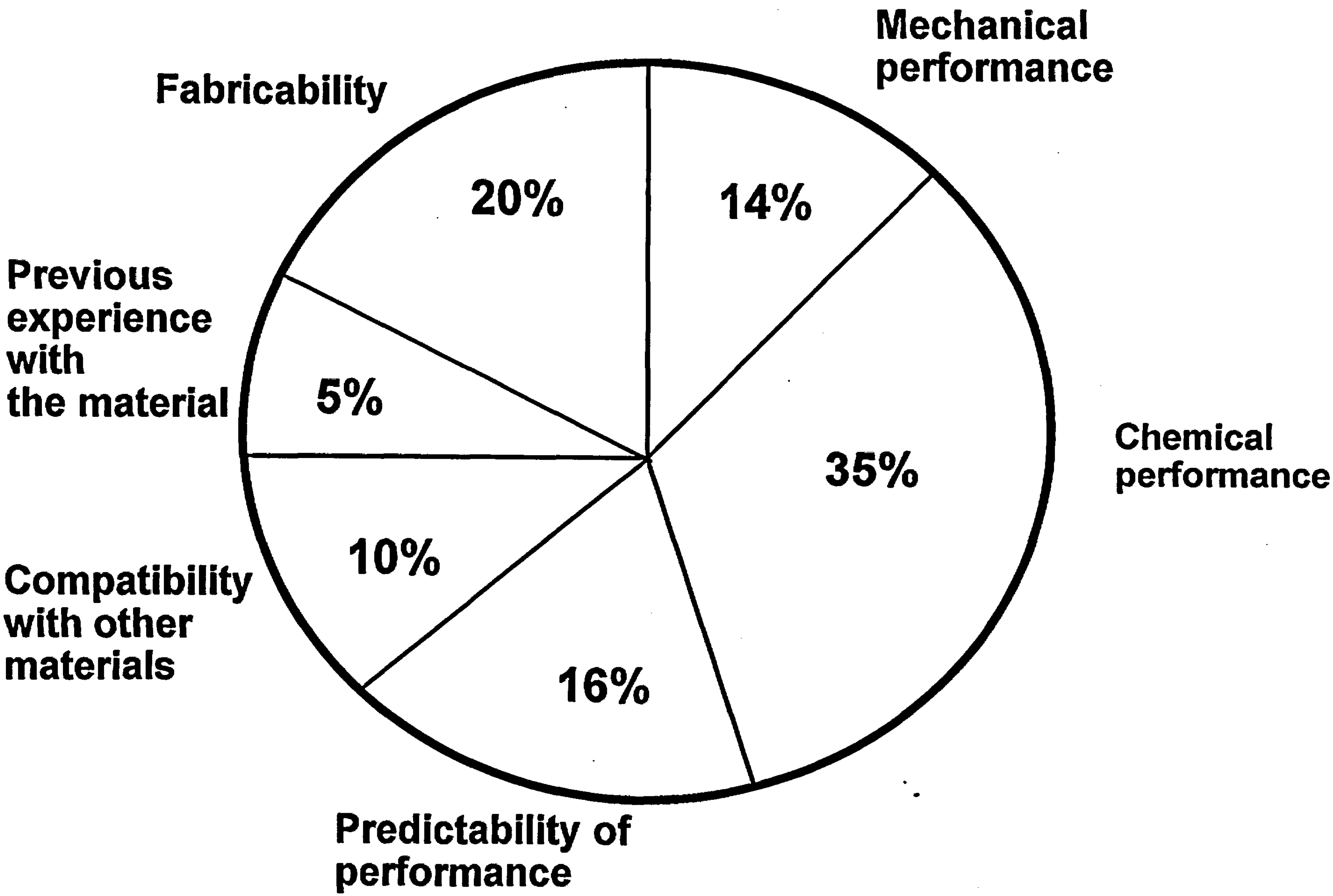
WASTE PACKAGE MATERIALS SELECTION PROCESS



Selection Criteria

- Performance-related criteria
  - Mechanical performance
  - Chemical performance
  - Predictability of performance
  - Compatibility with other materials
- Engineering-related criteria
  - Cost
  - Previous engineering experience
  - Fabricability, closure, and availability of materials

Technical Weighting Factors for Containment Barriers



Materials Recommended for Testing

Component	Commercial Designation
Outer Containment Barrier	A 516 (Wrought Carbon Steel)
	A 27 (Cast Carbon Steel)
	2-1/4 Cr - 1 Mo (Low Alloy Steel)
	CDA 715 (70/30 Copper - Nickel)
	Alloy 400 (70/30 Nickel - Copper)

Materials Recommended for Testing

Component	Commercial Designation
Inner Containment Barrier	Alloy 825 (Nickel - Base Alloy)
	Alloy 821 (825 with higher Mo)
	Alloy C - 4 (Nickel -Base High Mo Alloy)
	Alloy C - 22 (C-4 with higher Cr)
	Ti Grade 12 (Titanium Alloy with Mo & Ni)
	Ti Grade 16 (Titanium Alloy with Pd)
Other Containment Barrier	Al_2O_3 (Non-Metallic Material)
	TiO_2 (Non-Metallic Material)

Materials in Conceptual Designs

	Primary	Alternate
Inner Barrier	Alloy 825	Alloy C-22
Outer Barrier	A 516	2-1/4Cr - 1Mo
Additional Barrier for Agressive Environments	Alloy 400	C71500
Basket Structural	Type 316 Stainless Steel	Alloy 825
Basket Criticality Control	Type 316 Stainless Steel-Boron	Open

Waste Package Design
Conceptual Materials

PRELIMINARY PREDECISIONAL DRAFT MATERIAL

Design Option	Inner Containment Barrier Material	Inner Containment Barrier Thickness	Outer Containment Barrier Material	Outer Containment Barrier Thickness	Loaded Weight
21 PWR MPC	Alloy 825	2 cm	A 516 Carbon Steel	10 cm	63,650 kg
12 PWR MPC	Alloy 825	2 cm	A 516 Carbon Steel	10 cm	46,010 kg
4 DHLW	Alloy 825	2 cm	70-30 Cupronickel	10 cm	35,580 kg
21 UCF WP	Alloy 825	2 cm	A 516 Carbon Steel	10 cm	52,650 kg

Thermal Considerations

- Thermal Criteria
- Thermal Performance
- Thermal Analysis

Thermal Criteria for Disposal

- Drift wall temperature <200°C
- Spent nuclear fuel (SNF) cladding temperature < 350°C
- Access drift temperature <50°C for 100 years after emplacement
- Calico Hills and TSw3 rock temperature <115°C
- Ground surface temperature rise <2°C
- Maximize time waste package above boiling consistent with thermal loading strategy

Factors Affecting Thermal Response

- **Waste package internal temperatures depend on:**

  Near-field temperatures

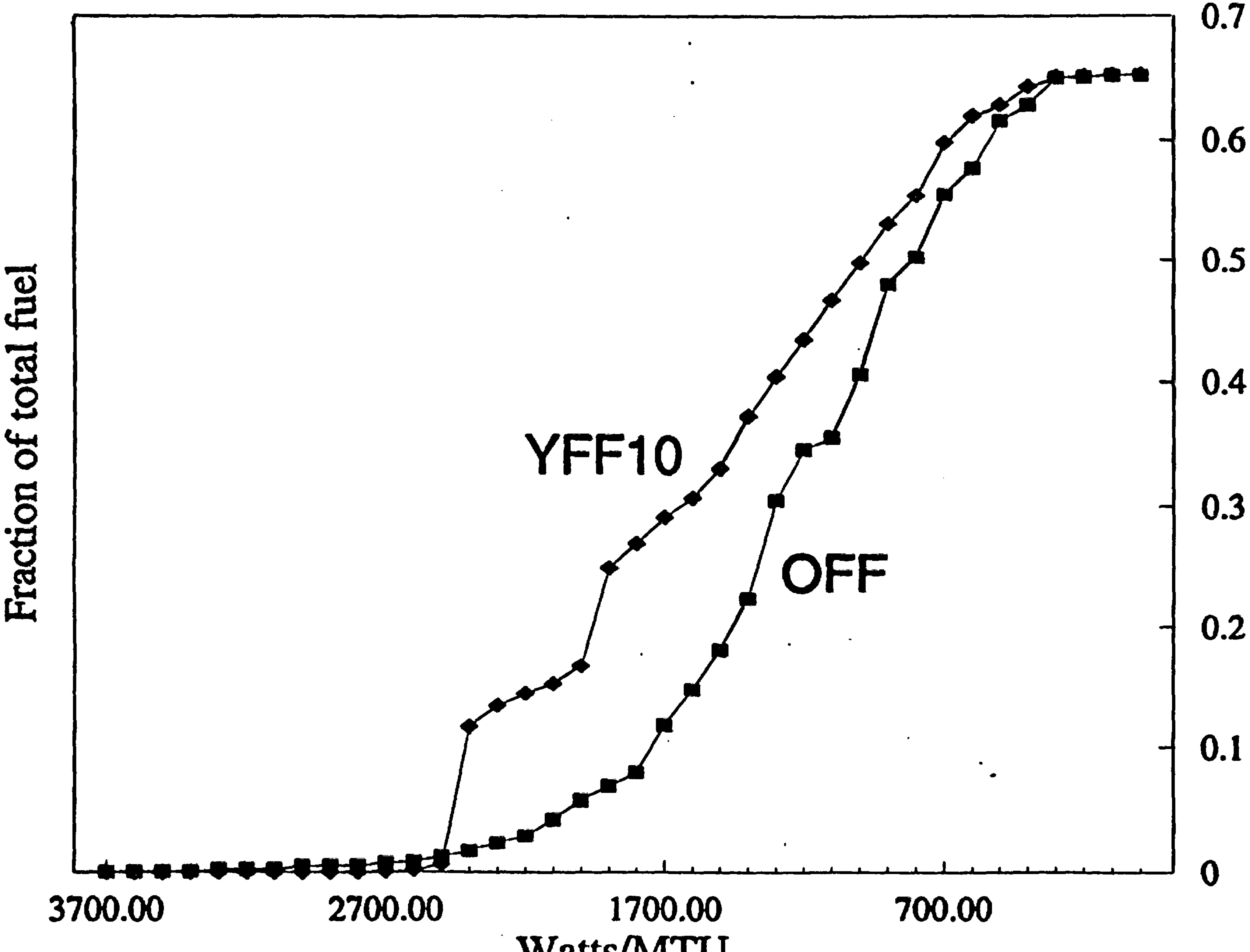
  SNF characteristics

  Number of assemblies

  Materials of fabrication

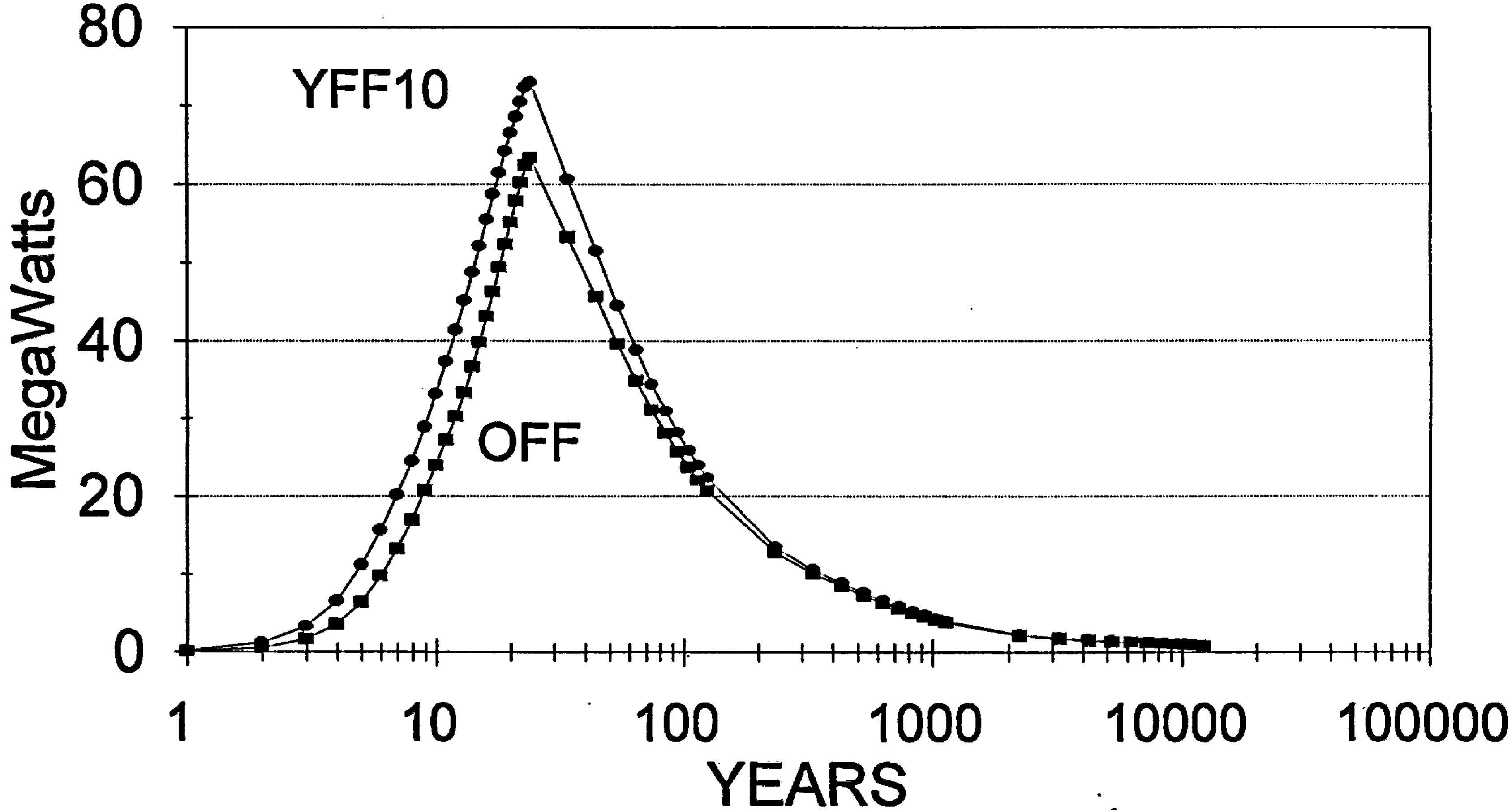
  Design type (flux trap, burnup credit)

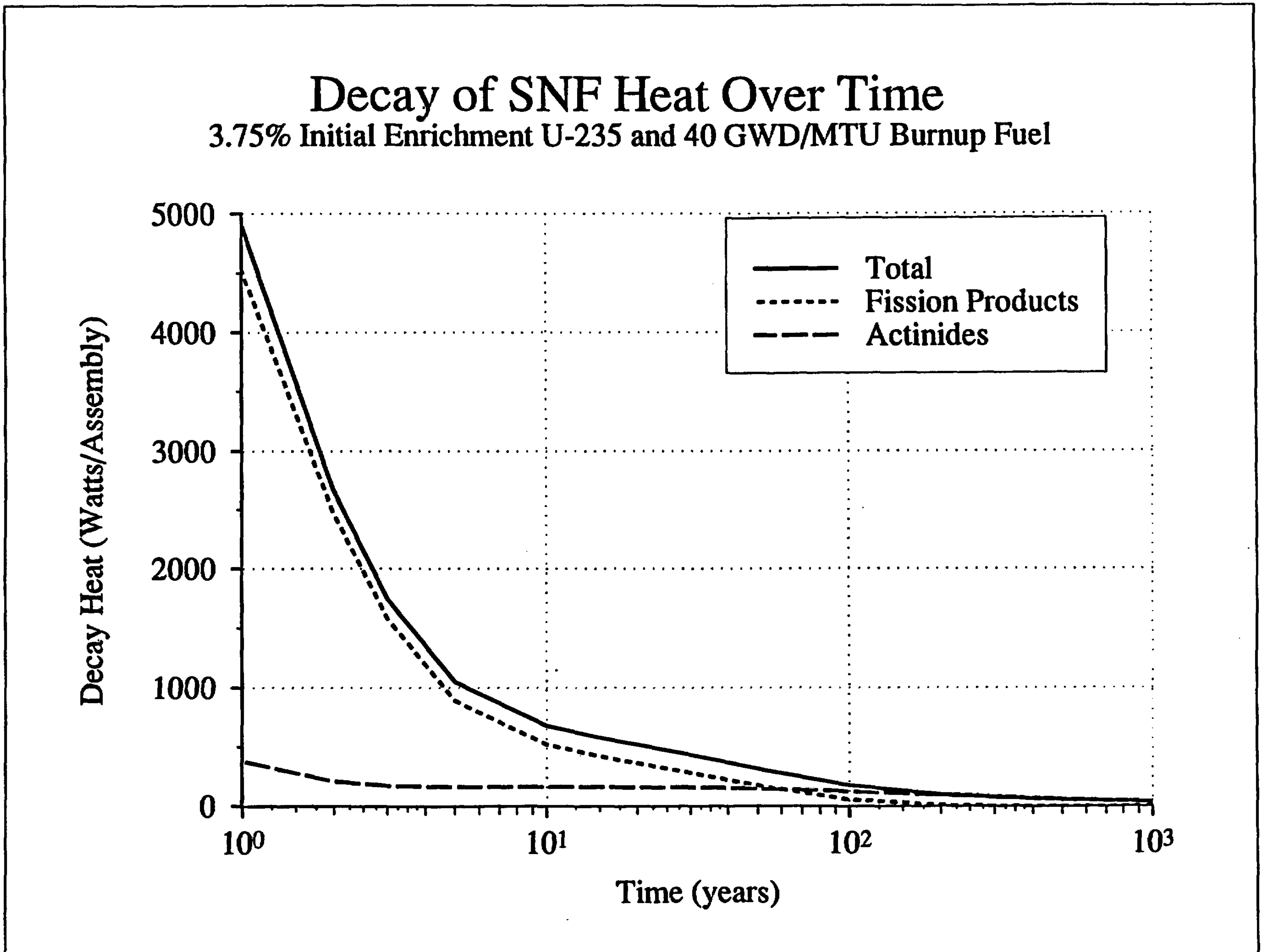
Heat Percentiles of PWR Fuel



PRELIMINARY PREDECISIONAL DRAFT MATERIAL

Repository Heat

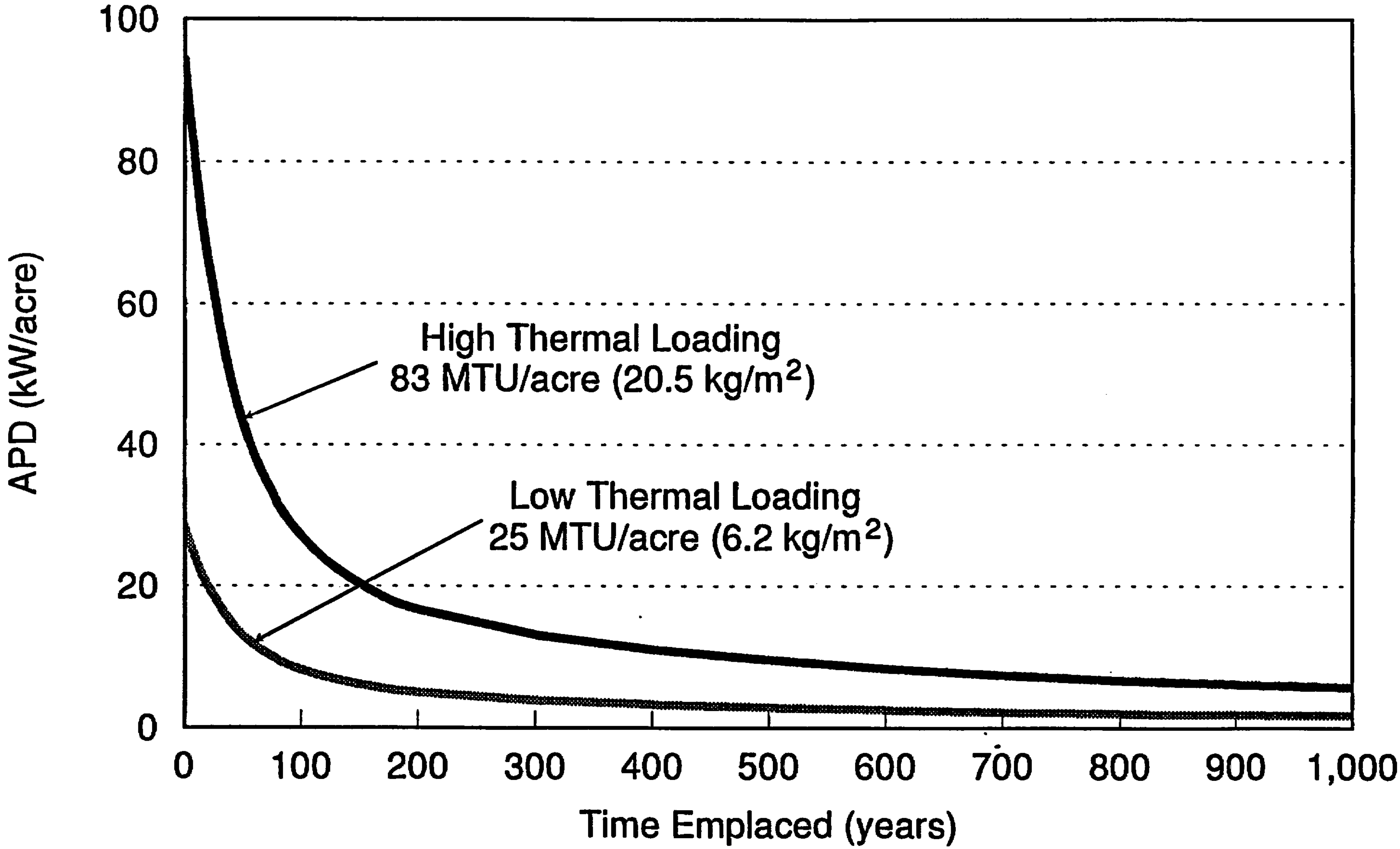




PRELIMINARY PREDECISIONAL DRAFT MATERIAL

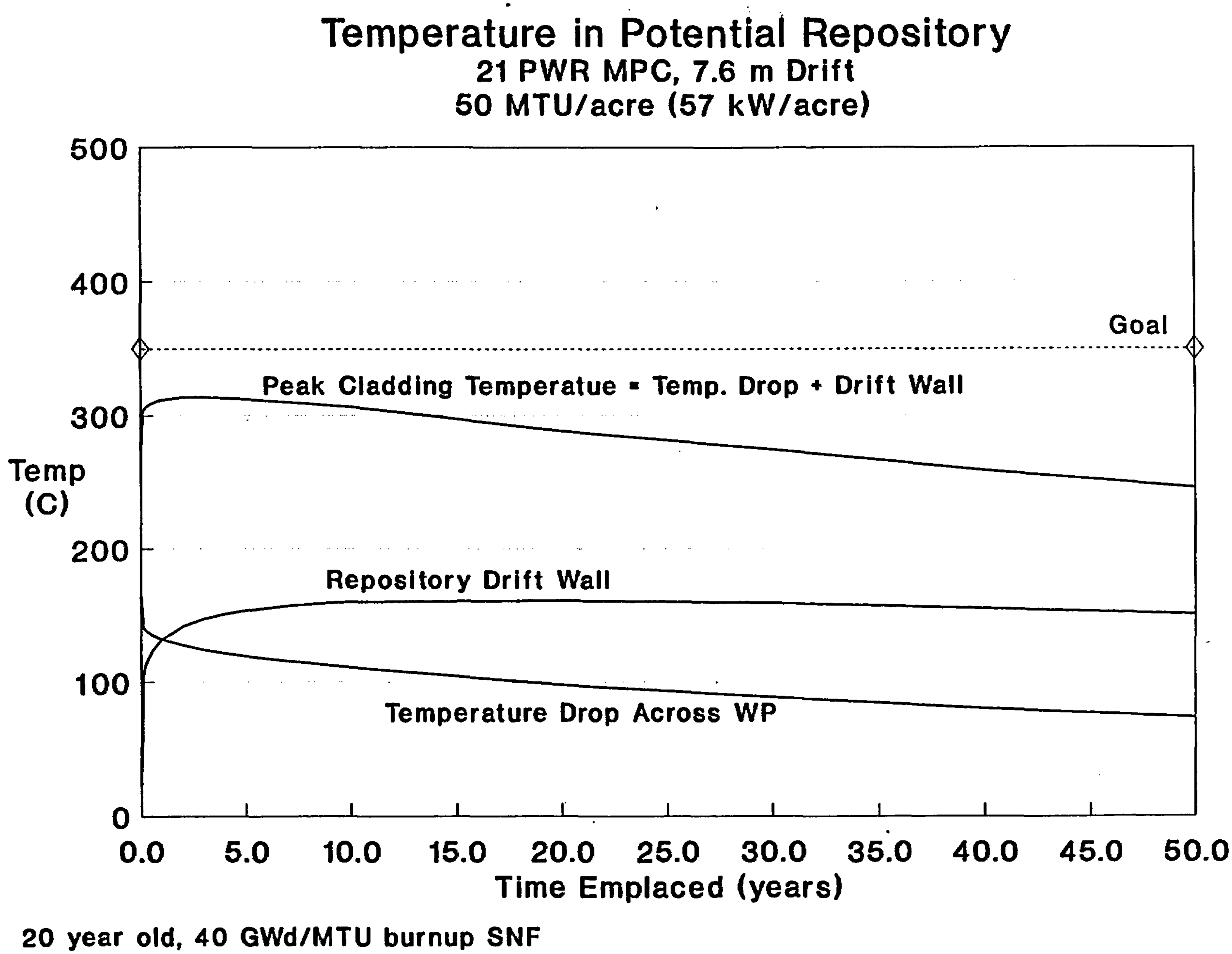
Time Decay of Areal Power Density

Instantaneous Local APD in kW/acre



22 year old, 42.2 GWd/MTU SNF

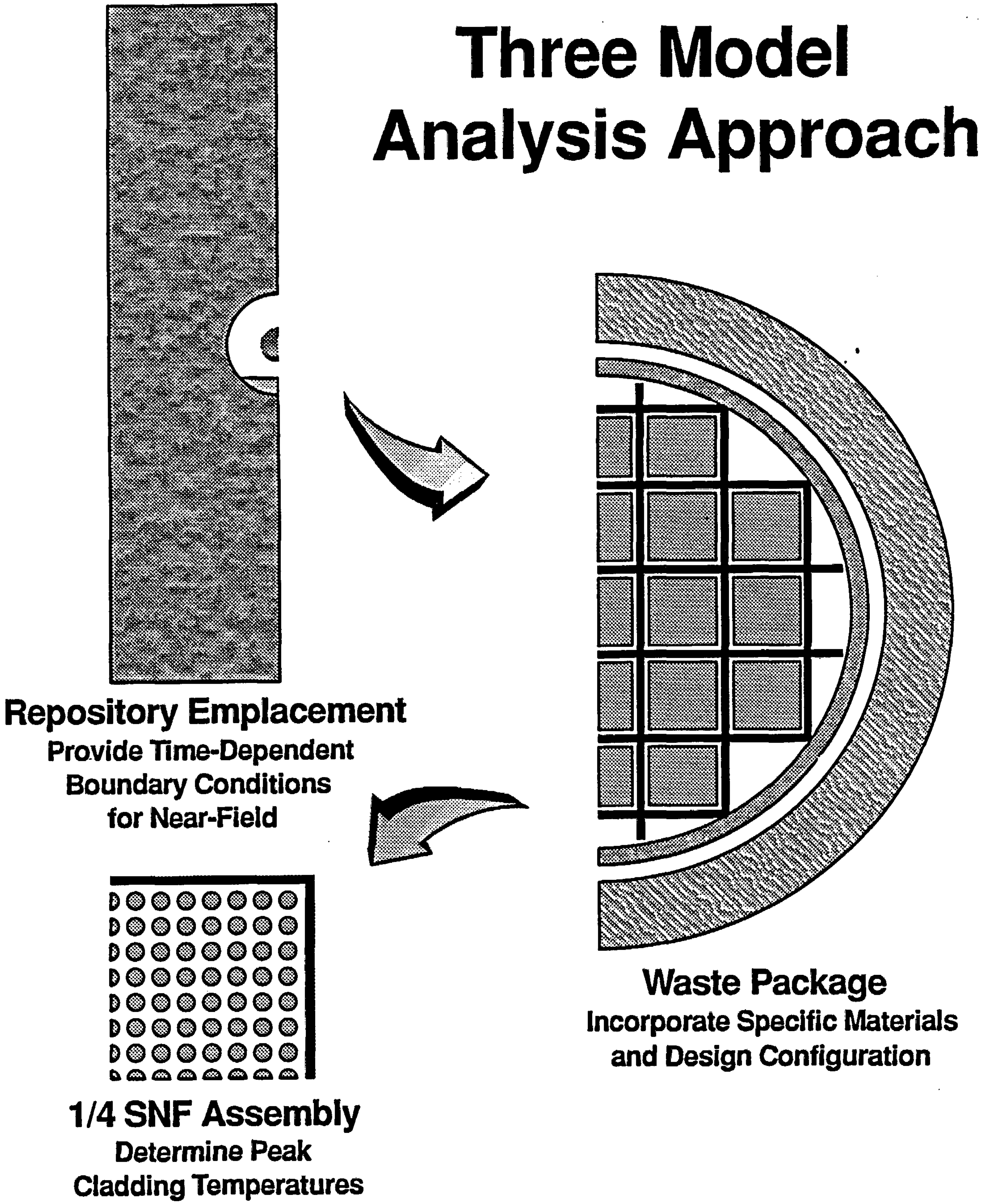
PRELIMINARY PREDECISIONAL DRAFT MATERIAL

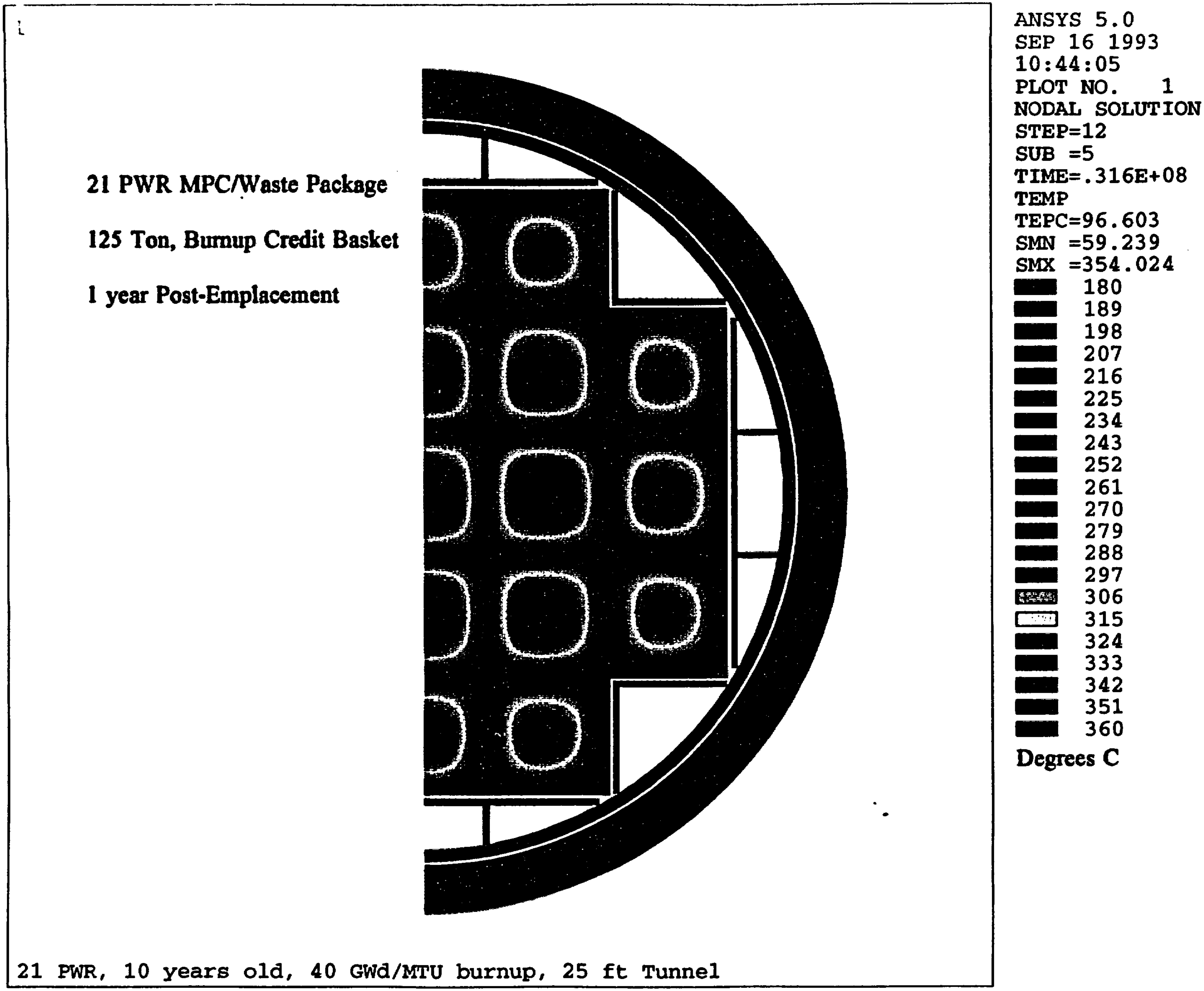

Temperature in Potential Repository
21 PWR MPC, 7.6 m Drift
50 MTU/acre (57 kW/acre)
Temp (C)
0
100
200
300
400
500
Goal
Peak Cladding Temperatue = Temp. Drop + Drift Wall
Repository Drift Wall
Temperature Drop Across WP
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
Time Emplaced (years)
20 year old, 40 GWd/MTU burnup SNF

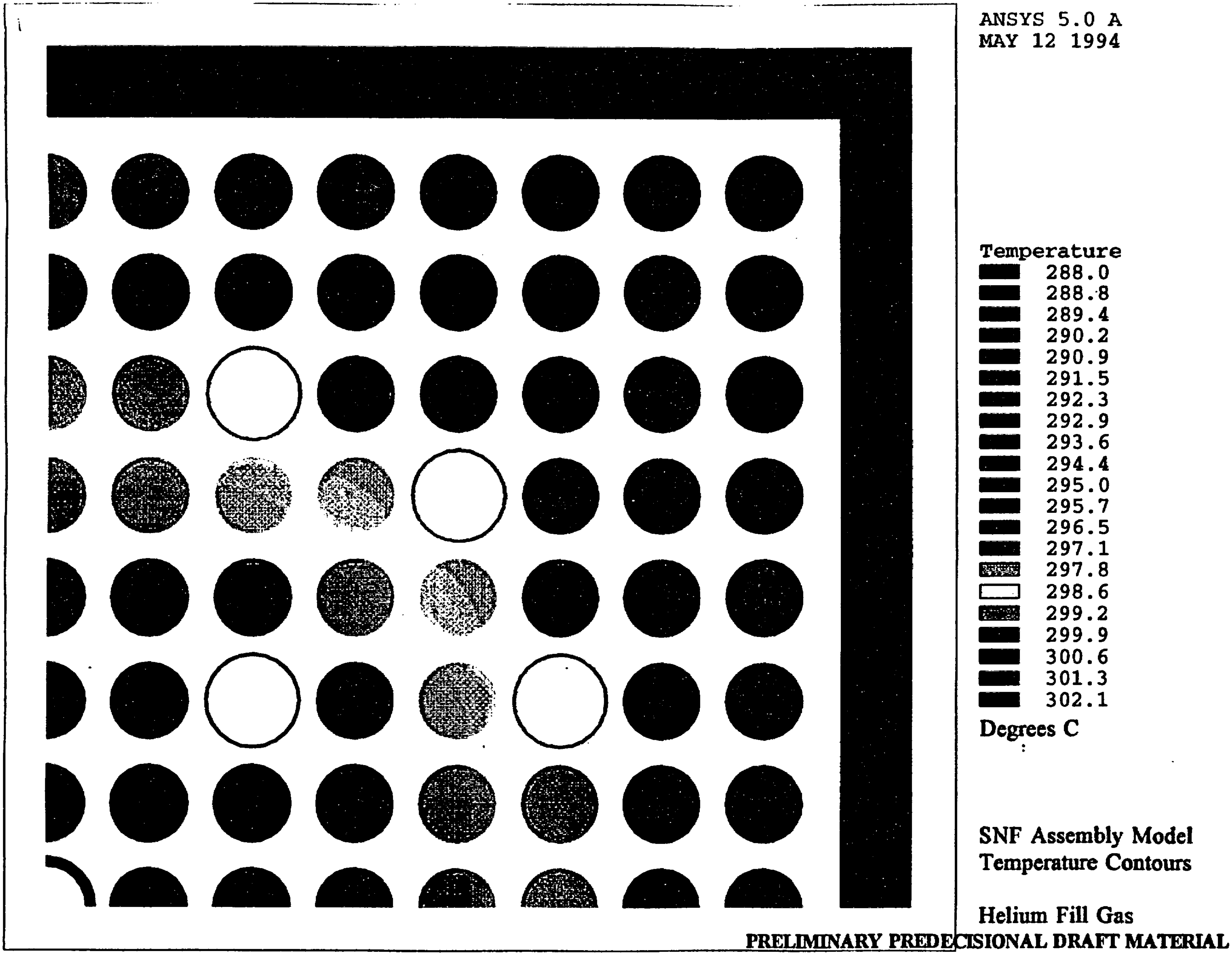
Waste Package Thermal Analysis

- Coordinated three-model approach
- Repository model provides time-dependent boundary conditions (near-field temperatures) for waste package analysis
- Detailed waste package evaluation dependent on material properties and design configuration
- Peak SNF cladding temperature determination

Three Model Analysis Approach




21 PWR MPC/Waste Package
125 Ton, Burnup Credit Basket
1 year Post-Emplacement
ANSYS 5.0
SEP 16 1993
10:44:05
PLOT NO. 1
NODAL SOLUTION
STEP=12
SUB =5
TIME=.316E+08
TEMP
TEPC=96.603
SMN =59.239
SMX =354.024
180
189
198
207
216
225
234
243
252
261
270
279
288
297
306
315
324
333
342
351
360
Degrees C
21 PWR, 10 years old, 40 GWd/MTU burnup, 25 ft Tunnel



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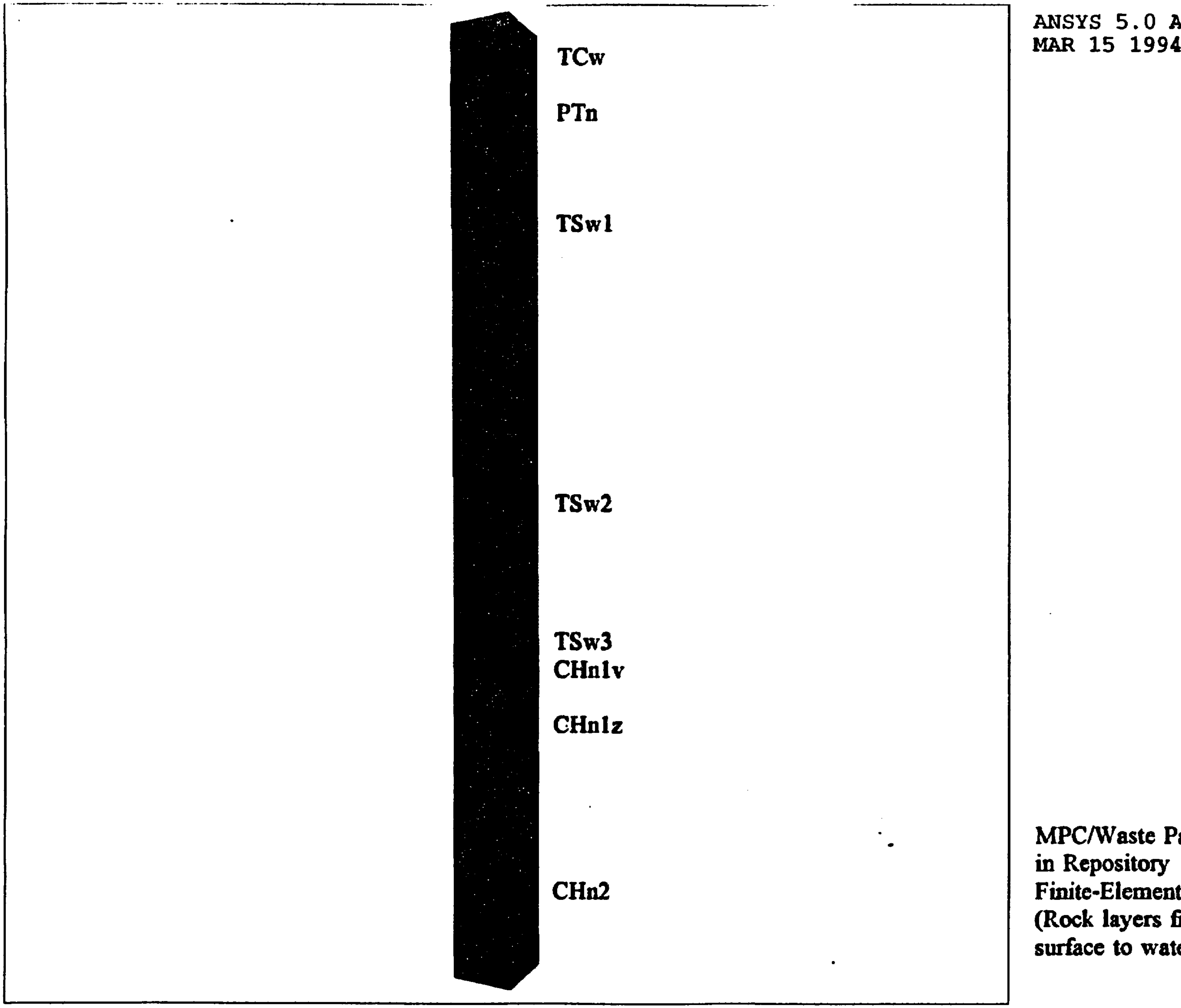
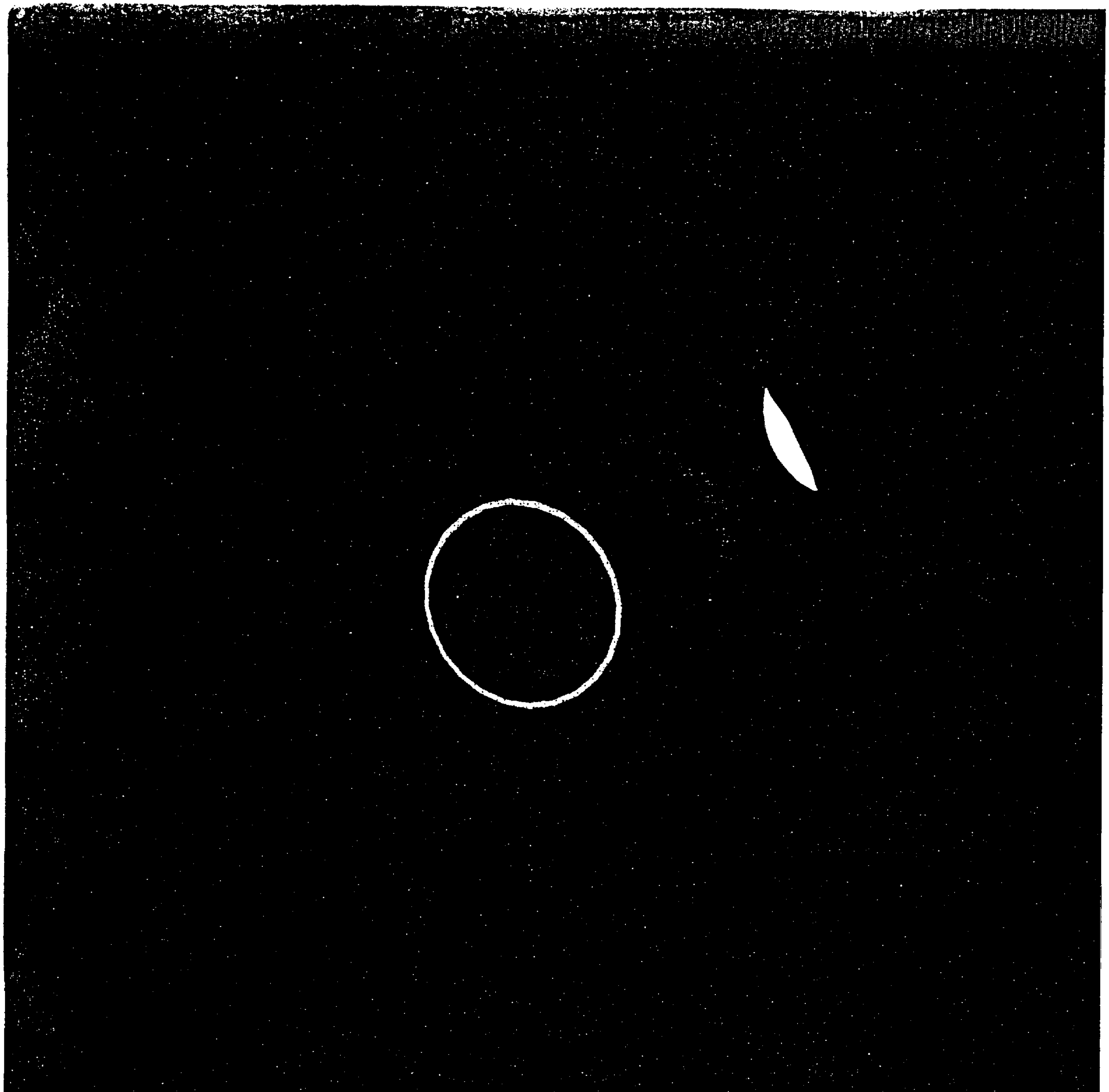
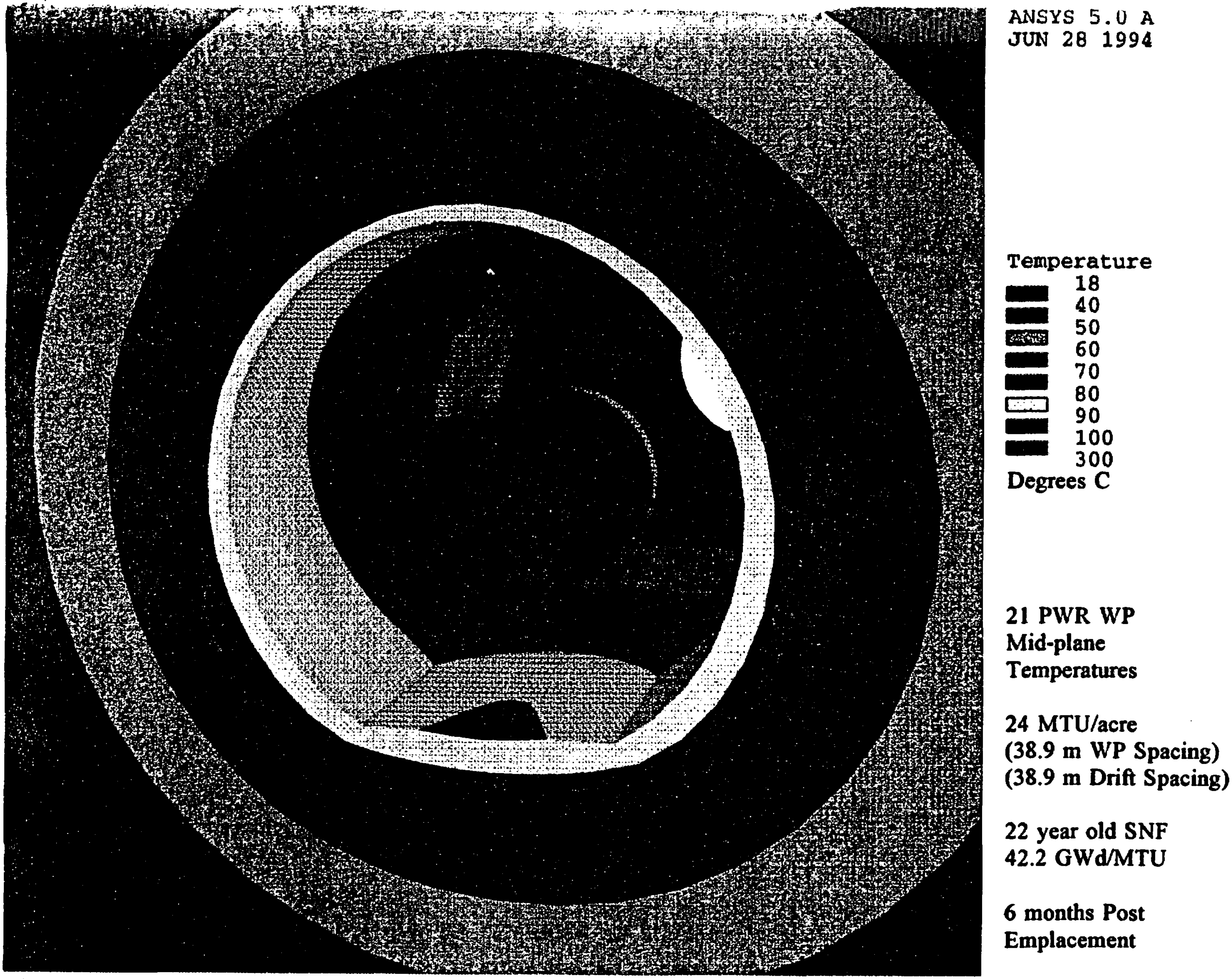
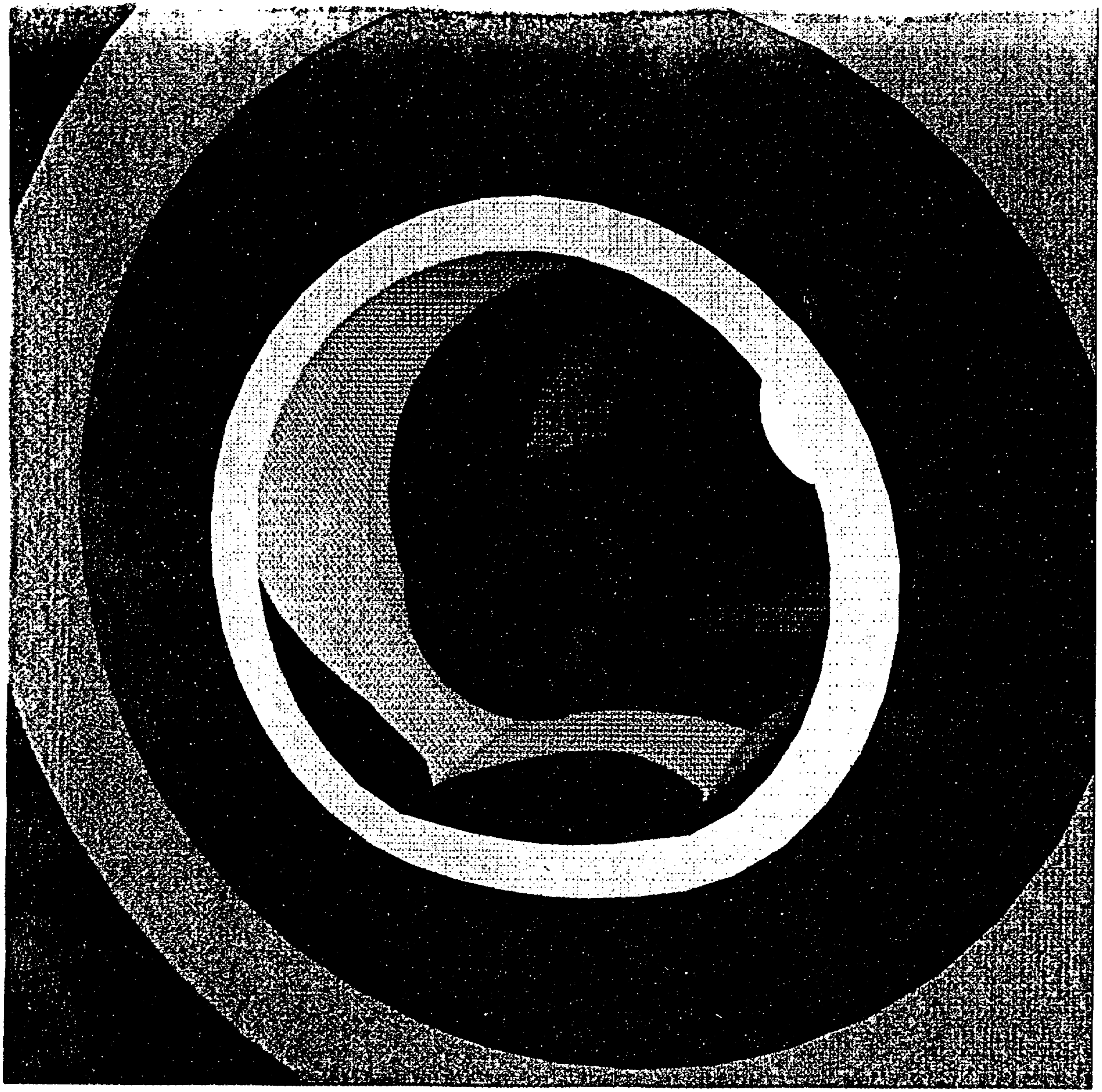


MPC/Waste Package
in Repository
Finite-Element Model
(Rock layers from
surface to water table)


ANSYS 5.0 A
JUN 28 1994
Temperature
18
40
50
60
70
80
90
100
300
Degrees C
21 PWR WP
Mid-plane
Temperatures
24 MTU/acre
(38.9 m WP Spacing)
(38.9 m Drift Spacing)
22 year old SNF
42.2 GWd/MTU
Initial (0 years)
Emplacement


ANSYS 5.0 A
JUN 28 1994
Temperature
18
40
50
60
70
80
90
100
300
Degrees C
21 PWR WP
Mid-plane
Temperatures
24 MTU/acre
(38.9 m WP Spacing)
(38.9 m Drift Spacing)
22 year old SNF
42.2 GWd/MTU
6 months Post
Emplacement



ANSYS 5.0 A
JUN 28 1994

Temperature
18
40
50
60
70
80
90
100
300
Degrees C

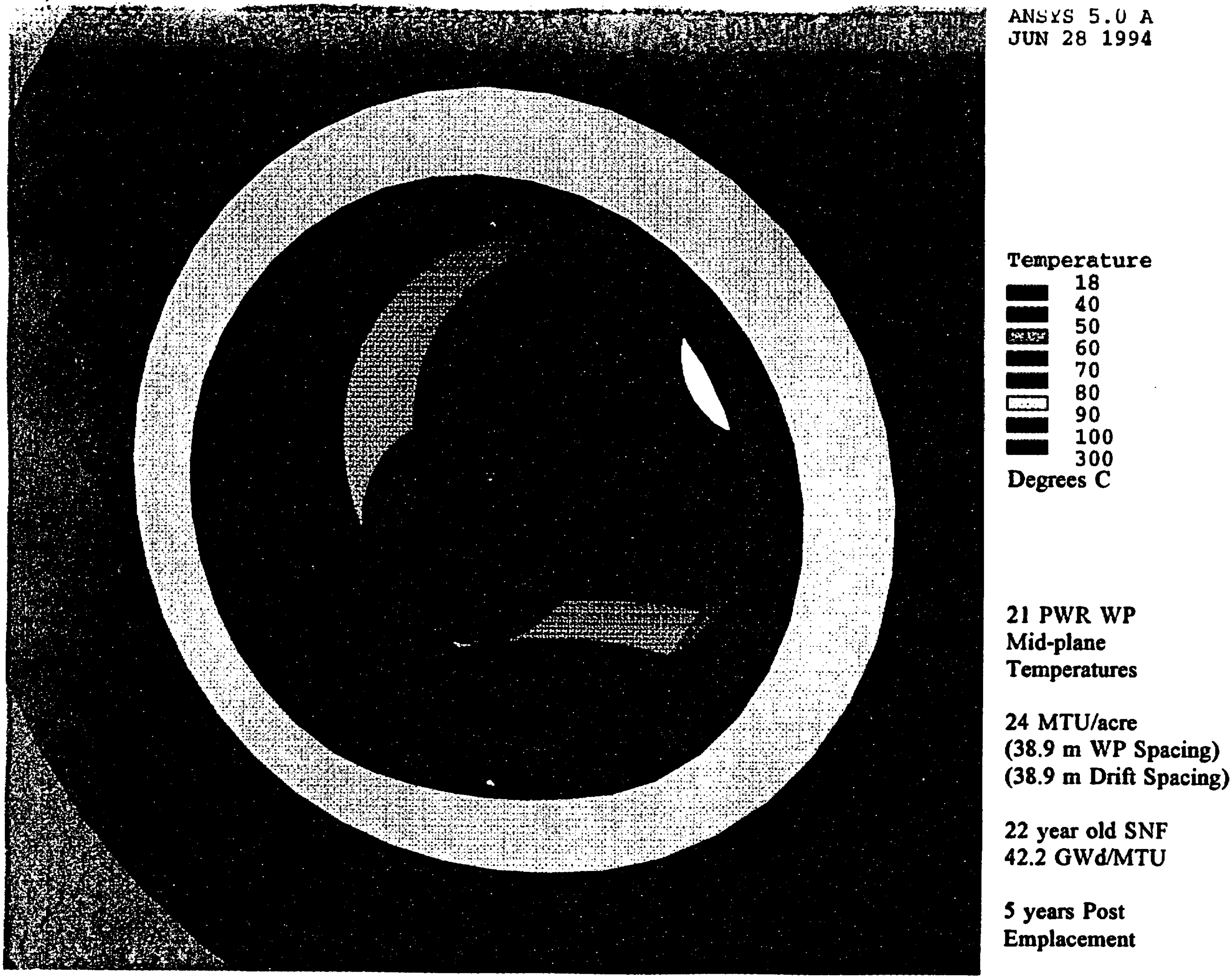
21 PWR WP
Mid-plane
Temperatures

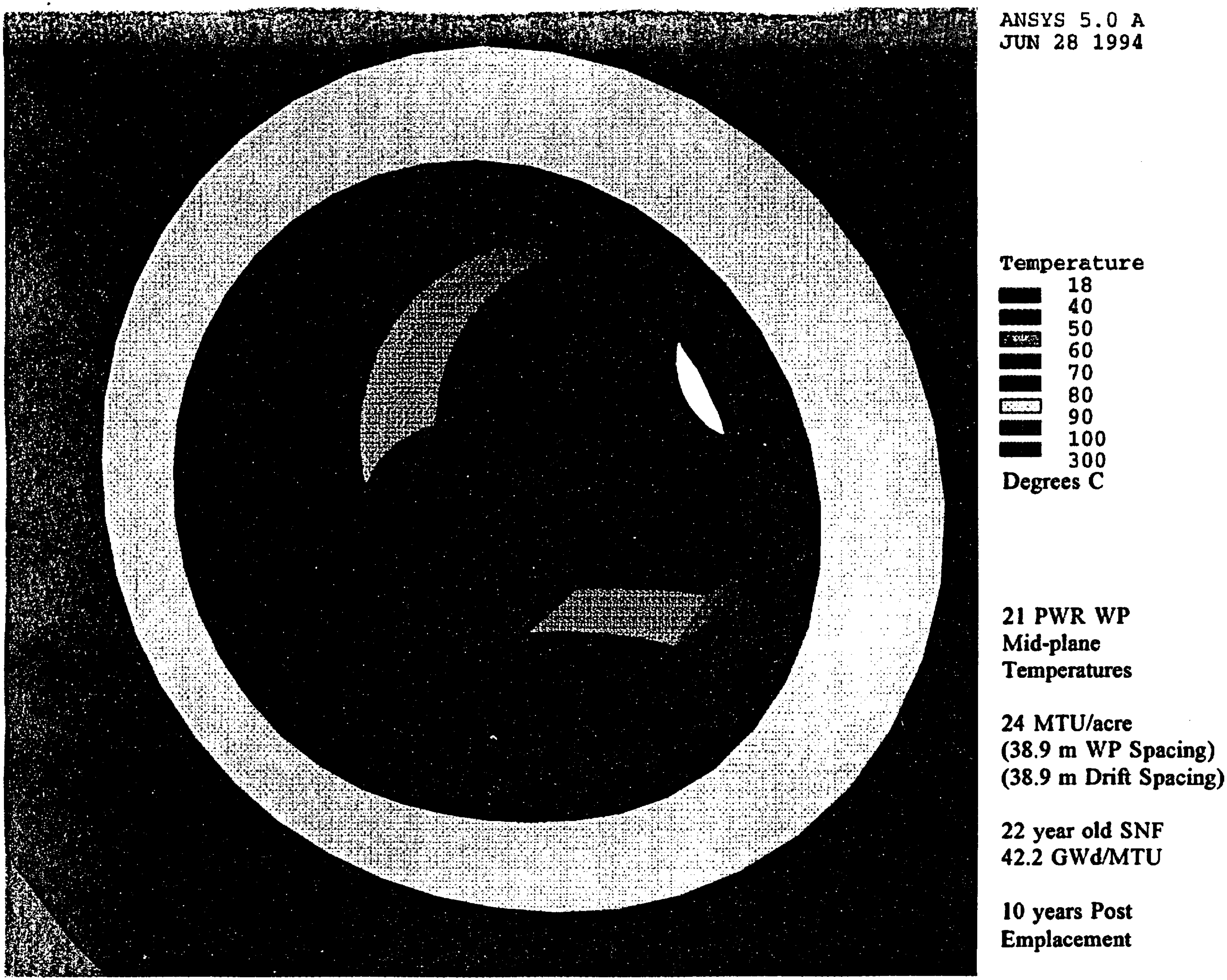
24 MTU/acre
(38.9 m WP Spacing)
(38.9 m Drift Spacing)

22 year old SNF
42.2 GWd/MTU

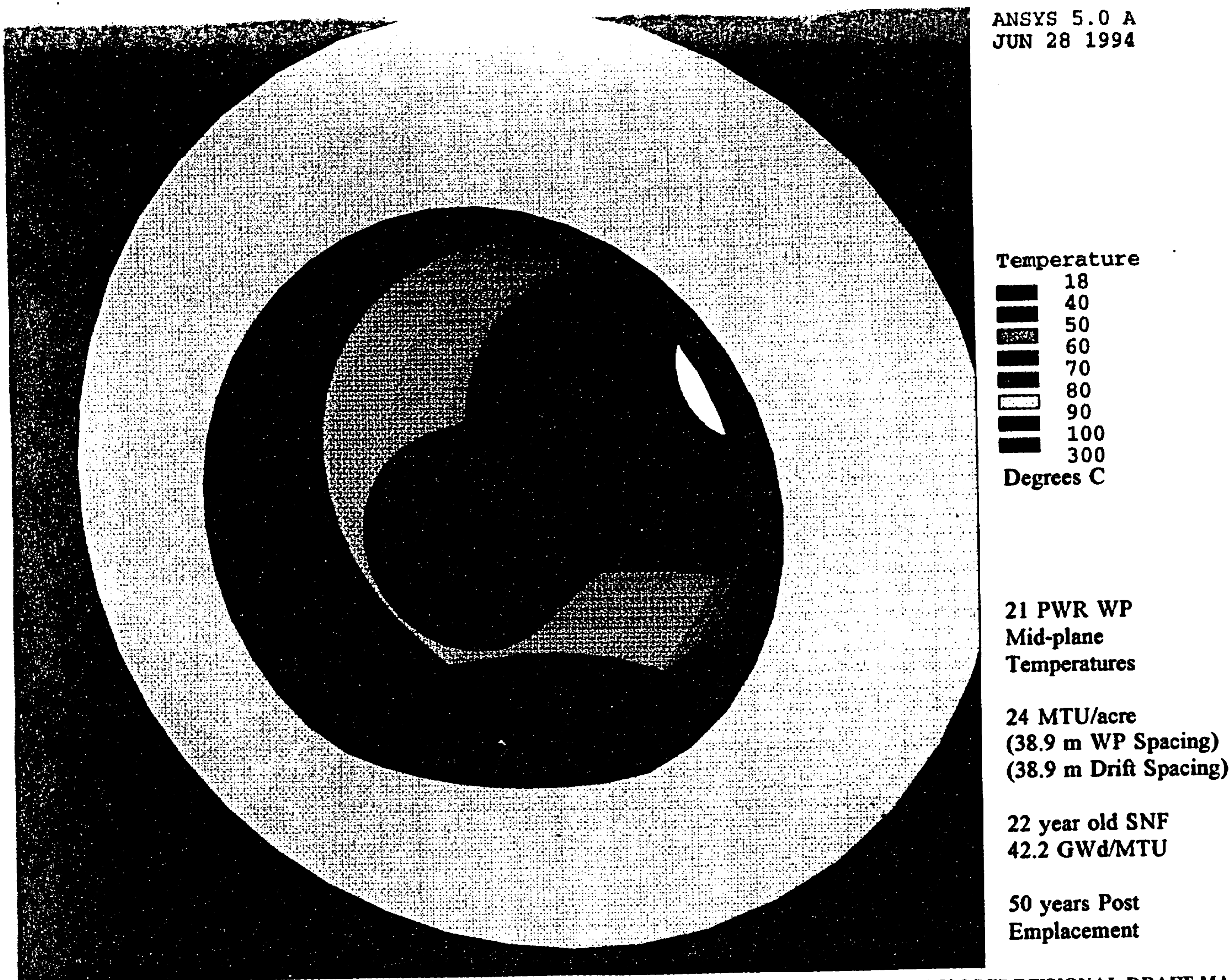
1 year Post
Emplacement

PRELIMINARY PREDECISIONAL DRAFT MATERIAL

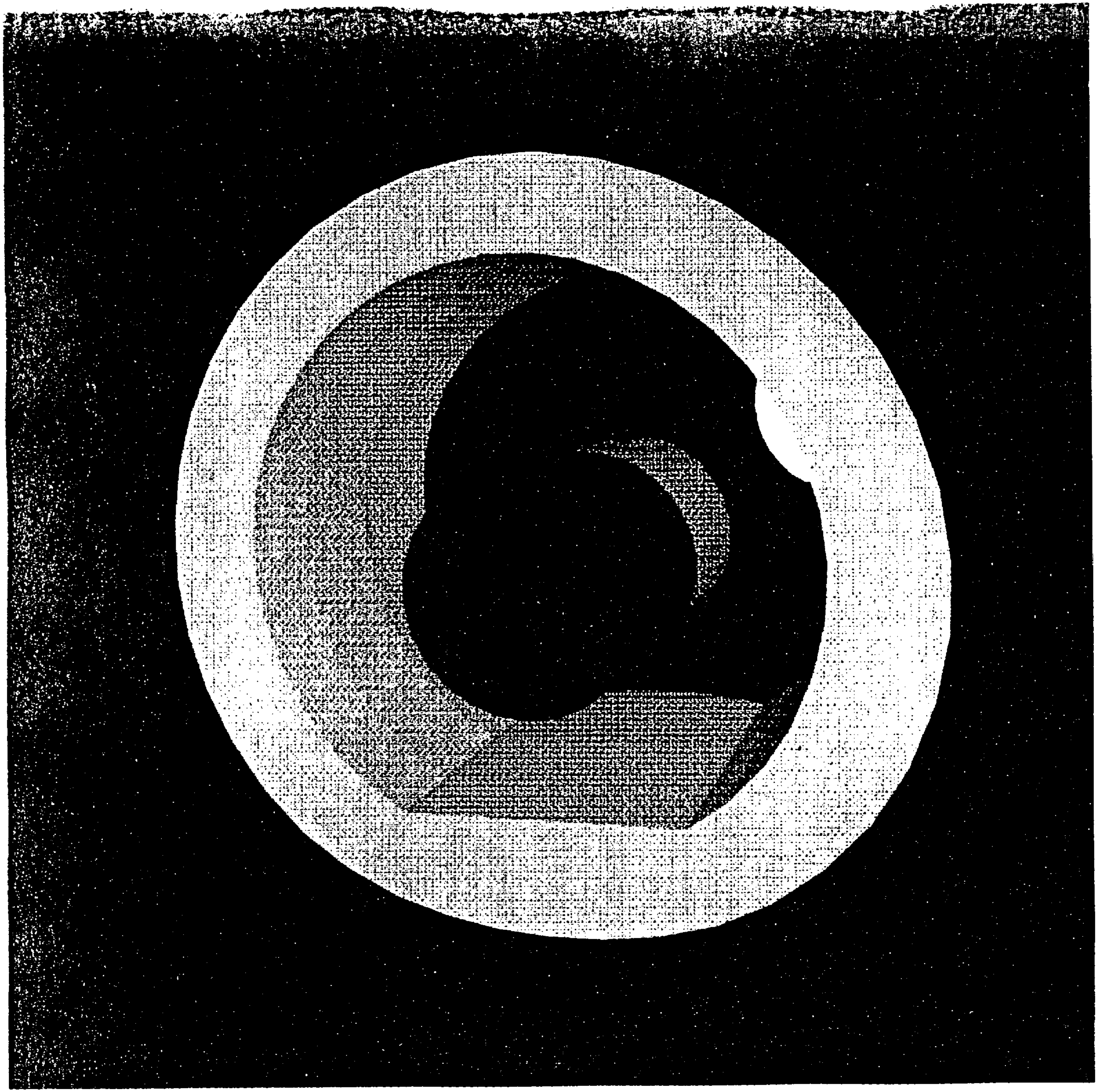

ANSYS 5.0 A
JUN 28 1994
Temperature
18
40
50
60
70
80
90
100
300
Degrees C
21 PWR WP
Mid-plane
Temperatures
24 MTU/acre
(38.9 m WP Spacing)
(38.9 m Drift Spacing)
22 year old SNF
42.2 GWd/MTU
5 years Post
Emplacement



PRELIMINARY PREDECISIONAL DRAFT MATERIAL



PRELIMINARY PREDECISIONAL DRAFT MATERIAL



ANSYS 5.0 A
JUN 28 1994

Temperature
18
40
50
60
70
80
90
100
300
Degrees C

21 PWR WP
Mid-plane
Temperatures

24 MTU/acre
(38.9 m WP Spacing)
(38.9 m Drift Spacing)

22 year old SNF
42.2 GWd/MTU

100 years Post
Emplacement

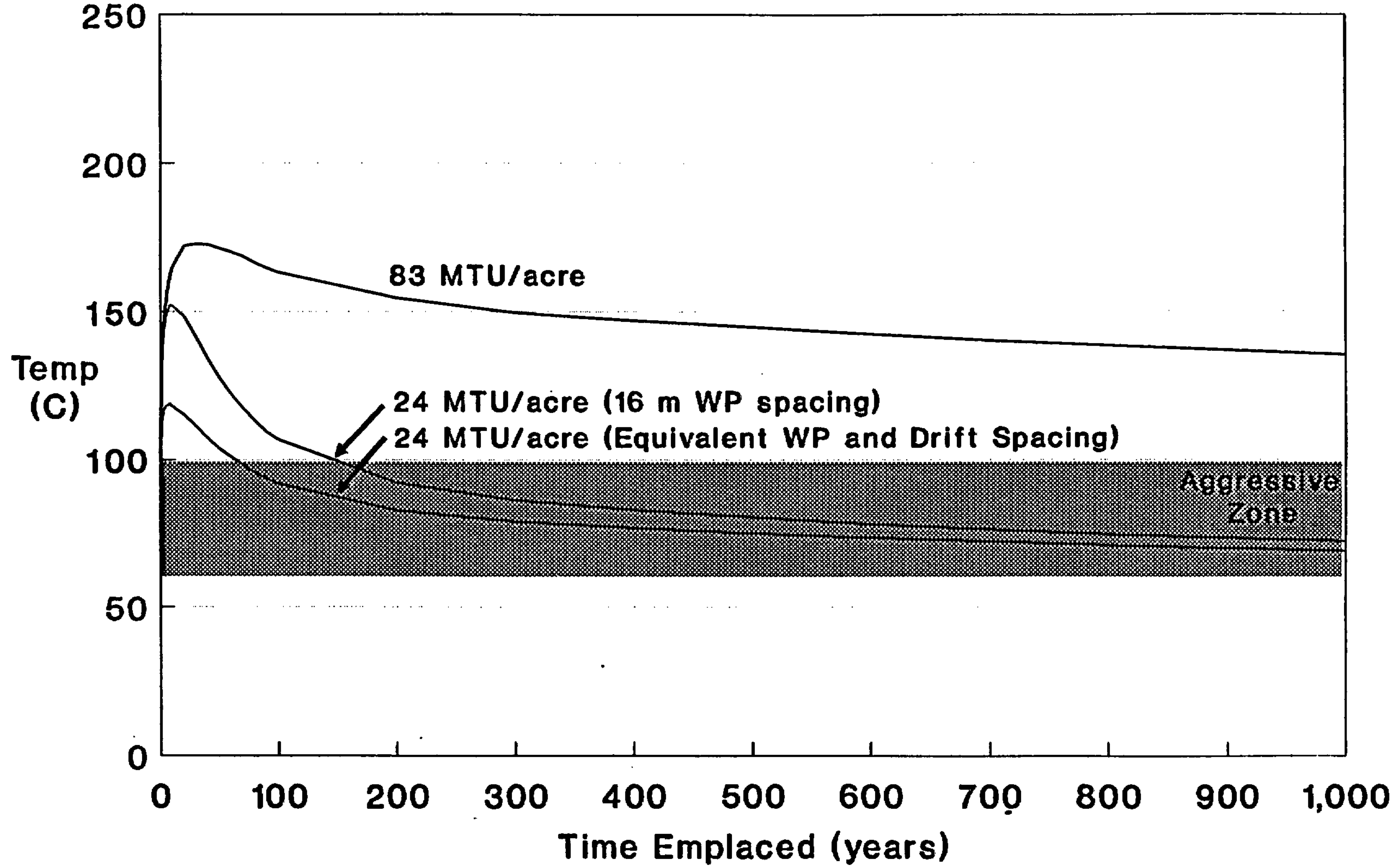
21 PWR WP
Mid-plane
Temperatures

24 MTU/acre
(38.9 m WP Spacing)
(38.9 m Drift Spacing)

22 year old SNF
42.2 GWd/MTU

500 years Post
Emplacement

21 PWR WP Surface Temperatures
And Potential for Aqueous Corrosion

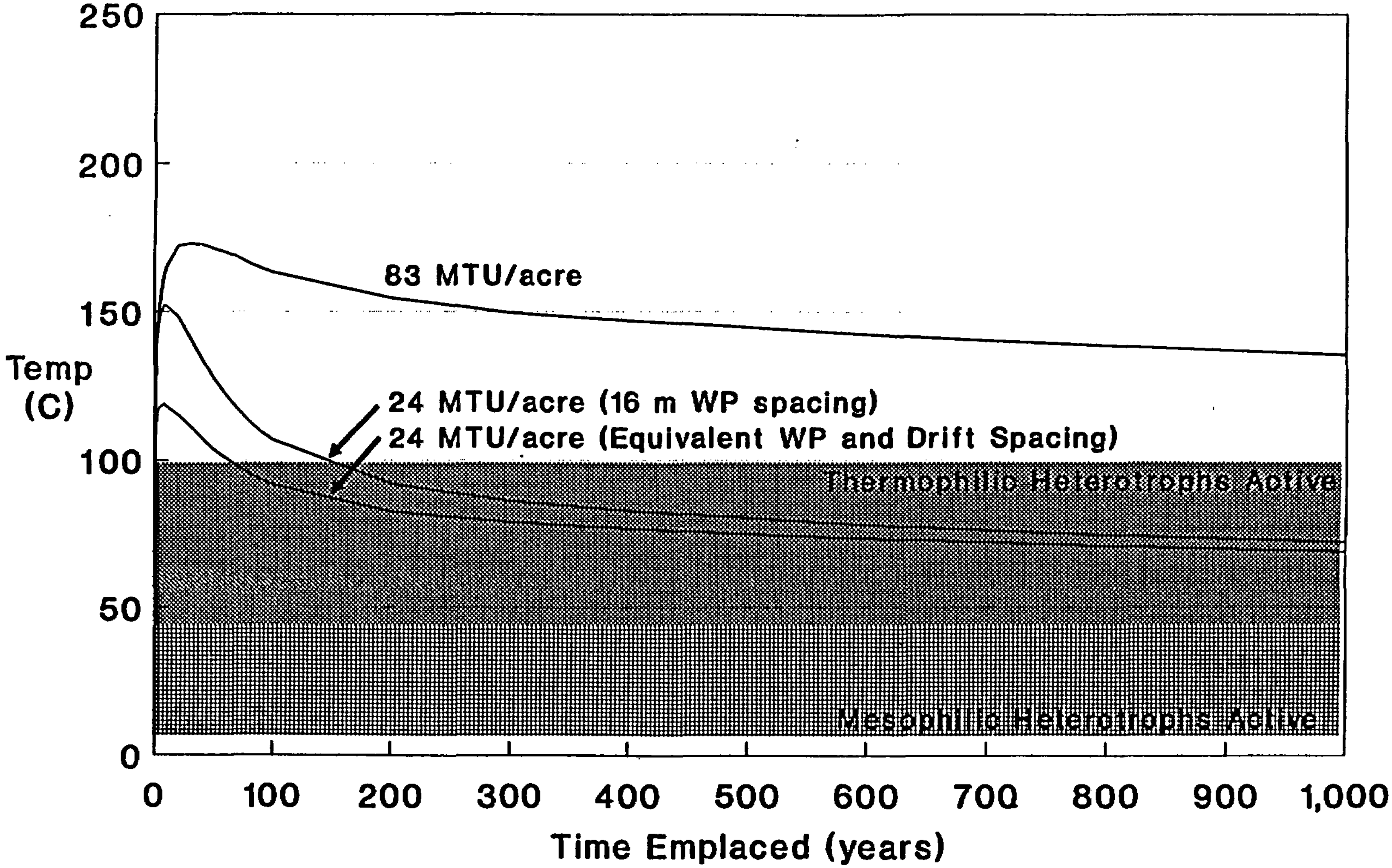


22 year old SNF, 42.2 GWd/MTU burnup

4.3 m (14 ft) Drift

21 PWR WP Surface Temperatures

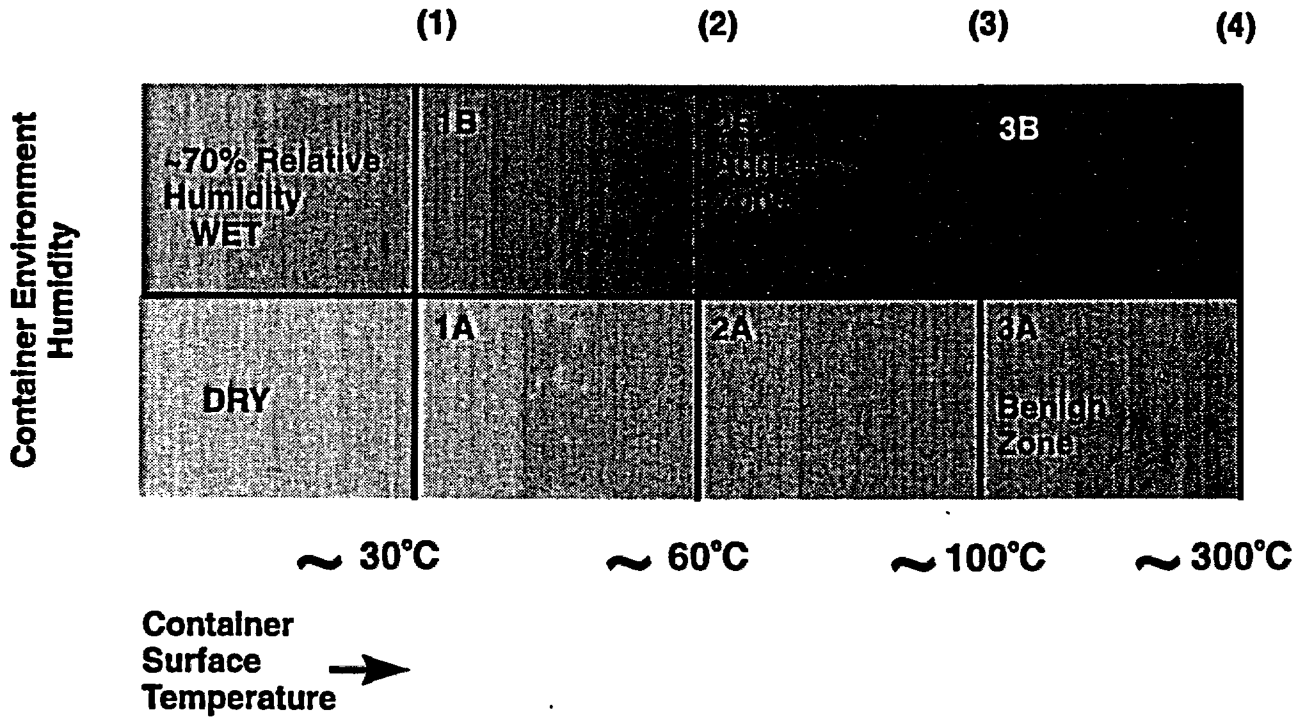
And Potential for Microbiologically Influenced Corrosion



22 year old SNF, 42.2 GWd/MTU burnup

4.3 m (14 ft) Drift

Thermal/Hydrological Zones Affecting Container Material Performance

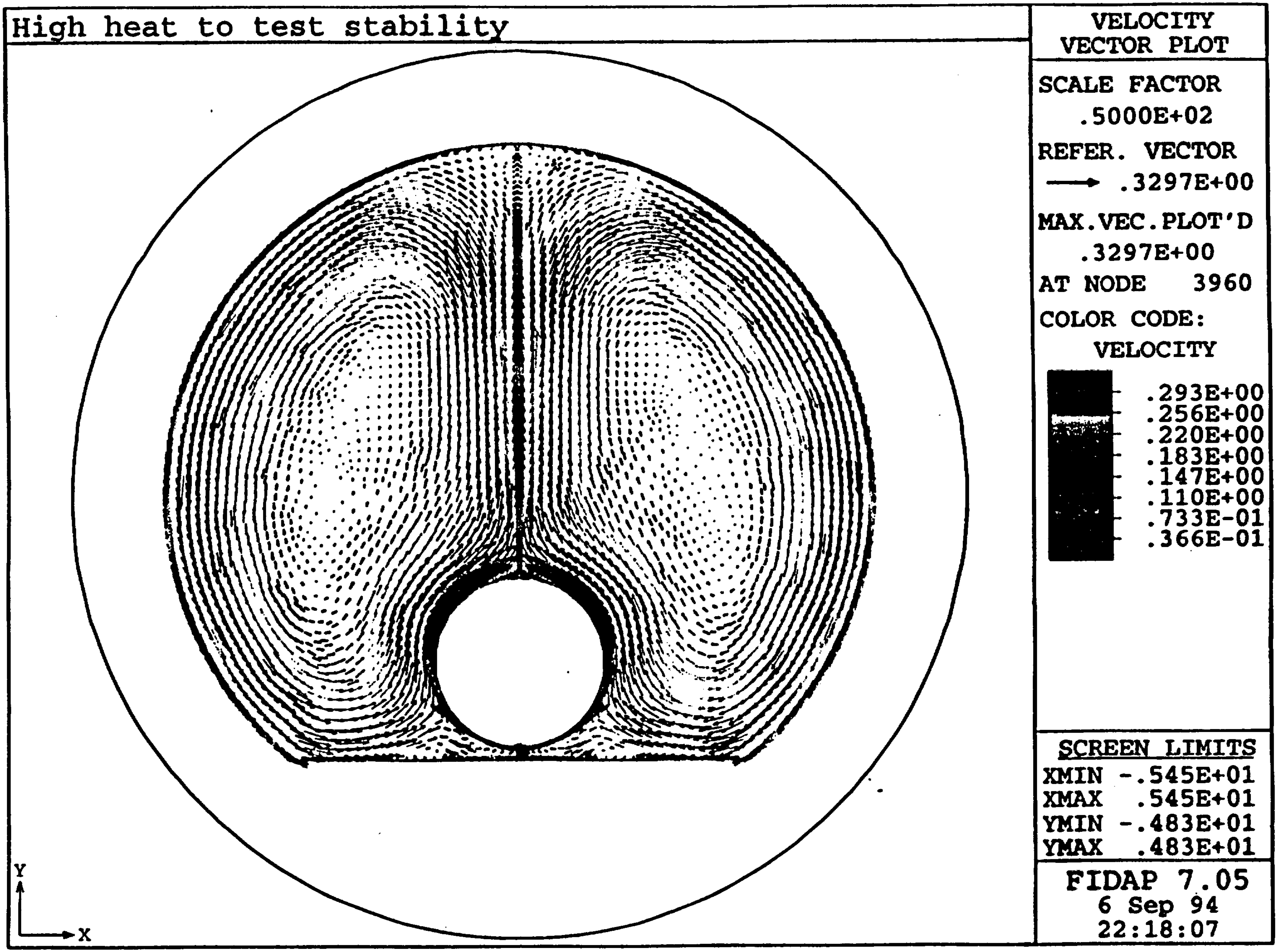


PRELIMINARY PREDECISIONAL DRAFT MATERIAL

THRMHYDR.CDR.122/11-15-94

Convective Cooling in Emplacement Drifts

- With no ventilation - drift temperature temperature increases for upwards of 200 years
  - Natural convection provides approximately 10% of total heat transfer to driftwall
  - 10 - 15°C temperature drop between package surface and drift wall, maintained primarily by radiative heat transfer
- With ventilation - extent to which drifts can be cooled (e.g. to facilitate retrieval)
  - Determined by velocity dependent heat transfer coefficient
  - Will evaluate efficiency improvements from cooling fins


High heat to test stability
VELOCITY VECTOR PLOT
SCALE FACTOR
.5000E+02
REFER. VECTOR
.3297E+00
MAX.VEC.PLOT'D
.3297E+00
AT NODE 3960
COLOR CODE:
VELOCITY
.293E+00
.256E+00
.220E+00
.183E+00
.147E+00
.110E+00
.733E-01
.366E-01
SCREEN LIMITS
XMIN -.545E+01
XMAX .545E+01
YMIN -.483E+01
YMAX .483E+01
FIDAP 7.05
6 Sep 94
22:18:07
Y
X

Thermal Analysis Conclusions

- Waste package reaches peak temperature within first few years
- Waste package spacing and SNF age are key to meeting near-field thermal goals
- Far-field temperatures are insensitive to size of waste package

Criticality

- Conditions Affecting Criticality Potential
- Criticality Control Methods
- Three Phase Approach
- Criticality Risk Analysis

Regulations

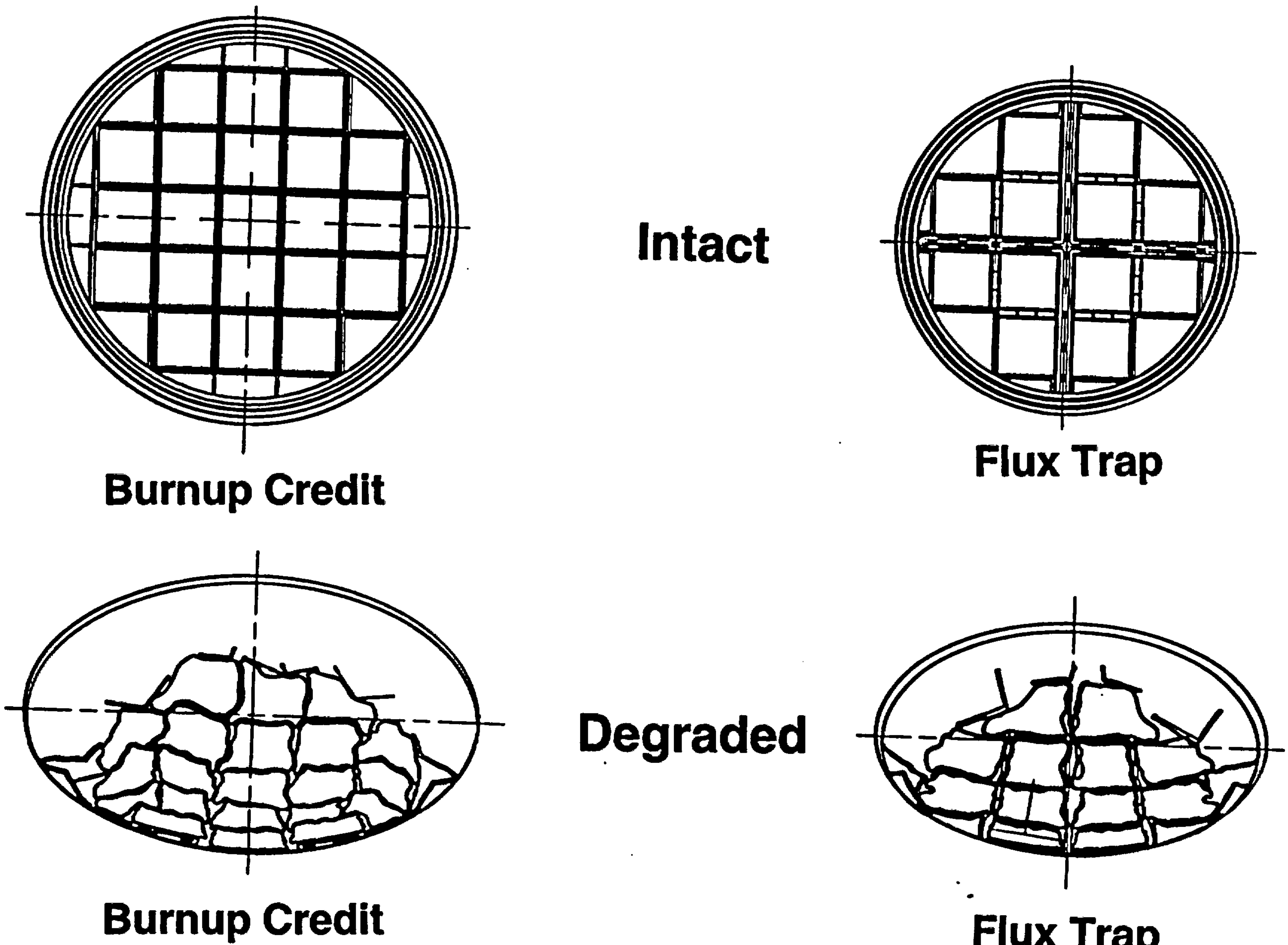
- Title 10 CFR Part 60.131.(b)(7)
  - Control criticality for all repository systems, including isolation
  - Criticality not allowed unless two unlikely, independent, and concurrent or sequential changes occur
  - Criticality safety required under normal and accident conditions
  - k_{eff} must be ≤ 0.95 (a 5% margin below unity), accounting for
    - bias in the calculational method
    - uncertainty in the experiments validating the calculational method

MGDS Waste Package Approach

- Examined the disposal criticality control regulations
- Examined long-term conditions (material degradation, waste form degradation)
- Evaluated the available criticality control methods for long-term
- Developed long-term criticality control strategies
- Developed the Three Phase Approach, for long-term criticality control/evaluations
- Developing the supporting technical information for the Three Phase Approach
- Present the Three Phase Approach for NRC review in a Long-Term Criticality Topical Report

Long-Term Conditions

- The repository/waste package conditions change with time:
  - Waste package materials will degrade
    - Containment barriers will breach
    - Basket structural members will fail
  - Waste form materials will degrade
    - Volatile/soluble materials will escape
    - Geometry of fuel pins in the assembly will change
  - Uncertainty in the condition increases with time



Long Time Effects

Available Criticality Control Methods

- **Three general methods for controlling criticality**
  - Limit fissile material
    - Reduced fissile content from fuel burnup (burnup credit)
    - Limited package capacity
  - Limit neutrons
    - Neutron absorbers present in fuel from burnup (burnup credit)
    - Supplemental neutron absorbing materials (neutron absorber credit)
    - Isolate neutrons from assemblies by the geometry (flux traps)
  - Limit moderator
    - Moderator displacement (filler material)
    - Moderator exclusion (sealed barriers)
    - Rod consolidation

Design Strategies for Long-Term Criticality Control

- **Burnup Credit**
  - Using "Principal Burnup Credit Isotopes"
    - Depletion of fissile material
    - Build in of neutron absorbers
  - Long-term changes in criticality potential
- **Neutron Absorber Credit**
  - Control panels
  - Control rods
  - Accounting for long-term removal
- **Moderator Displacement**
  - Loading into waste package
  - Long-term performance
- **Low Capacity ($\leq$4 PWR (~9 BWR) SNF assemblies)**

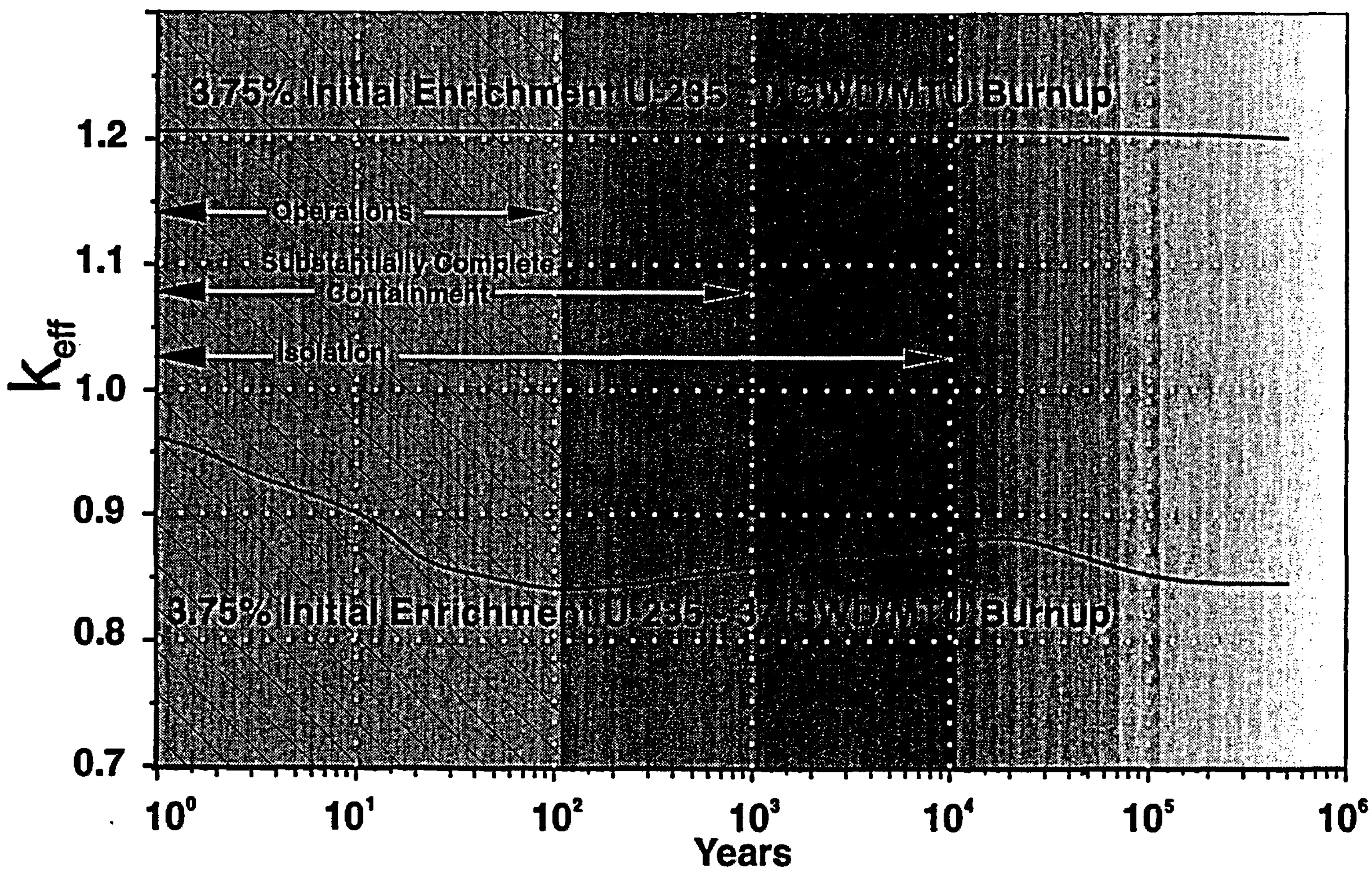
Three Phase Approach

- **Divide the disposal criticality control period into three time phases**
  - Pre-closure - Operations Phase
  - Post-closure - Substantially Complete Containment Phase
  - Post-containment - Isolation Phase

Time Effects on Criticality Potential

21 PWR MPC Conceptual Design

(No Additional Neutron Absorbers Added)



PRELIMINARY PREDECISIONAL DRAFT MATERIAL

CRITMEF.122.CDR/5-31-94

Pre-closure/Operations Phase

- Anticipated time line, 0 to ~100 years
- Human presence in repository
- Criticality a personnel safety issue
- Monitored/Controlled environment
- Well defined systems
  - Deterministic models of systems

Post-closure/Substantially Complete Containment Phase

- Anticipated time line, to ~1,000 years
- No human presence in repository
- Criticality a radionuclide regeneration/release issue
- Slowly deteriorating systems
- Increasingly more questionable conditions over time
  - Starts with deterministic models
  - Models become more probabilistic

Post-Containment/Isolation Phase

- Anticipated time line, to currently ~10,000 years
- No human presence in repository
- Criticality a radionuclide regeneration/release issue
- Uncertainties in system conditions

Criticality Probabilistic Risk Analysis Methodology

- Identify initiating events, examples:
  - Water intrusion into the repository from perched water
  - Water intrusion into the repository from rise in water table
- Identify subsequent events, examples:
  - Breach of containment barriers
  - Loss of neutron absorber materials
  - Sufficient water in package
- Define probabilities for events
- Combine events into fault trees
- Compute the number (and kinds) of criticality events, based upon the fault tree scenarios
- Present the probability and consequence of various scenarios

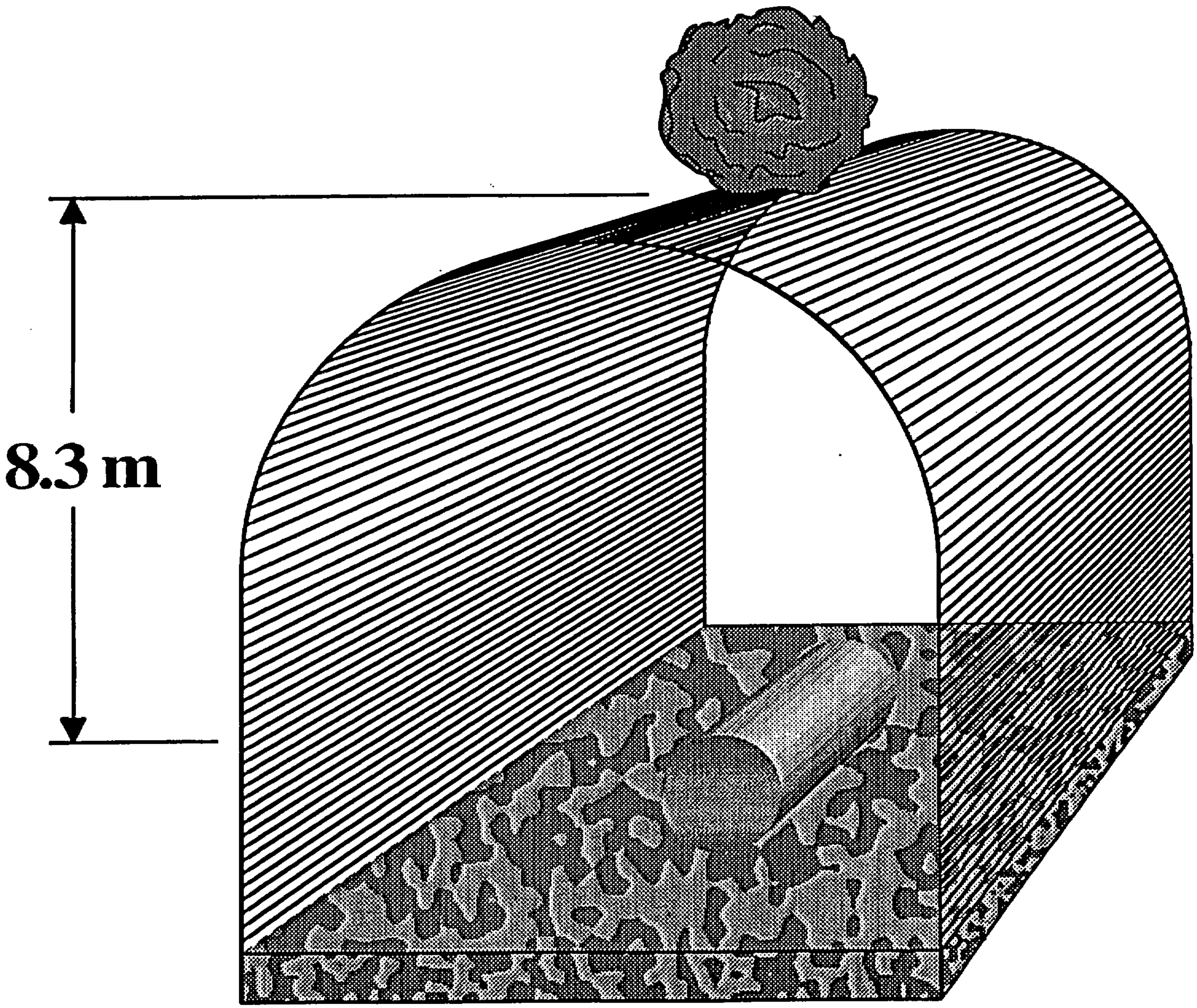
Structural Considerations

- Rock Drop Analysis
- Other Structural Analysis

Structural Scoping Analysis

- **Loads due to Normal Operations**
  - Handling, SNF / HLWG
  - Differential Thermal Stress
  - Internal Structural Loads

- **Off-normal Conditions**
  - Handling Accidents
  - Rock Drops, etc.



Rock Drop Analysis of the Multi-Barrier Waste Package in Starter Tunnel

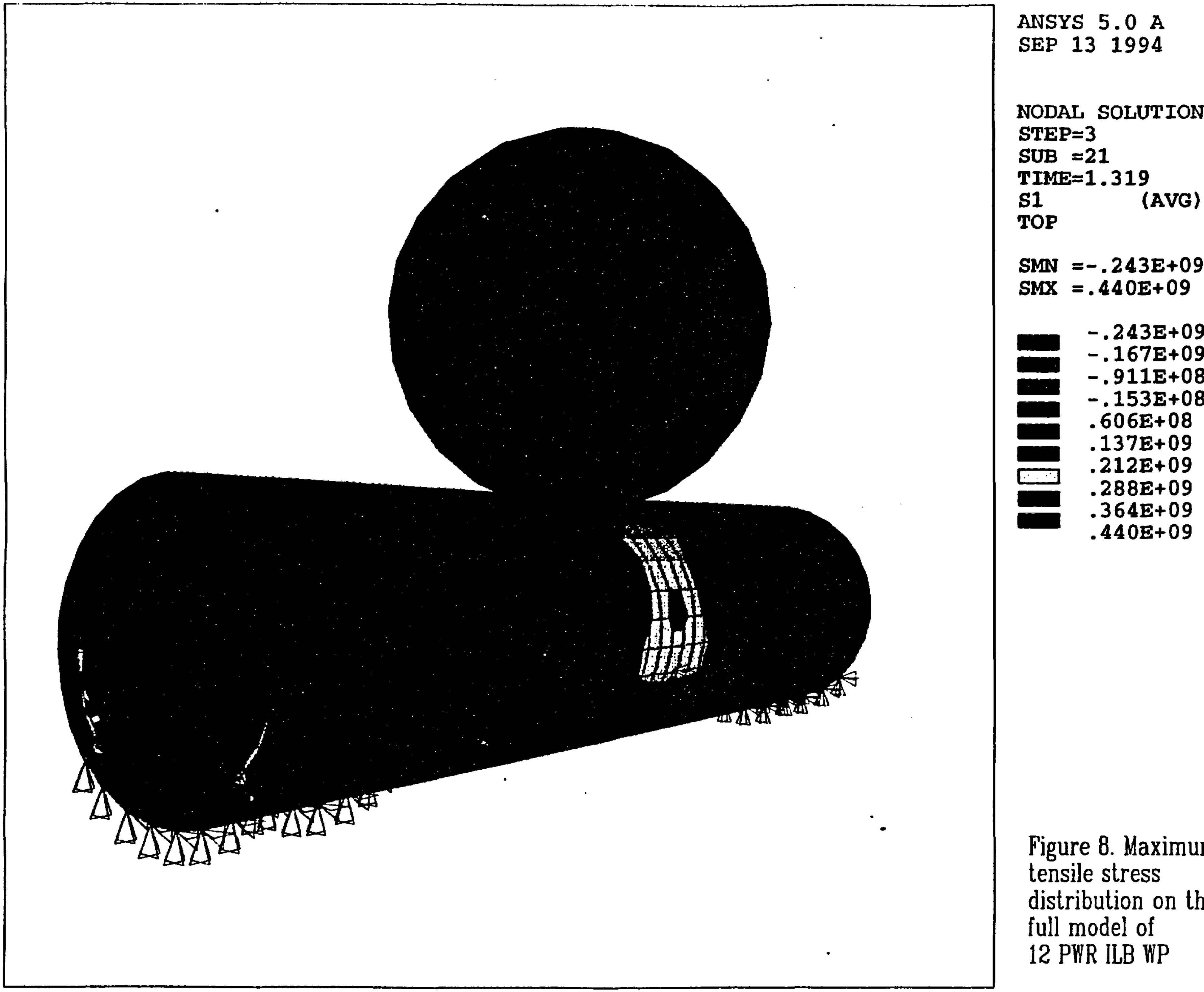


Figure 8. Maximum tensile stress distribution on the full model of 12 PWR ILB WP

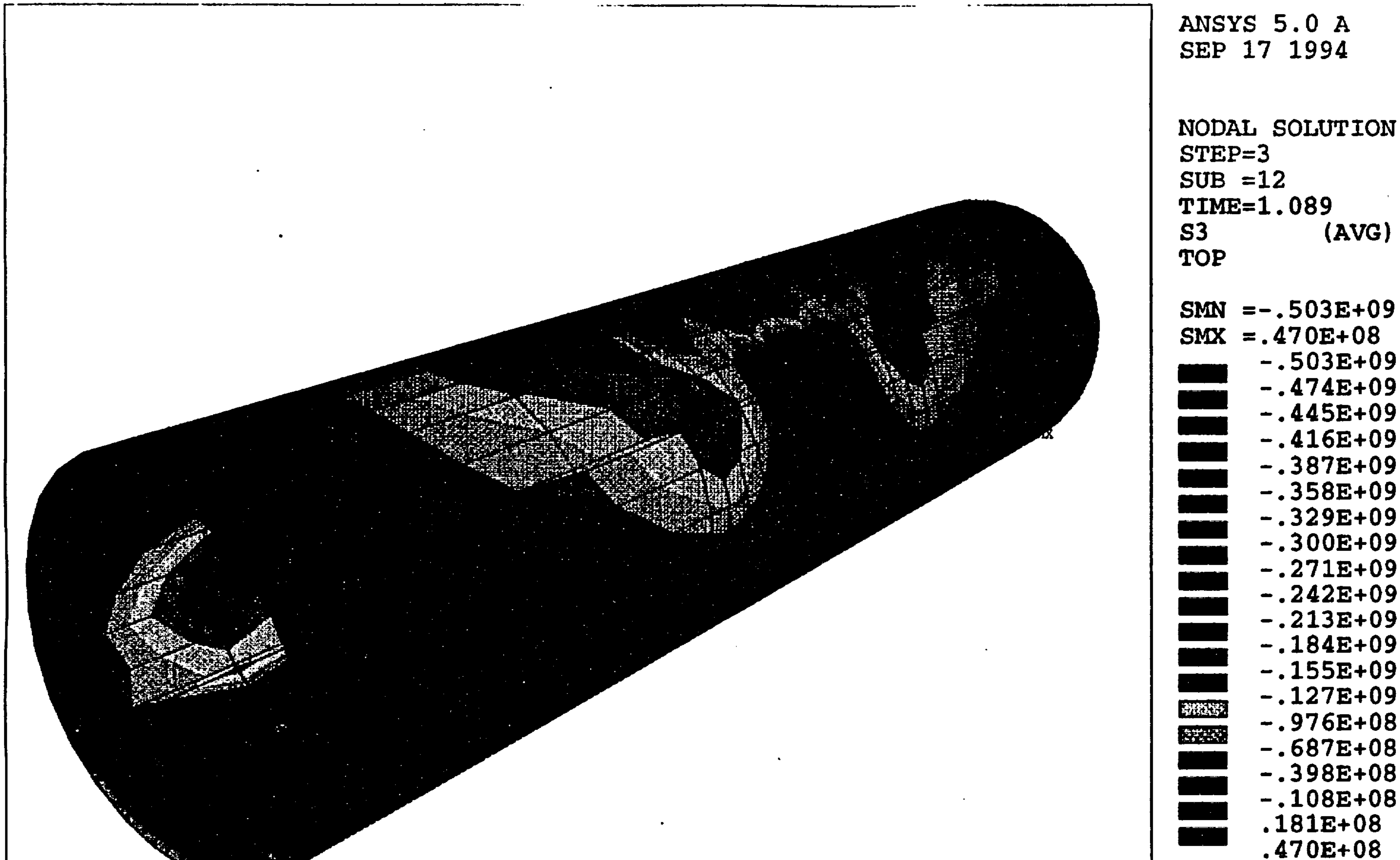


Figure 13. Maximum compressive stress distribution in the outer barrier of 12 PWR ILB WP (Rock Drop in the ESF Tunnel)

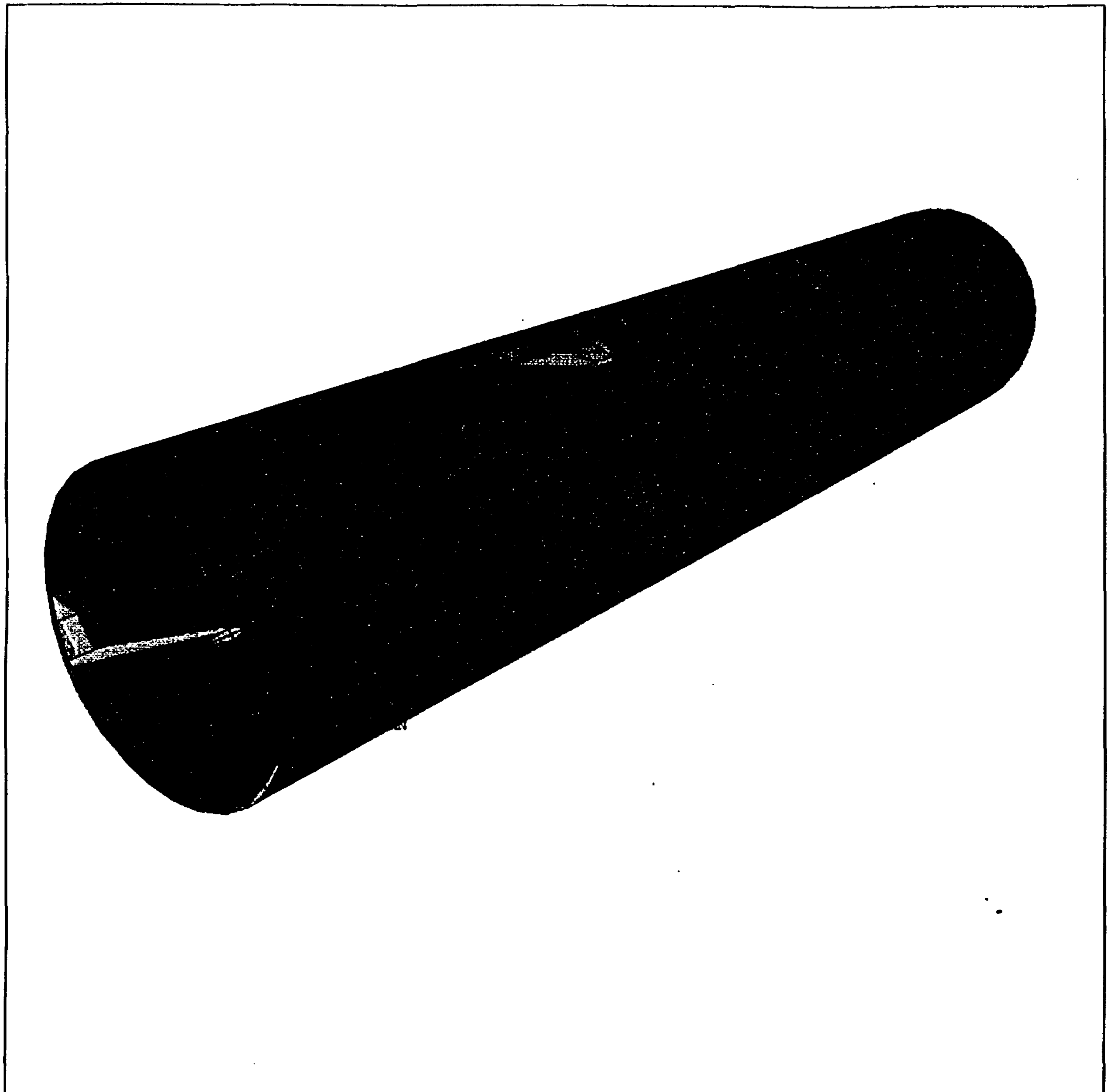
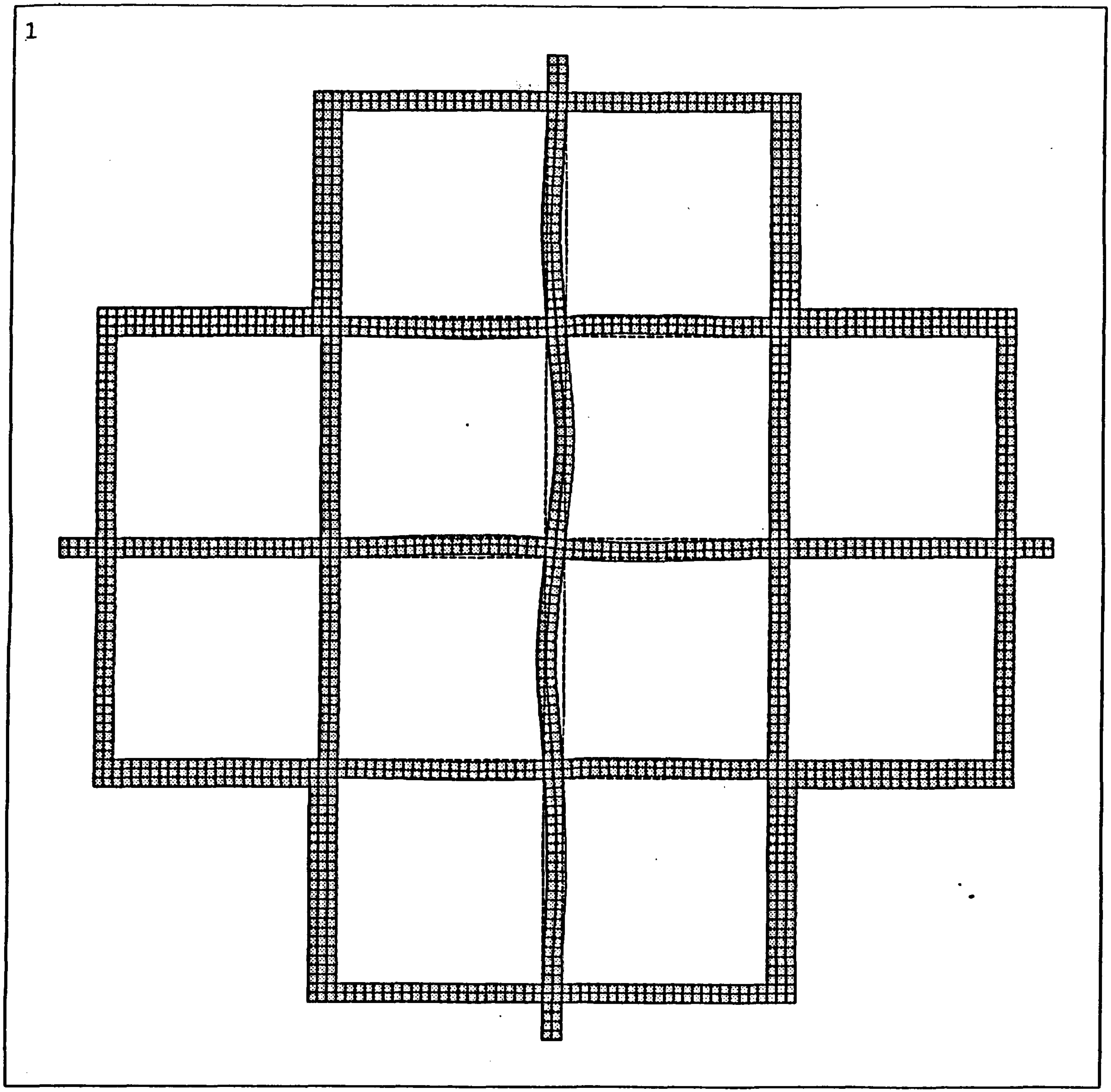


Figure 14. Maximum tensile stress distribution in the inner barrier of 12 PWR ILB WP (Rock Drop in the ESF Tunnel)



ANSYS 5.0A Critical Buckling Evaluation of 12 PWR Basket

Future Work

Future structural analyses will exam the following internal and external loads:

- Routine handling loads
- Fabrication stresses
- Differential thermal stresses
- Residual fabrication stresses
- Internal structural loads
- Imposed loads such as backfill loads
- Handling accidents

Performance Analysis

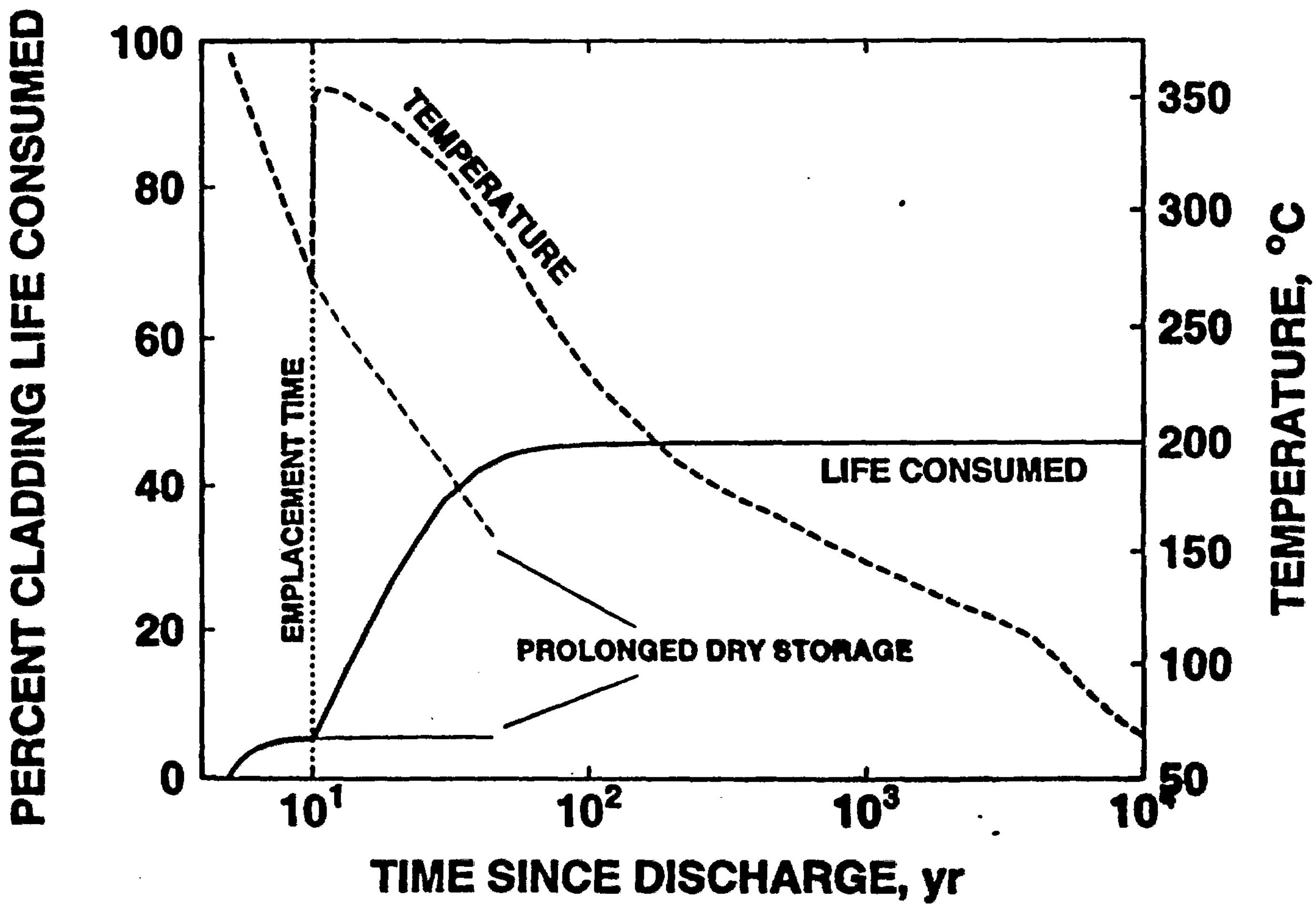
- Cladding Degradation

- Water in MPCs

Performance Analysis: Cladding Degradation

- Developed extension of creep rupture model approved by NRC
- Degradation accumulates according to time at temperature
- Extension includes effects of microstructure to reduce level of conservatism

Damage Accumulation in Storage and Disposal



Performance Analysis: Water in MPCs

- Specification for allowable amount of water was evaluated
- Considered potential for effects of
  - Nitric acid formation by radiolysis
  - Hydrogen embrittlement
  - Oxidation
- Specification was found to be sufficiently stringent that effects of water are negligible

Activities - FY 1995

Activities - FY 1995

- Initiated Title I Waste Package Design Oct 1994
- Prepare Waste Package Conceptual Design Report
- Initiate waste package closure development
- Prepare technical requirements documents for engineering tests
- Support the MPC process
  - Analytical support
  - MPC compatibility with the repository

Activities - FY 1995
(Continued)

- Develop draft of Long-Term Criticality and Burnup Credit Topical Report

- Evaluate performance of waste package designs

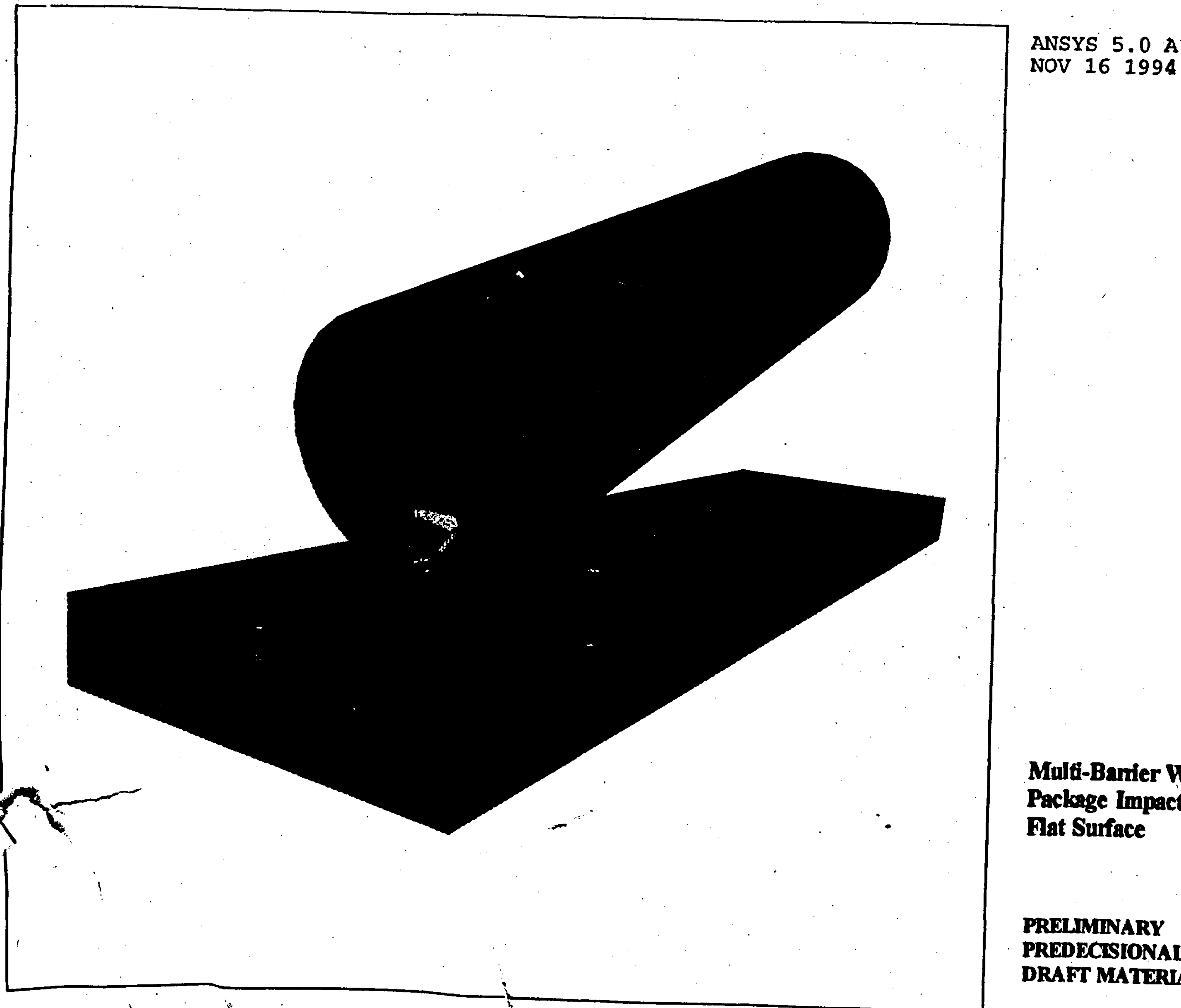
- Initiate long-term materials tests

- Continue waste form testing

MAXIMUM ROCK DROP THAT WILL NOT CAUSE BREACH

	Interlocking Basket Waste Package	Drop Height (m)	Rock Size Diameter (m)	Mass of Rock (metric tons)
TBM Starter Tunnel (9.8 m height)	12-PWR	8.4	2.6	20
	21-PWR*	8.4	2.8	27
ESF Tunnel (7.62 m Diameter)	12-PWR	5.7	2.9	29
Emplacement Drift (4.88 m Diameter)	12-PWR	3.2	3.5	50

*Analytical Evaluation Performed by Correlation with FEA Solution



Multi-Barrier Waste Package Impacted on a Flat Surface

PRELIMINARY
PREDECISIONAL
DRAFT MATERIAL

STATUS OF WASTE PACKAGE MATERIALS TESTING EFFORT

R. Daniel McCright
Lawrence Livermore Laboratory
Waste Package Materials
Technical Area Leader

Presentation to:
DOE/NRC Technical Exchange on
Substantially Complete Containment and
Waste Package Design

Rockville, Maryland
December 7, 1994

DM:11/16/94

Outline of Presentation

- Candidate materials for container
- Plans for short and long term testing
- Results from thermogravimetric analysis testing
- Results from crack growth testing
- Summary and forecast

Workshop on Container Materials Focused on Three Areas

Conducted:

- LLNL organized
- Many materials interested people from YMP (DOE, M&O, LLNL, ANL, Iowa State University, University of Nevada, Weston, and NWTRB)
- Met for three-days, (May 1994), broke up into three study groups to identify the following:

Identified:

- Candidate materials for multiple barrier designs
- Test environments — especially "bounding environments"
- Test methods — short term and long term

DM:11/16/94

Candidate Container Materials
(Highly Corrosion Resistant Materials)

UNS No.	Common or Commercial Name	ASTM No.	Nominal Composition
Ni-rich stainless alloys			
N08825	Alloy 825, Incoloy 825	B 424 (plate)	Ni-rich alloy containing 42% Ni, 21% Cr, 32% Fe, 3% Mo, 2% Cu, 1% Ti
N08221	Alloy 825hMo, NiCrFe 4221	B 424 (plate)	High Mo version (6% Mo) of 825
Ni-Cr-Mo alloys			
N06022	Alloy C-22, Hastelloy C-22	B 575 (plate)	Ni-base alloy containing 58% Ni, 21% Cr, 13% Mo, 4% Fe, 3% W (very low carbon and residuals)
N06455	Alloy C-4, Hastelloy C-4	B 575 (plate)	Ni-base alloy containing 62% Ni, 16% Cr, 16% Mo, 3% Fe,1% Ti (very low carbon and residuals)
Titanium			
R53400	Titanium Grade 12	B 265 Grade 12 (plate)	Ti-base "lean" alloy containing 0.7% Ni, 0.3% Mo
None yet	Titanium Grade 16	none yet	Ti-base "lean" alloy with 0.05% Pd

DM:11/16/94

Candidate Container Materials
(Moderately Corrosion Resistant Materials)

UNS No.	Common or Commercial Name	ASTM No.	Nominal Composition
Copper and Nickel alloys			
N04400	Alloy 400, Monel 400	B 127 (plate)	Ni-Cu alloy containing 67% Ni, 32% Cu, 1% Fe
C71500	70/30 Copper-Nickel, CDA 715	B 171 (plate)	Cu-Ni alloy containing 31% Ni, 67% Cu, 1% Fe

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Corrosion Allowance Materials

Carbon and Alloy Steels			
G10200	1020 Wrought Carbon Steel	A 516 (grade 55)	0.22 max C, 0.6-1.2 Mn, 0.15-0.40 Si
J02501	Centrifugally Cast Carbon Steel	A 27 (grade 70-40)	0.20 max C, 1.40 max Mn, 0.8 max Si
K21590	2-1/4 Cr-1Mo Alloy Steel	A 387 (grade 22)	2.0-2.5 Cr, 0.9-1.1 Mo, 0.15 max C, 0.3-0.6 Mn, 0.5 max Si

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Close Interaction is Maintained Between Design Effort and Materials Effort

- Give design team a repository-relevant information base on performance and properties of different candidate materials
- Support decisions on particular materials and configurations influenced by design factors
  - repository thermal load
  - glass waste form package vs. spent fuel waste package
  - peripheral vs. central location of individual waste packages

Fabrication and Welding Considerations Play an Important Part in Testing Program

- Microstructural evaluation of base metal, weld metal, heat affected zone may reveal potential detrimental phases
- Some welding processes set up galvanic effects in weld zone
- Final closure weld leaves residual stress
- Co-fabrication processes can produce favorable galvanic couple between two metal barriers
- Fabrication in concentric shells can produce unfavorable crevice between two metal barriers

Future Workshops Planned on Materials

- Contacts made with Nickel Development Institute (NiDI)
  - Workshop planned for Spring 1995
    Involve YMP-AECL-NRC-NWTRB participation
    as users
  - Involve North American nickel alloy fabricators as producers
  - Increase awareness of information available from
    Ni industry (alloys, fabrication, welding, applications)

- Plan similar activity with titanium industry

Plans for Short and Long Term Testing

- Metal Barrier Scientific Investigation Plan (SIP)
- 5-Yr comprehensive corrosion tests
- Electrochemical tests (short-term)
- Microbiologically influenced corrosion (short and long term)
- Thermogravimetric analysis (TGA) test (short term)
- Crack Growth Tests (short and long term)

Organization of Metal Barrier SIP Activities

- Degradation Mode Surveys and Information Surveys
  - Corrosion and Oxidation Behavior in Previous Applications
  - Metallurgical Stability
  - Physical and Mechanical Properties
- Testing and Physical Evaluation
  - Accelerated Laboratory Tests (individual tests last up to 1 year)
  - Long Term Laboratory Tests (individual tests last up to 5 years)
  - Support to Field Testing
  - Physical and Microstructural Evaluation
  - Advanced Technique Development
- Modeling for Performance Prediction
  (organized according to degradation mode)
- Recommendations
  - Input to selection criteria, weighting factors, final selection

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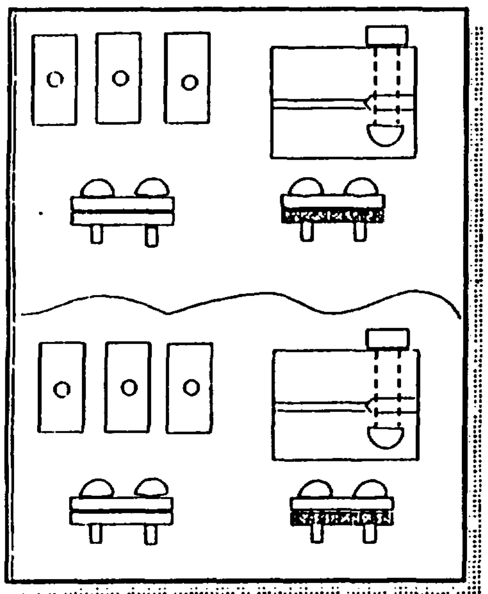
Testing Underway or Planned for FY-95 with Constrained Funding

- TGA
- Fracture mechanics crack growth studies (limited range of conditions)
- "5-Yr" comprehensive corrosion test
  - 4 water chemistries (water and vapor)
  - 2 locations (in water, in vapor)
  - 2 temperatures
  - 5 to 8 materials (depending on water chemistry)
  - 2 metallurgical conditions (base metal, weld metal)
  - 4 specimen geometries
  - 3 replicates
  - 5 time intervals
- MIC initial studies

INITIATION OF A 5-YEAR COMPREHENSIVE CORROSION TEST IS A HIGH PRIORITY



"MULTITUDE" OF SPECIMENS REQUIRED

- Candidate Materials
- Specimen Types
- Replicates
- Water Chemistries
- Temperatures
- Exposure Regions (Water, Vapor, Water-Line)
- Metallurgical Conditions (Base Metal, Weld)
- Evaluation Intervals

EACH PARAMETER IS MULTIPLICATIVE

"Bounding Environments" Proposed for 5-Year Corrosion Tests

Dilute Groundwater

- like J-13
- base case

Acidified Concentrated Groundwater	*Concentrated Groundwater*	*Alkalized Concentrated Groundwater*
• pH as low as 2	• 20-100x J-13 ionic cencentation	• pH as high as 12
• simulates extreme case of "man made" materials conditioning environment (diesel fuels, organics, sulfur containing comp'ds)	• simulates dry-out and resaturation of ionic species as temperature increases and decreases	• simulates water conditioning by concretes, grouts
• chemically simulates microbial metabolism		

- Test at 60° and 90°C
- Test in liquid phase, in vapor phase over liquid (possible some specimens at water line)

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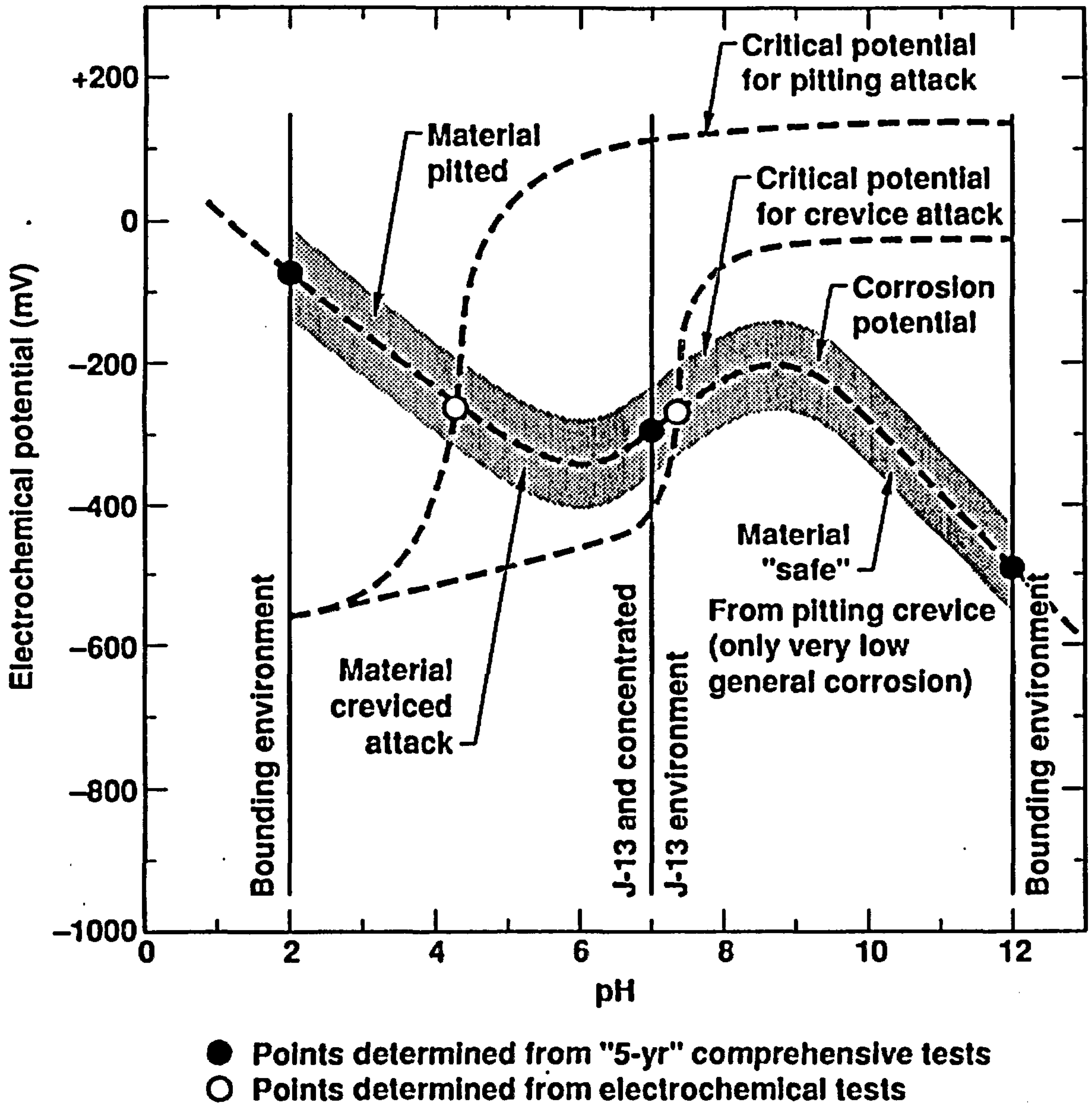
Features of 5-Year "Comprehensive" Corrosion Test

- Expose multitude of specimens of different materials and different geometries
  - flat coupons for weight loss, pitting, intergranular observation
  - sandwich coupons for crevice attack
  - self-loaded stress specimens with and without welds (for stress corrosion, hydrogen embrittlement attack)
  - galvanically coupled specimens
- Withdraw specimens at periodic intervals
  - examine for attack
  - quantify degradation where possible
  - destructively examine some specimens
  - archive or replace specimens back in test cell for additional exposure
  - expose for 5 years or longer

Features of 5-Year "Comprehensive" Corrosion Test (Cont.)

- Results will indicate
  - general corrosion rates
  - pitting corrosion attack (number pits, depth of attack)
  - crevice corrosion attack (depth of attack)
  - intergranular/selective attack (depth of attack)
  - stress corrosion or hydrogen embrittlement (stress level)
  - galvanic attack/galvanic protection

2-dimensional schematic map of corrosion regions



In addition to pH, need to determine curves for:

- Alloy composition
- Chloride ion concentration
- Sulfate, nitrate, other ions in groundwater
- Temperature
- Metallurgical features (welds, heat affected zones, inclusions, microstructures)
- Applied stress/strain

To establish "safe" and "unsafe" volumes

ES1111/94BC#5-01

Impact of Microbiologically Influenced Corrosion (MIC)

Candidate Material	Susceptibility*
Carbon Steel	Many kinds of bacteria, both aerobic and anaerobic, attack steels, resulting in enhanced general corrosion, pitting, and hydrogen embrittlement (many studies)
70/30 Copper Nickel	Sulfate reducing bacteria caused pitting. Acid Polysaccharides increased corrosion (several studies)
Monel 400	Sulfate reducing bacteria caused deep pitting, intergranular attack (several studies)

* Summarized from G. Geesey, " A review of the potential for microbially influenced corrosion of high -level nuclear waste containers" CNWRA 93-014 (June, 1993)

DM:11/16/94

Impact of Microbiologically Influenced Corrosion (MIC) (cont.)

Candidate Material	Susceptibility*
Incoloy 825	Sulfate reducing bacteria caused pitting and crevice attack in lake water and sea water (2 studies)
Hastelloy C-4, C-22	Appears to be immune, but pure Ni is attacked
Titanium	Appears to be immune

* Summarized from G. Geesey, " A review of the potential for microbially influenced corrosion of high -level nuclear waste containers" CNWRA 93-014 (June, 1993)

Plans for MIC Evaluation and Testing

- Evaluate Yucca Mountain repository site for presence of microbial species known to enhance corrosion of candidate container materials

  - native microbial populations
  - microbes associated with introduction of "man-made materials" into repository
  - consortiums of microbial populations
  - moisture films initiating aqueous corrosion also act as biofilms

- Conduct experimental measurement of corrosion in controlled microbiological environments, as suggested from above evaluation

Thermogravimetric Analysis (TGA)

- Background
- Apparatus
- Results
- Plans

Effect of Relative Humidity and Sulfur Dioxide Concentration on the Corrosion of Copper

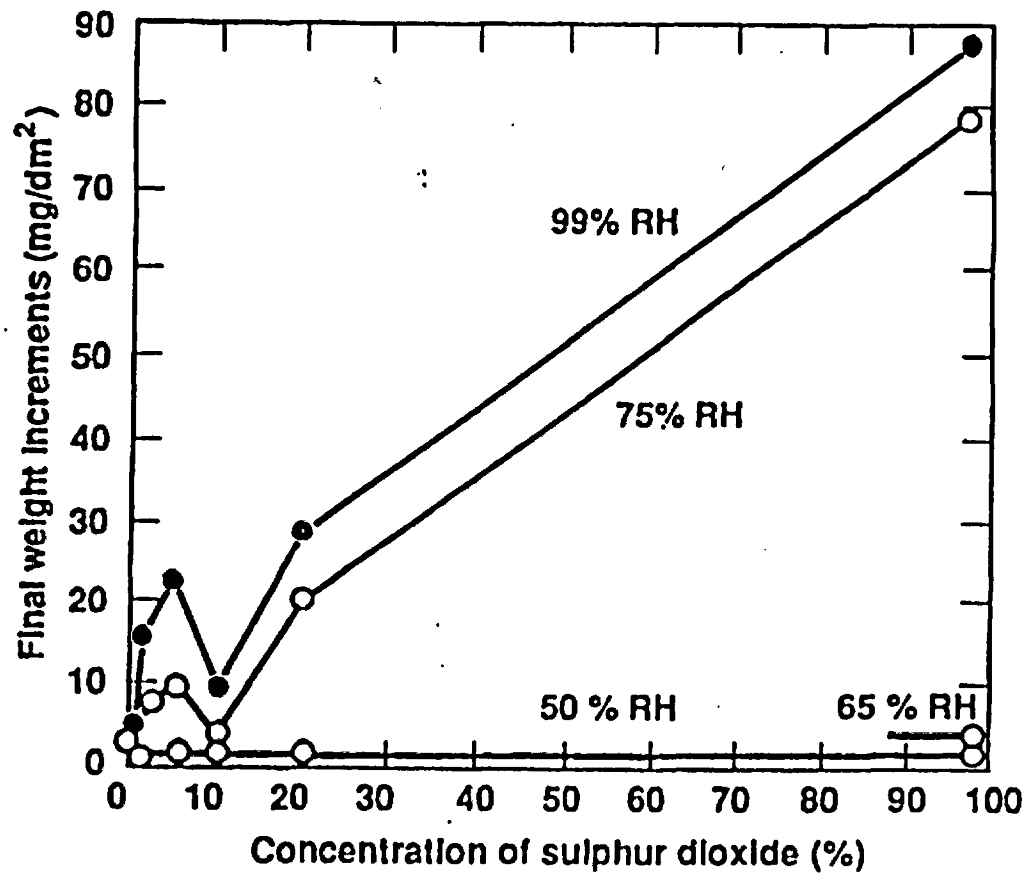


Figure 25. Relationship between corrosion and concentration of SO_2 in atmospheres of high relative humidity [87].

P.M. Aziz, H.P. Godard, "Mechanism by Which Non-Ferrous Metals Corrode in the Atmosphere," Corrosion Vol. 15 , 1959, pp. 529t-541t.

Corrosion Rate as a Function of Relative Humidity for Various Metals

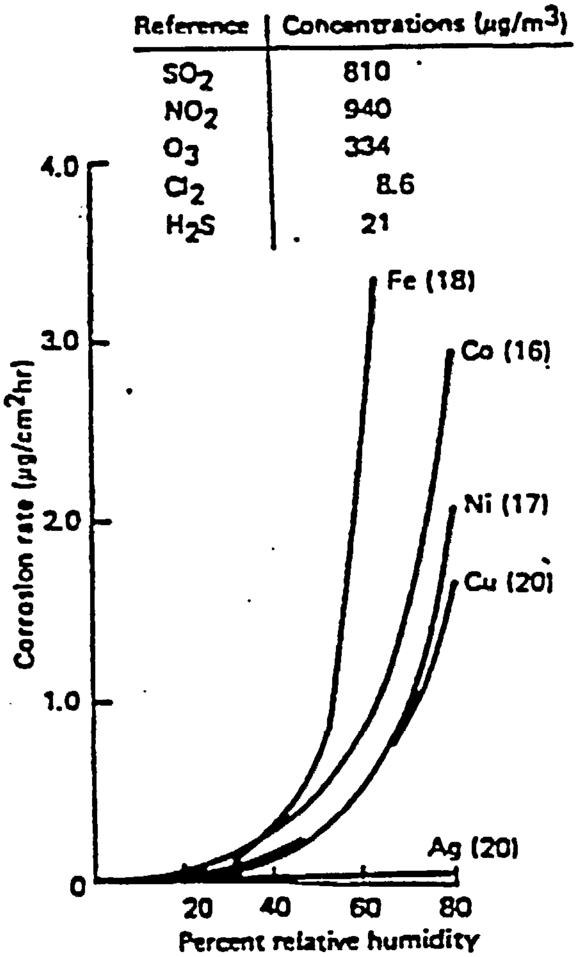
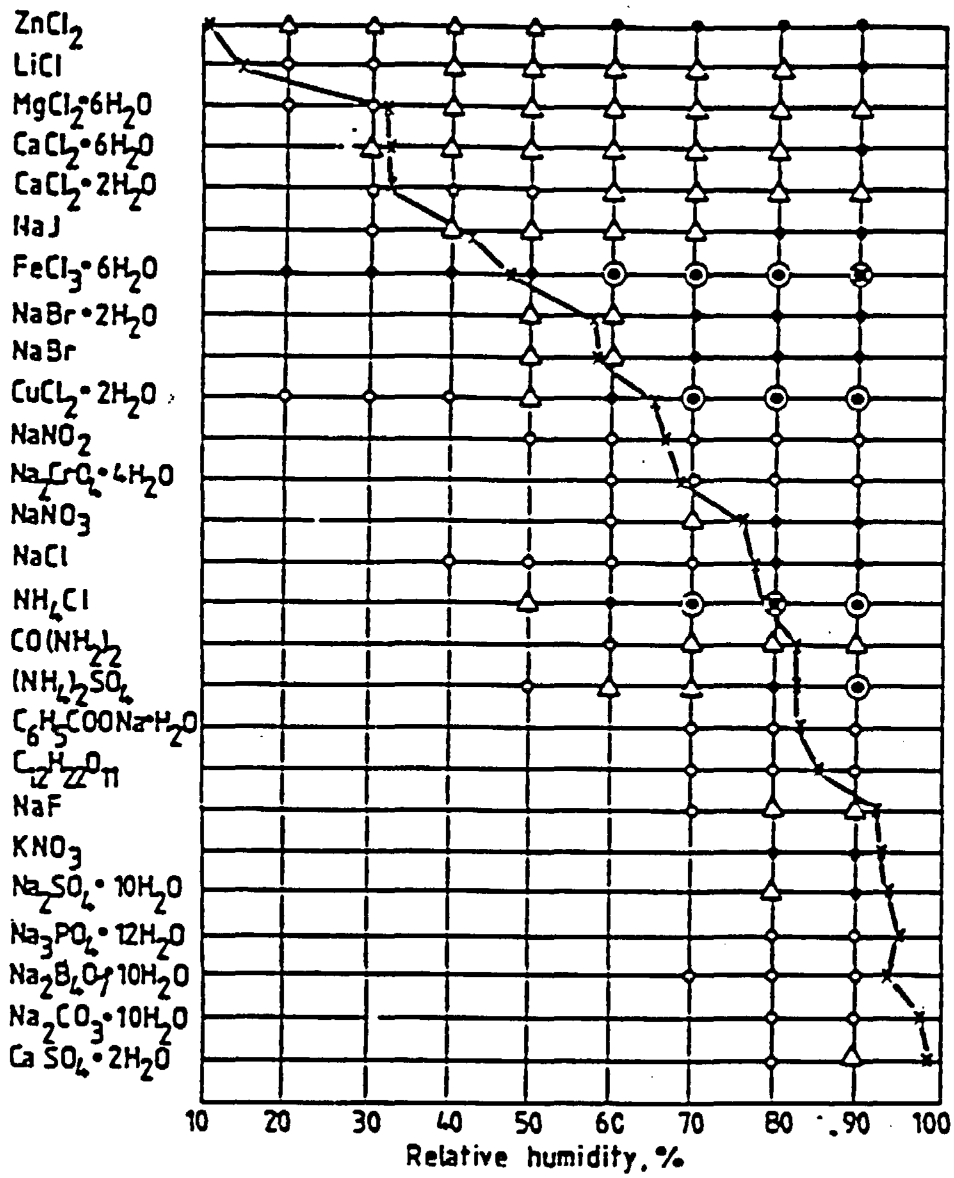


Figure 46.5. Corrosion rate versus relative humidity ($T = 25°C$).

D.W. Rice, R.J. Cappell, P.B.P.Phipps, P. Peterson, "Indoor Atmospheric Corrosion of Copper, Silver, Nickel, Cobalt, and Iron," in Atmospheric Corrosion, W.H. Ailor, ed., The Electrochemical Society, 1980, pp. 651-666.

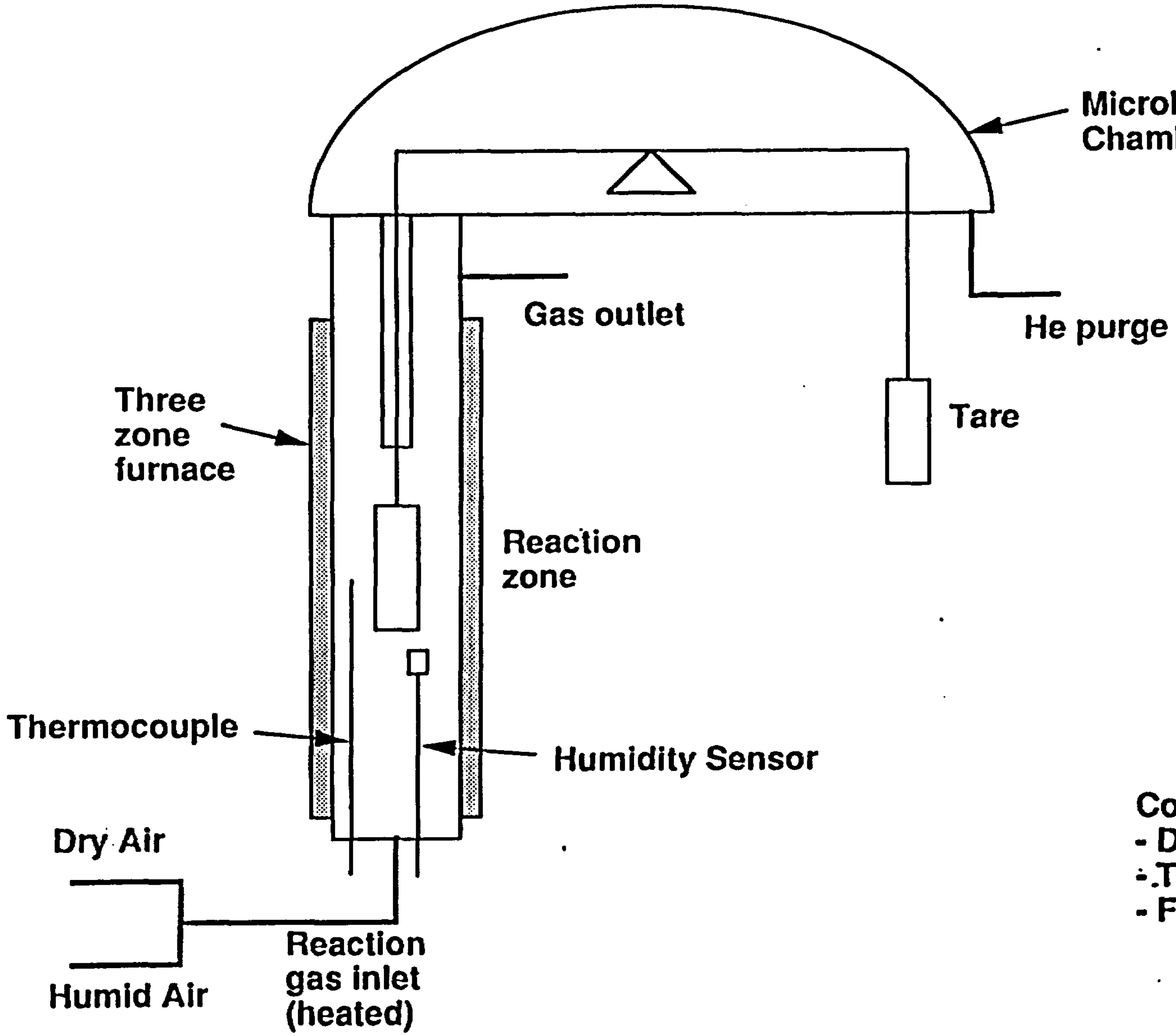
Corrosivity of Various Salts to Steel



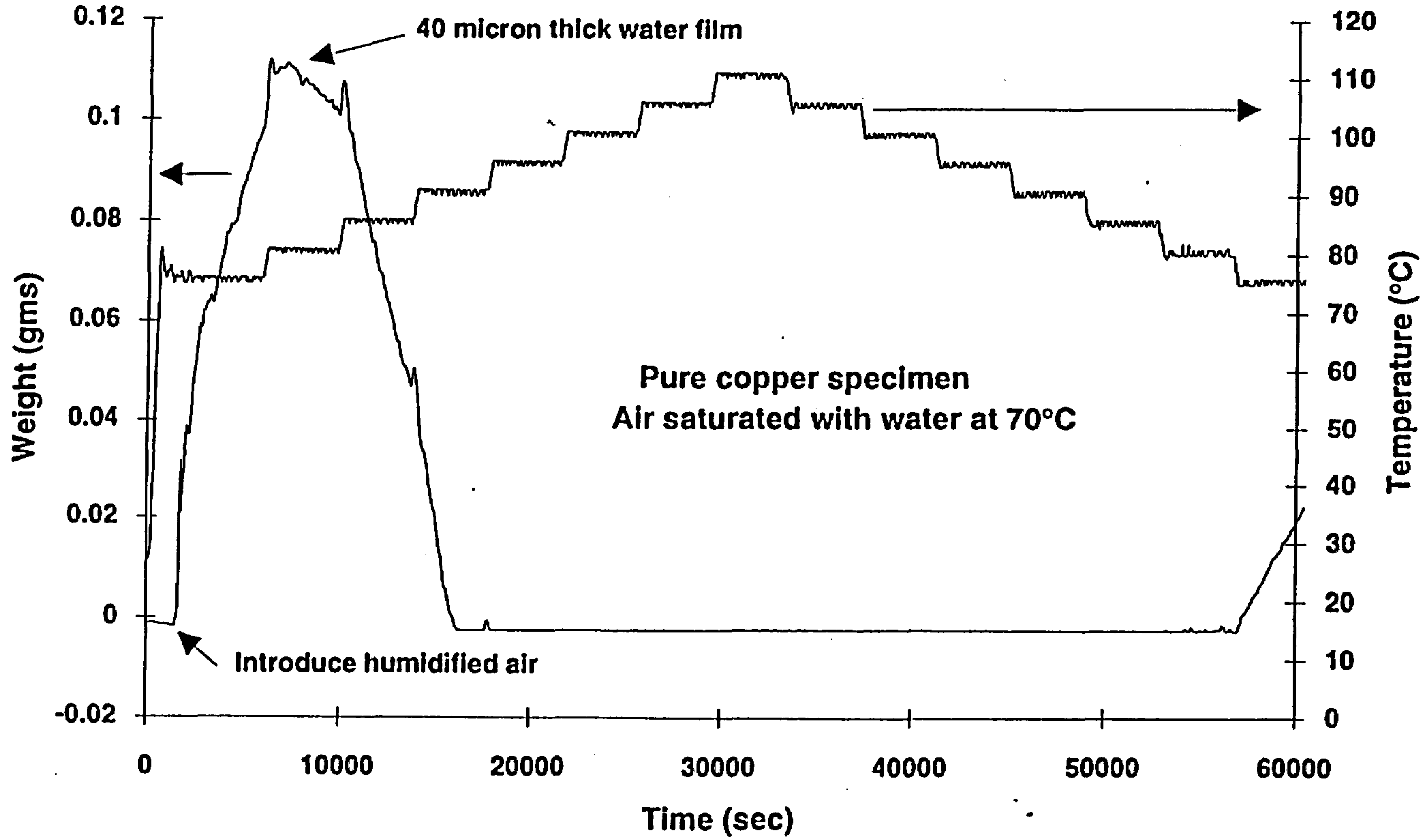
20°C, 7 days, excess salt
x - relative humidity above sat'd solution
O = 0-1mg; Δ = 2-5mg; • = 6-20mg; ⊙ = 21-100mg

V. Kucera, E. Mattsson, "Atmospheric Corrosion" in Corrosion Mechanisms, F. Mansfeld, ed., Marcel Dekker, Inc. New York, 1987, p. 214.

Thermogravimetric Analyzer Apparatus



Computer Controlled
- Data Acquisition
- Temperature control
- Flow control



40 micron thick water film
Pure copper specimen
Air saturated with water at 70°C
Introduce humidified air
Weight (gms)
Temperature (°C)
Time (sec)
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
120
110
100
90
80
70
60
50
40
30
20
10
0
0
10000
20000
30000
40000
50000
60000

Plans for Thermogravimetric Studies

- Investigate the potential for water film corrosion in humidified air

- Obtain conditions of material susceptibility to water film corrosion with respect to relative humidity, temperature, surface conditions, and gas phase composition

- Metals investigated
  - Carbon steels
  - Copper-nickel alloys
  - Corrosion resistant alloys

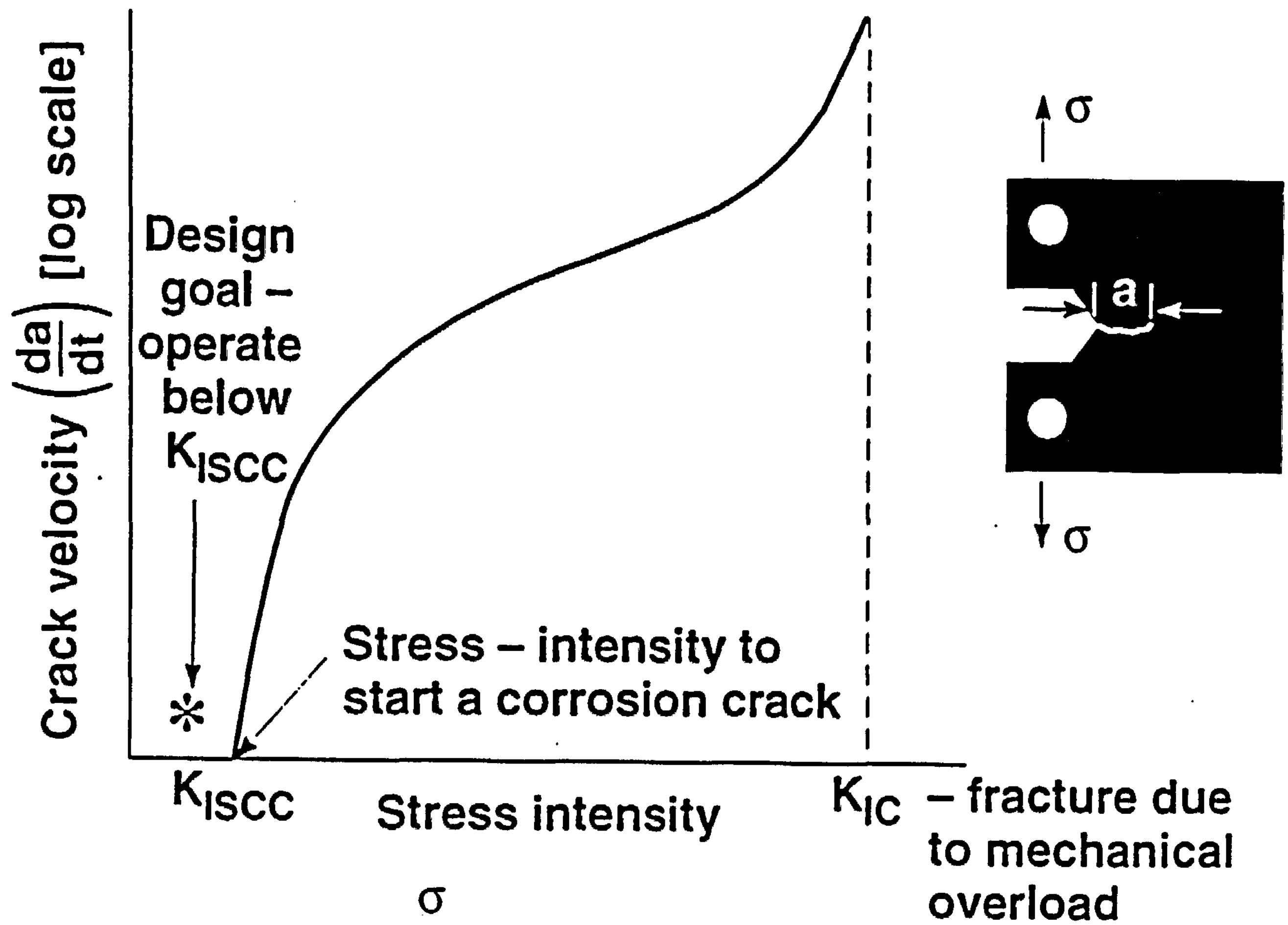
- Experimental conditions
  - Relative humidities: 50-95%
  - Temperature: 50 - 90°C
  - Salts ($NaCl$, $CaCO_3$)
  - Gas composition (CO_2)

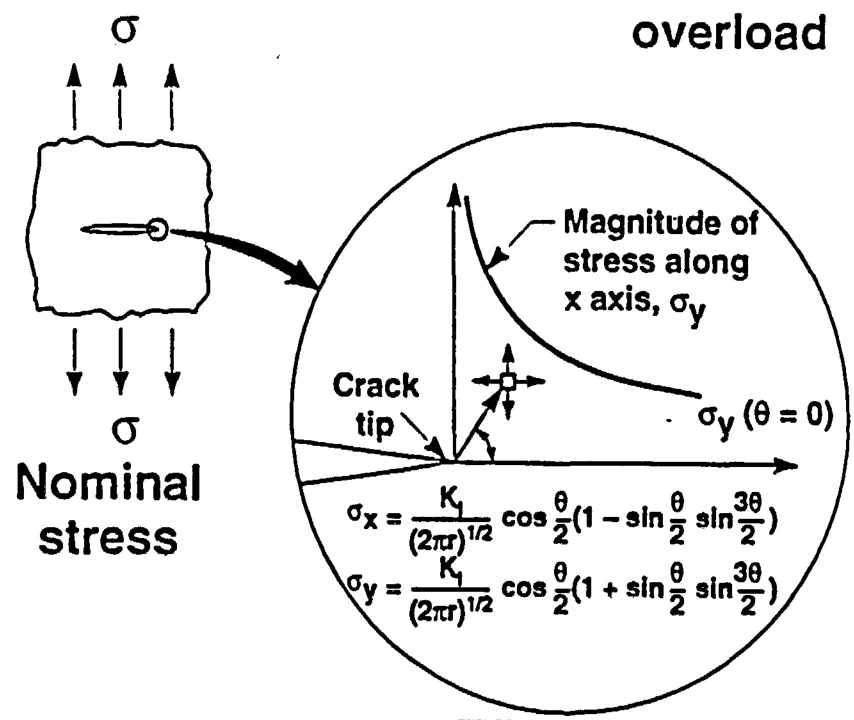
- Obtain mechanistic and kinetic information on high T oxidation

Fracture Mechanics Crack Growth Studies

- Background
- Apparatus
- Results
- Plans

Background for fracture mechanics





Stress – intensity, $K_I = \sigma \sqrt{\pi a}$ f [geometry]

R = load ratio = $\frac{K_{MIN}}{K_{MAX}}$

Summary of ANL Stress Corrosion Cracking Results at 93° C in Simulated J-13 Water

- No measurable crack-growth for 304L, 316L, or Incoloy 825 at $K_{max} = 22.5$ Ksi$\sqrt{in}$, R=0.9 for times of 19,000 hours projects a crack-growth rate of "less than 8×10^{-13} m/sec," which is less than an allowable growth-rate of 1×10^{-12} m/sec for the waste container.

- At lower R and higher K_{max} measureable cracking was found, but is consistent with published A.S.M.E B.P.V.C. Section XI, data. No environmental acceleration seen for growth rates as low as 10^{-11} m/sec.

Cost-Constrained FY95 Program

- Materials (four):
  - I-825 Ni-rich stainess alloy
  - C-22 nickel-base alloy
  - Ti-12 titanium alloy
  - CDA 715 copper alloy

- Materials Conditions (one):
  - Mill-annealed plate

- Temperatures (one):
  - 90°C

- Environments (two):
  - Acidified concentrated J-13 well waters
  - Alkaline concentrated J-13 well waters

- Stress Intensity Levels (two):
  - K_{max} = 30, T.B.D. $KSI\sqrt{IN}$
  - R= 0.10

Total Samples : 32

DM:11/16/94

FY-95 Constrained Funding Stress Corrosion Cracking Rate Test (1)

Material	Temp. (°C)	Water Chemistry	Kmax	$R=\frac{K_{min}}{K_{max}}$	Comments
C-22	90	J-13	$30 Ksi\sqrt{in}$	0.2	Short Time Test
" "	"	" "	" "	0.5	" "
" "	"	" "	" "	0.7	" "
C-4	90	J-13	" "	0.2	" "
" "	"	" "	" "	0.5	" "
" "	"	" "	" "	0.7	" "

(1) Will carry over into FY-96

DM:11/16/94

FY-95 Constrained Funding Stress Corrosion Cracking Rate Test (1) (Cont)

Material	Temp. (°C)	Water Chemistry	Kmax	R= $\frac{K_{min}}{K_{max}}$	Comments
C-22	90	J-13	$30 Ksi\sqrt{in}$	0.2	Short-Time Test
" "	"	"	" "	0.5	" "
" "	"	"	" "	0.7	" "
Ti-12	"	"	" "	0.2	Long-Time Test
C-4	"	"	" "	0.2	" "
C-22	"	"	" "	0.2	" "
I-825	"	"	" "	0.2	" "

(1) Will carry over into FY-96

DM:11/16/94

The Full Planned Program - Fracture Mechanics Stress Corrosion Cracking

- Materials (eight):
  - I-825 and other Ni-rich stainless alloys
  - C-22, C-4, and M-400 Nickel-base alloys
  - Ti-12 and other titanium alloys
  - 70/30 Cu-Ni alloy

- Material Conditions (two):
  - Mill-annealed plate, one type of fusion-weld (process and filler metal T.B.D.)

- Temperatures (two)
  - 60°C and 90°C

- Environments (four):
  - J-13 well water
  - J-13 well water with 20-100 X impurities (aka "concentrated" J-13 well water)
  - Concentrated J-13 well-water acidified to pH2.
  - Concentrated J-13 well-water alkalized to pH12.

The Full Planned Program - Fracture Mechanics Stress Corrosion Cracking (cont.)

- Stress-intensity levels (four):
  - (K_{max} stated)
  - 15, 25, 35, 45 $KSI\sqrt{IN}$
  - R= 0.1
- Time duration of test: 2 years

Total number of samples = materials (8) x material conditions (2) X temperatures (2) X environments (4) X stress- intensity levels (4) = 512

Mix of "Short term" and "Long term" Laboratory Tests Assures Wide Range of Parameters

Examples:

- Short term electrochemical tests to determine critical potentials enhance the chemical range of the "five year corrosion test"

  - more values of pH, T, Cl, etc.
  - more metallurgical nuances (microstrucures, microchemistries)

- Short term TGA experiments delineate critical humidity levels to guide long term oxidation and corrosion tests

- Short term crack growth test (in aggressive environments or under high stress conditions) supplement similar crack growth tests conducted under more "realistic" repository environment conditions

  - expensive equipment
  - expensive test specimens

Summary and Forecast

- Candidate materials, bounding test environments, test methods identified from workshop
- Features of a 5-year comprehensive corrosion test highlighted
- Additional testing activities discussed
  - TGA work
  - fracture mechanics crack growth work
- Plans for near future tests formulated
- Concentrated effort needed in container materials work to support arguments for substantially complete containment

Model Predictions for Containment Barrier Performance

Presented to
DOE/NRC Technical Exchange

Presented by
Dr. David Stahl
Manager
Waste Package Materials & Performance Analysis
M&O/B&W Fuel Company
Las Vegas, Nevada

December 7, 1994

Purpose

- Evaluate the corrosion of waste package components as part of the total evaluation of the impact of thermal loading
- Utilize simple kinetic models for both atmospheric and aqueous corrosion that take account of temperature and relative humidity effects as a function of time
- Determine failure times for the corrosion-allowance containment barrier (and later for the corrosion-resistant containment barrier)

Method

- Determine the amount of penetration of the corrosion-allowance containment barrier
- Evaluate the penetration as a function of time and temperature using the "Stahl" correlation modified for surface films
- Determine the sensitivity of penetration to time exponent and microbiologically-influenced corrosion factors
- Utilize concurrent corrosion processes including elevated temperature oxidation and corrosion in humid air
- Utilize the data of T. Buscheck on humidity as a function of time
- Determine penetration and failure times for three thermal loads

Equations Used

- General kinetic expressions developed of the form:

  $$\text{Penetration} = At^{c}\exp(-B/T)$$

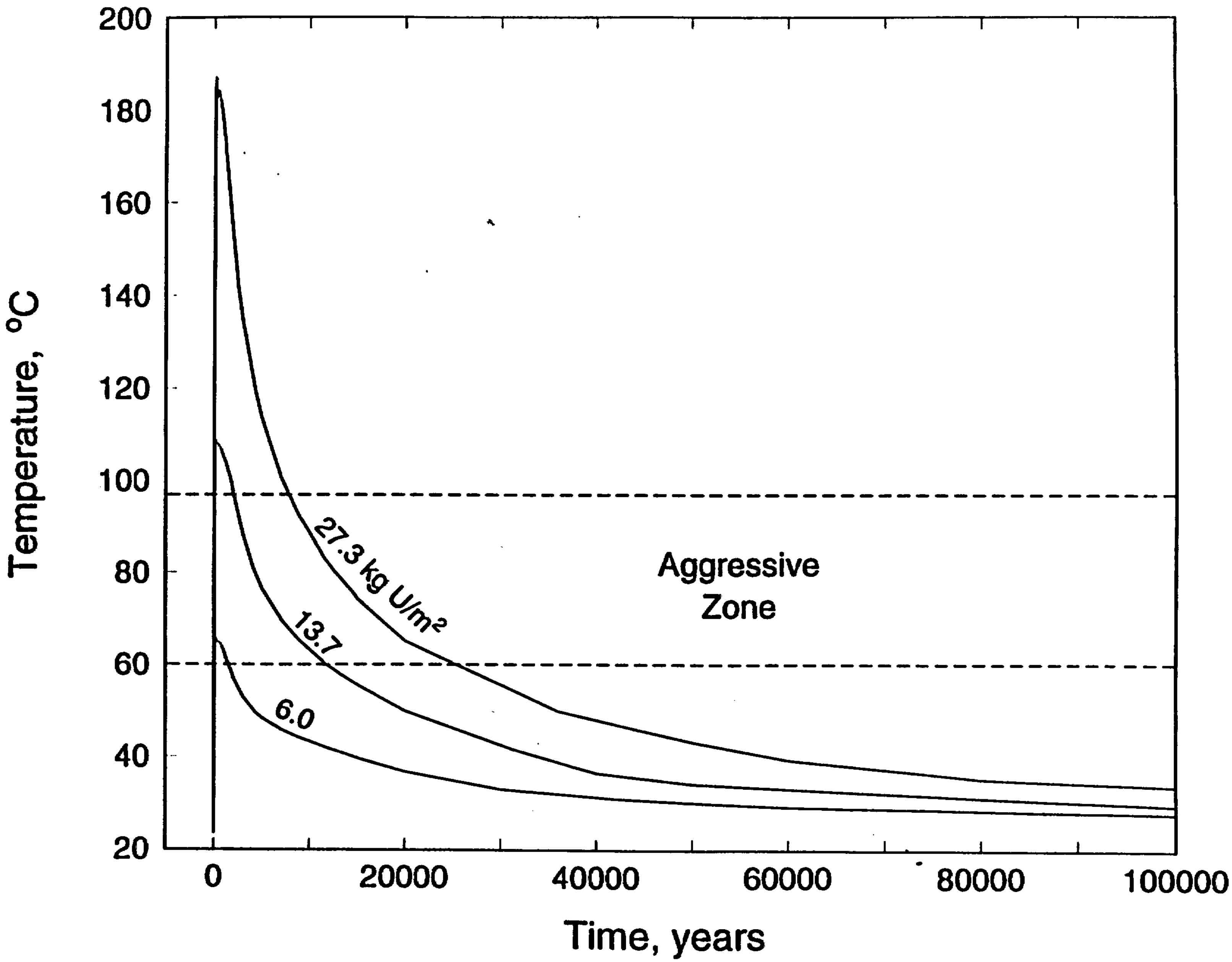
- For High-Temperature Oxidation:

  $$\text{Penetration } (\mu m) = 178{,}000\ t_y^{0.33}\ e^{-6870/T}$$

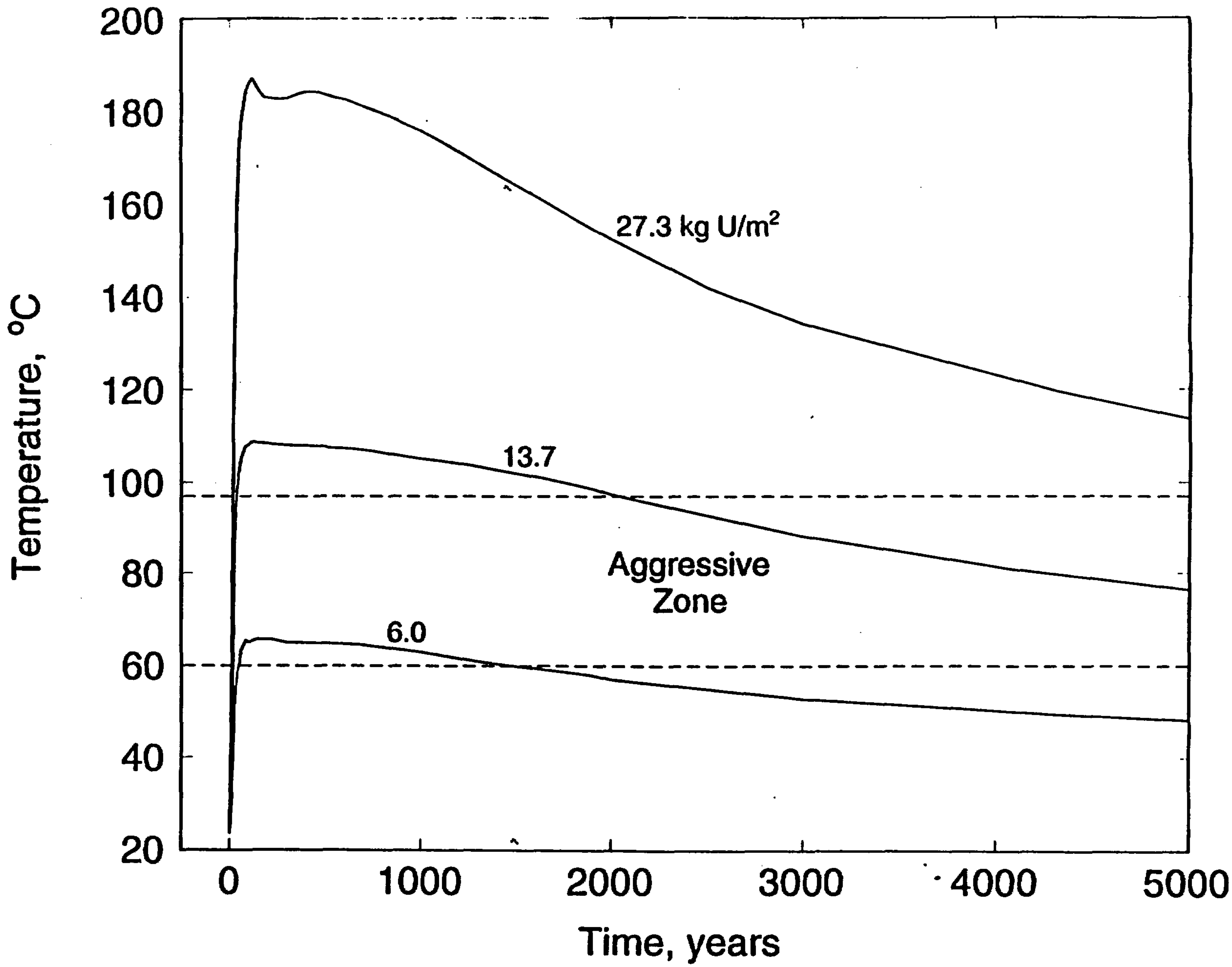
- For General Aqueous Corrosion:

  $$\text{Penetration } (\mu m) = 2{,}525{,}000\ \ t_y^{0.47}\ e^{-2850/T}$$

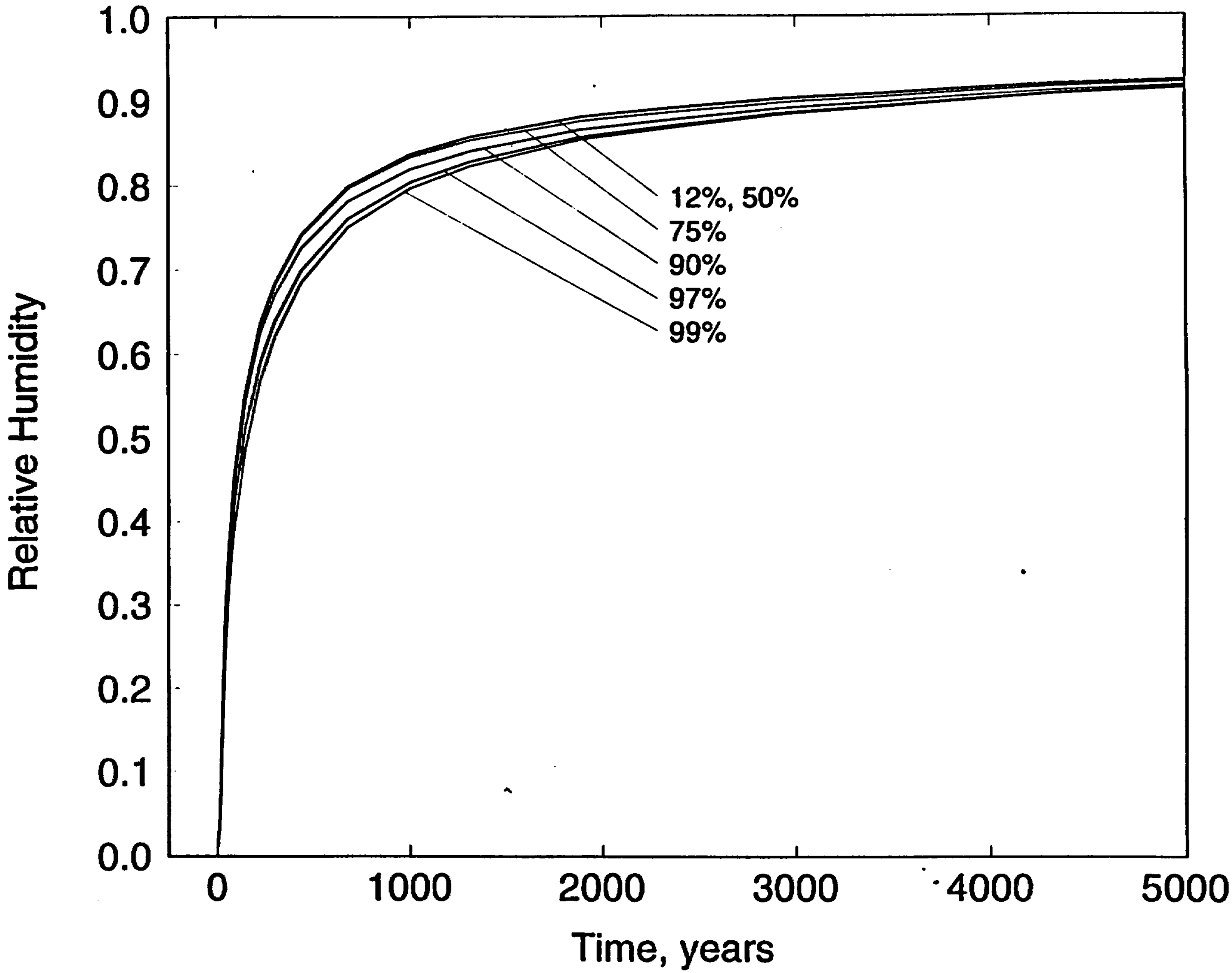
- Aqueous corrosion expression modified to include linear relation of log of penetration in humid air to the relative humidity



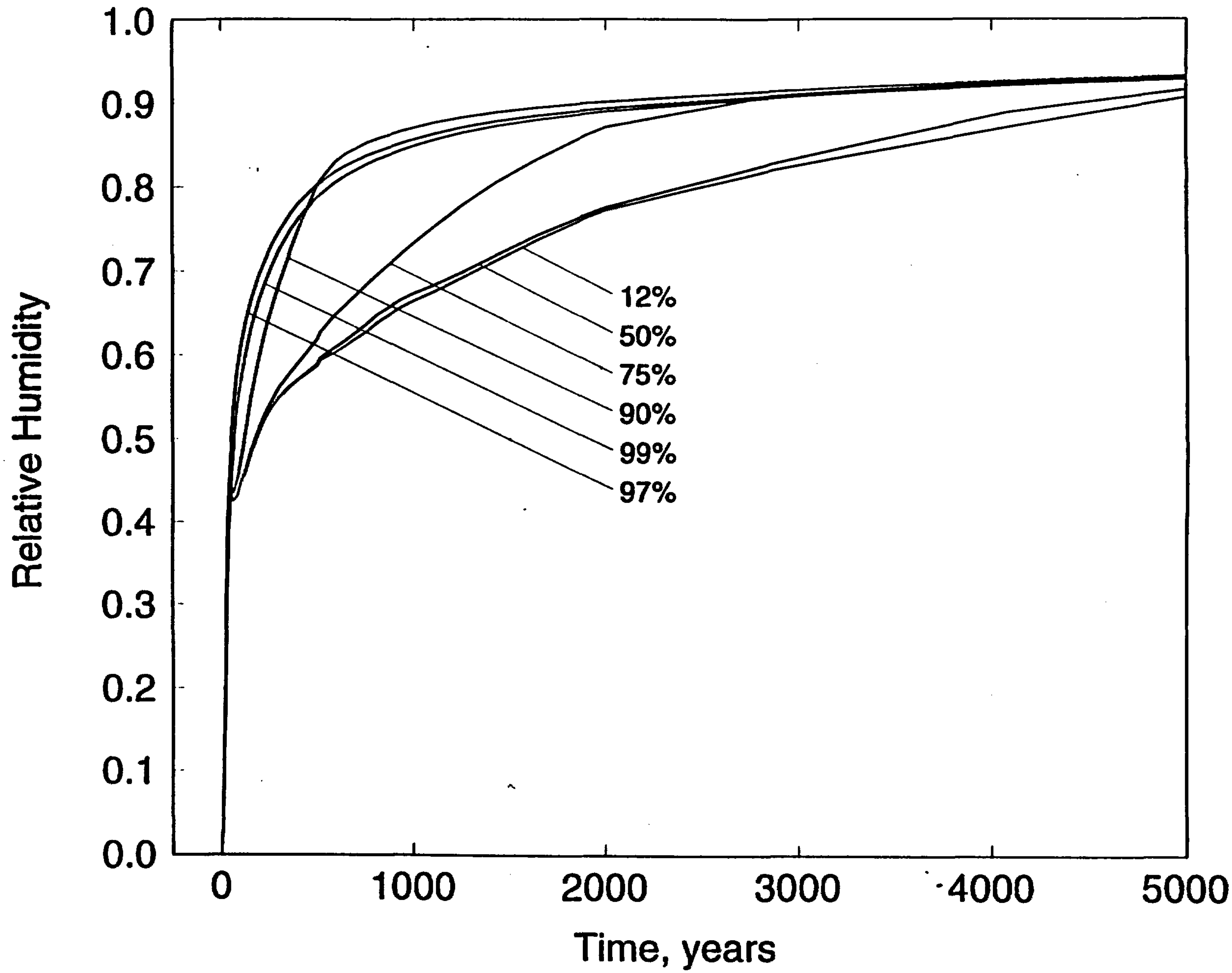
Calculated Temperature Profiles for Three Thermal Loadings at the Midpoint of the Repository



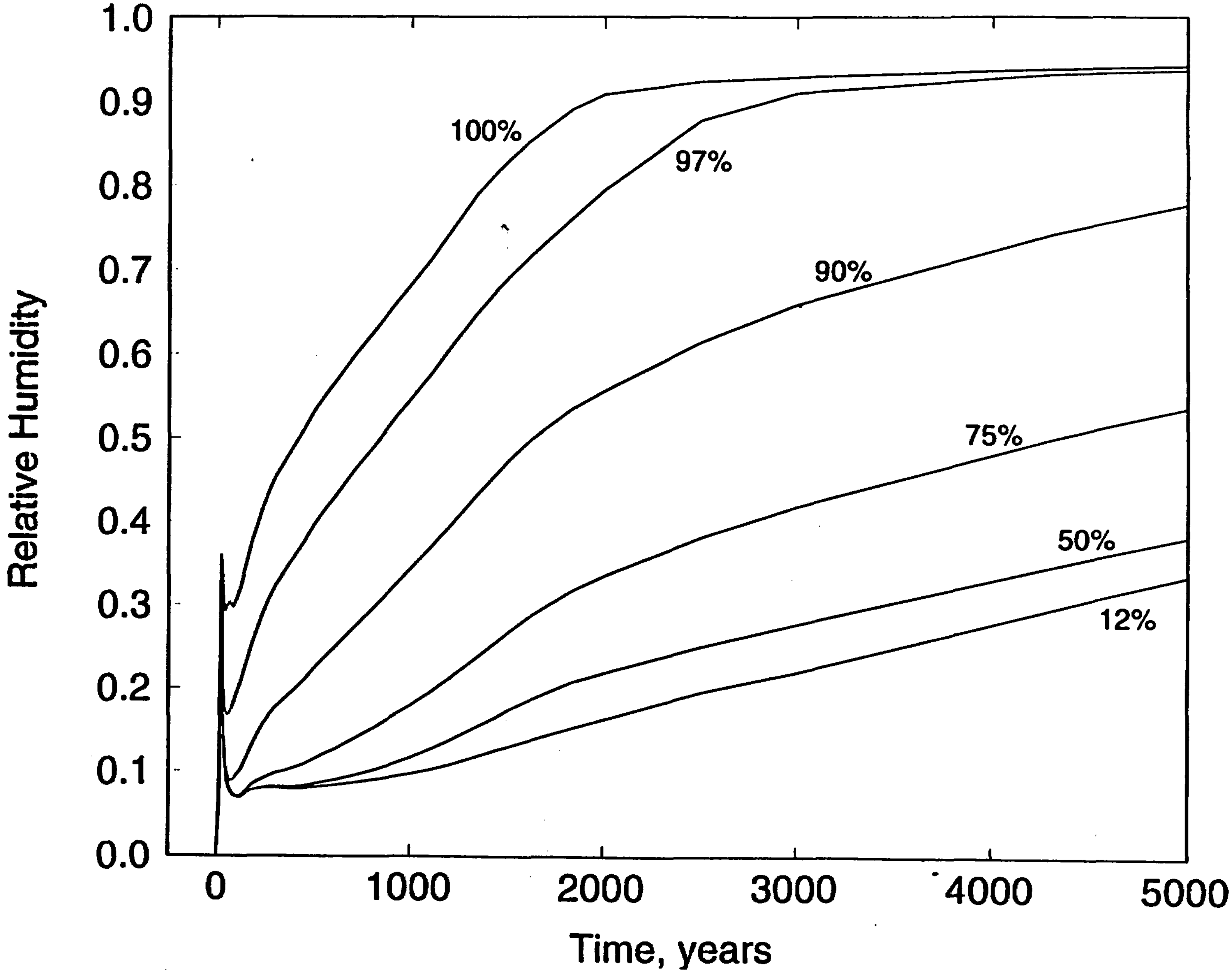
Calculated Temperature Profiles for Three Thermal Loadings at the Midpoint of the Repository



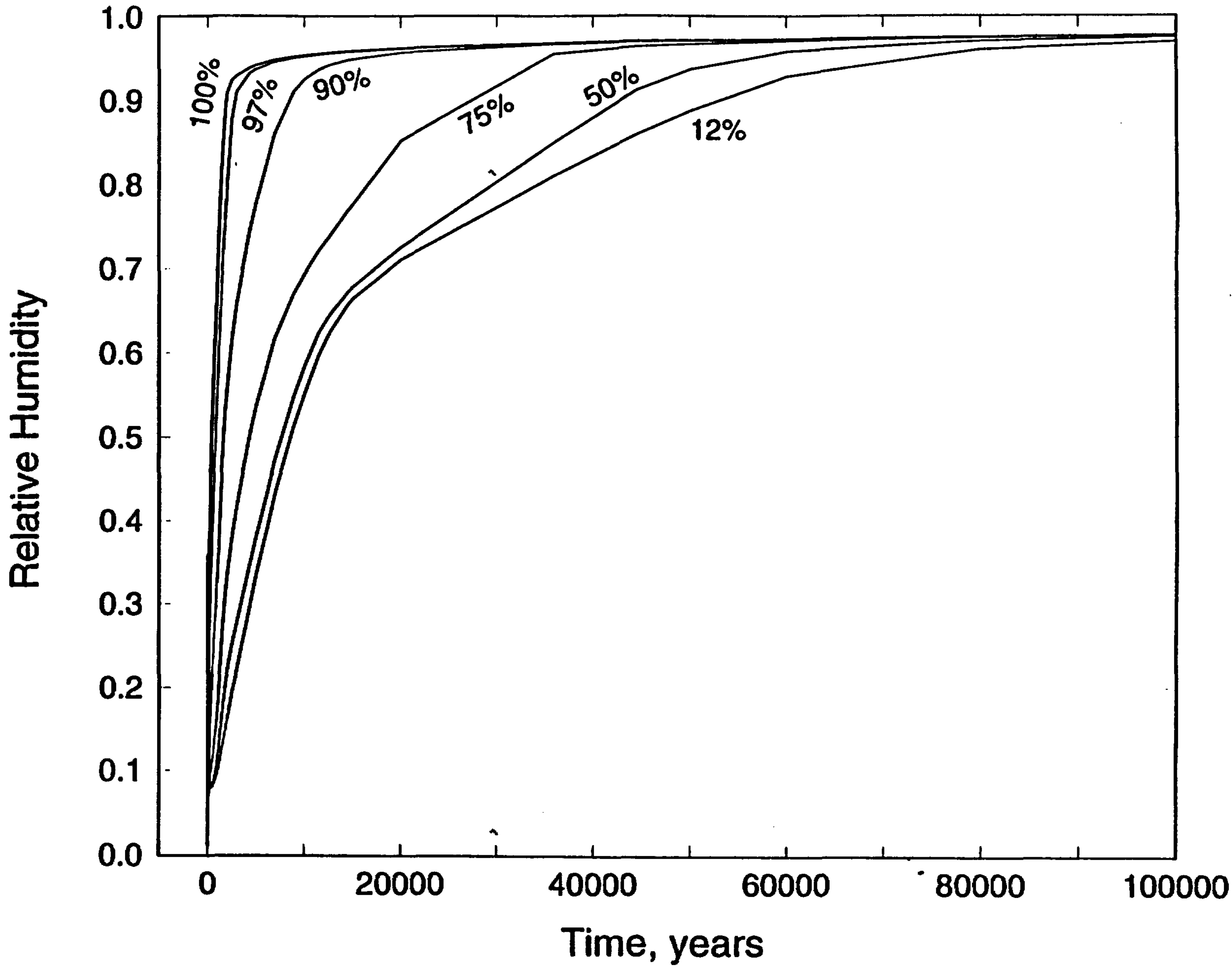
Calculated Relative Humidity at Waste Package Surface as a Function of Time for 6.0 kg U/m^2 (24.2 MTU/acre)



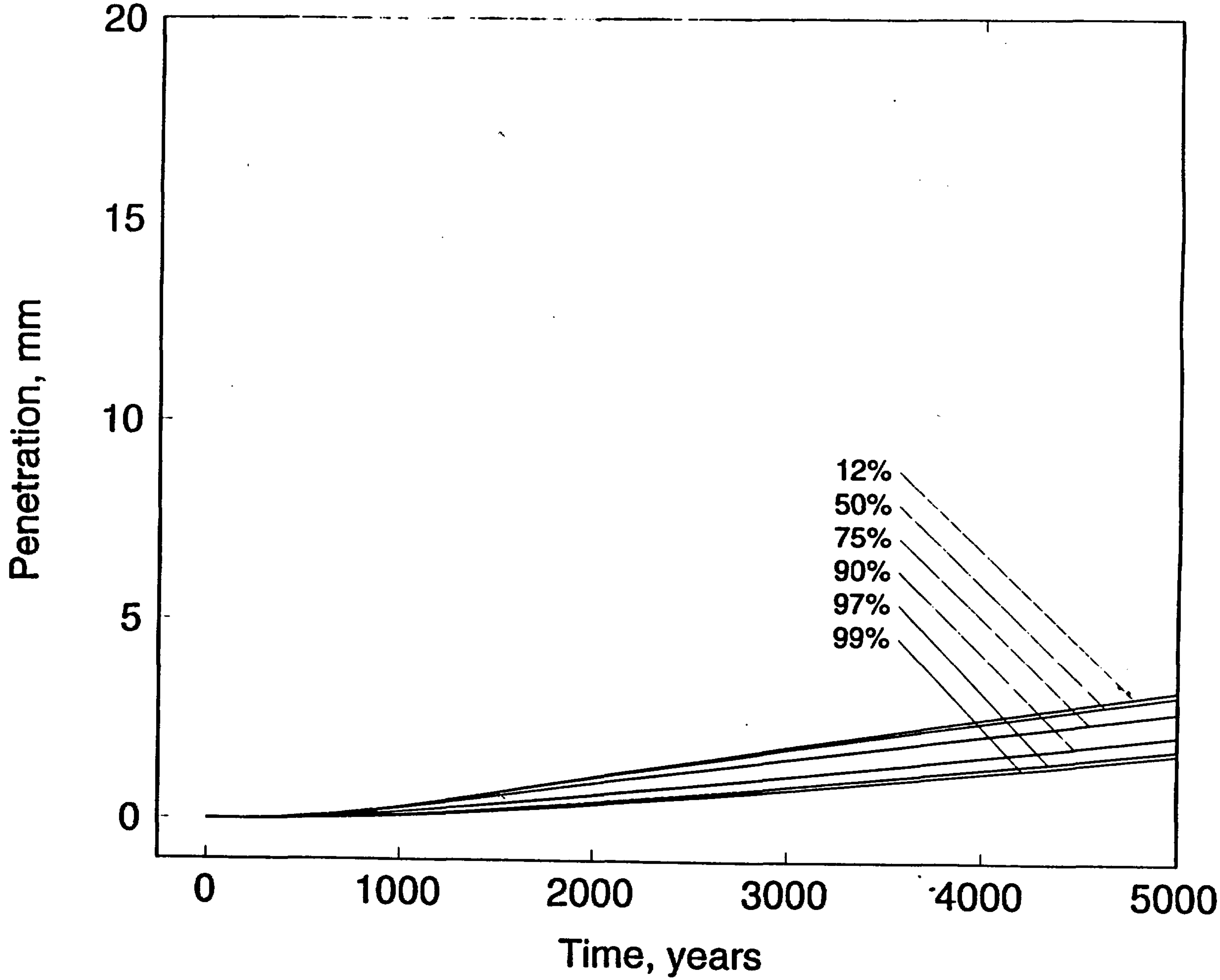
Calculated Relative Humidity at Waste Package Surface as a Function of Time for 13.7 kg U/m^2 (55.3 MTU/acre)



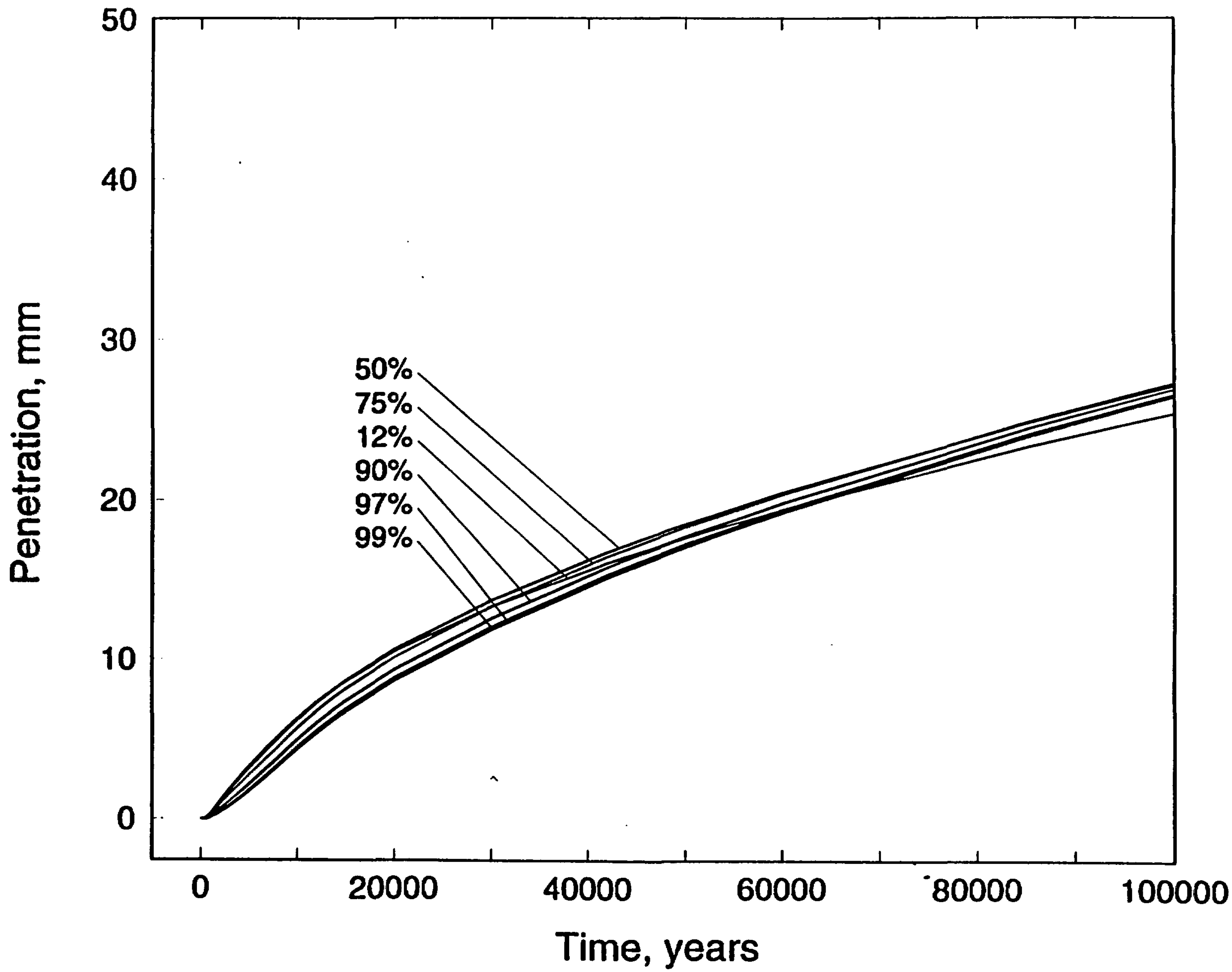
Calculated Relative Humidity at Waste Package Surface as a Function of Time for 27.3 kg U/m^2 (110.5 MTU/acre)



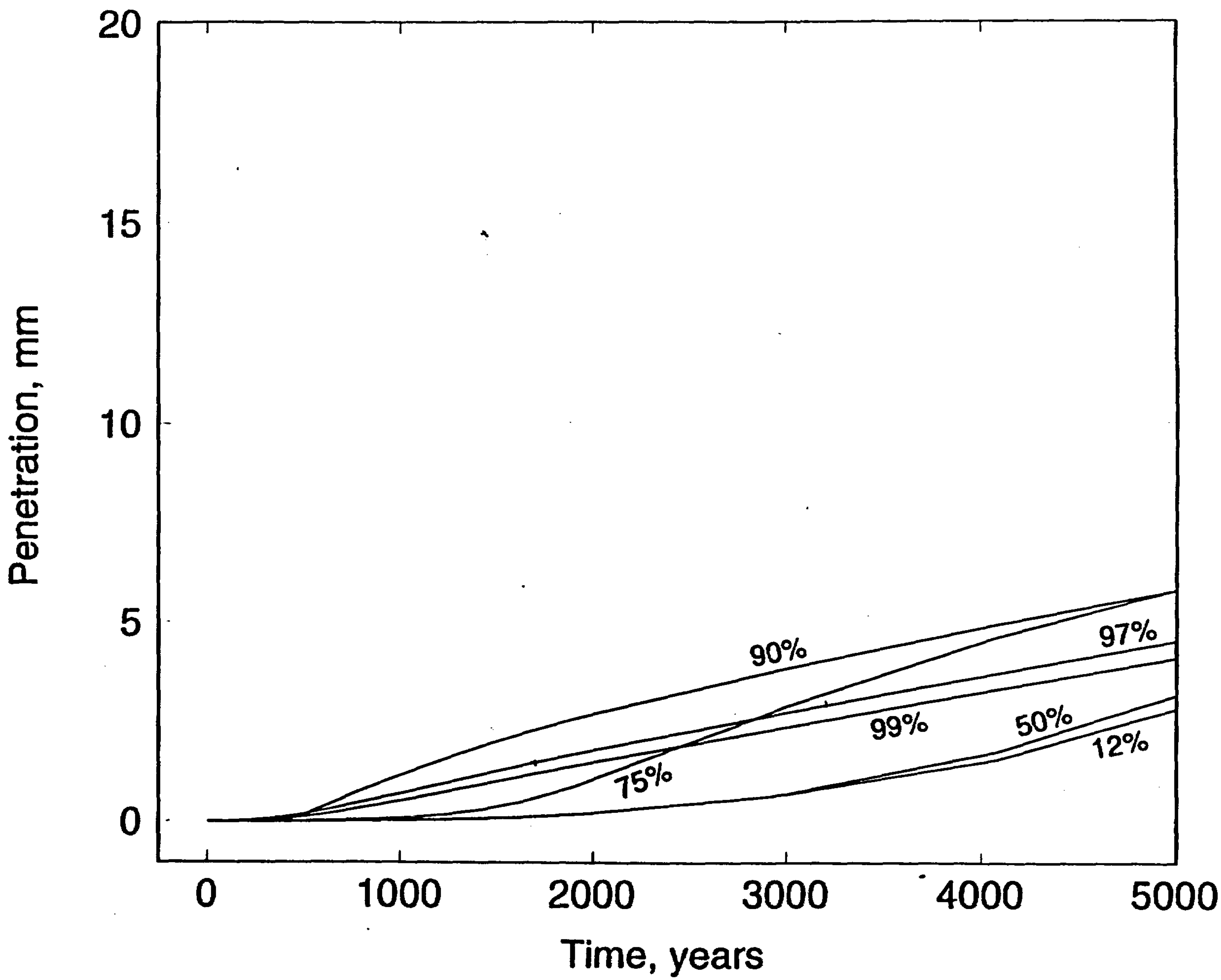
Calculated Relative Humidity at Waste Package Surface as a Function of Time for 27.3 kg U/m^2 (110.5 MTU/acre)



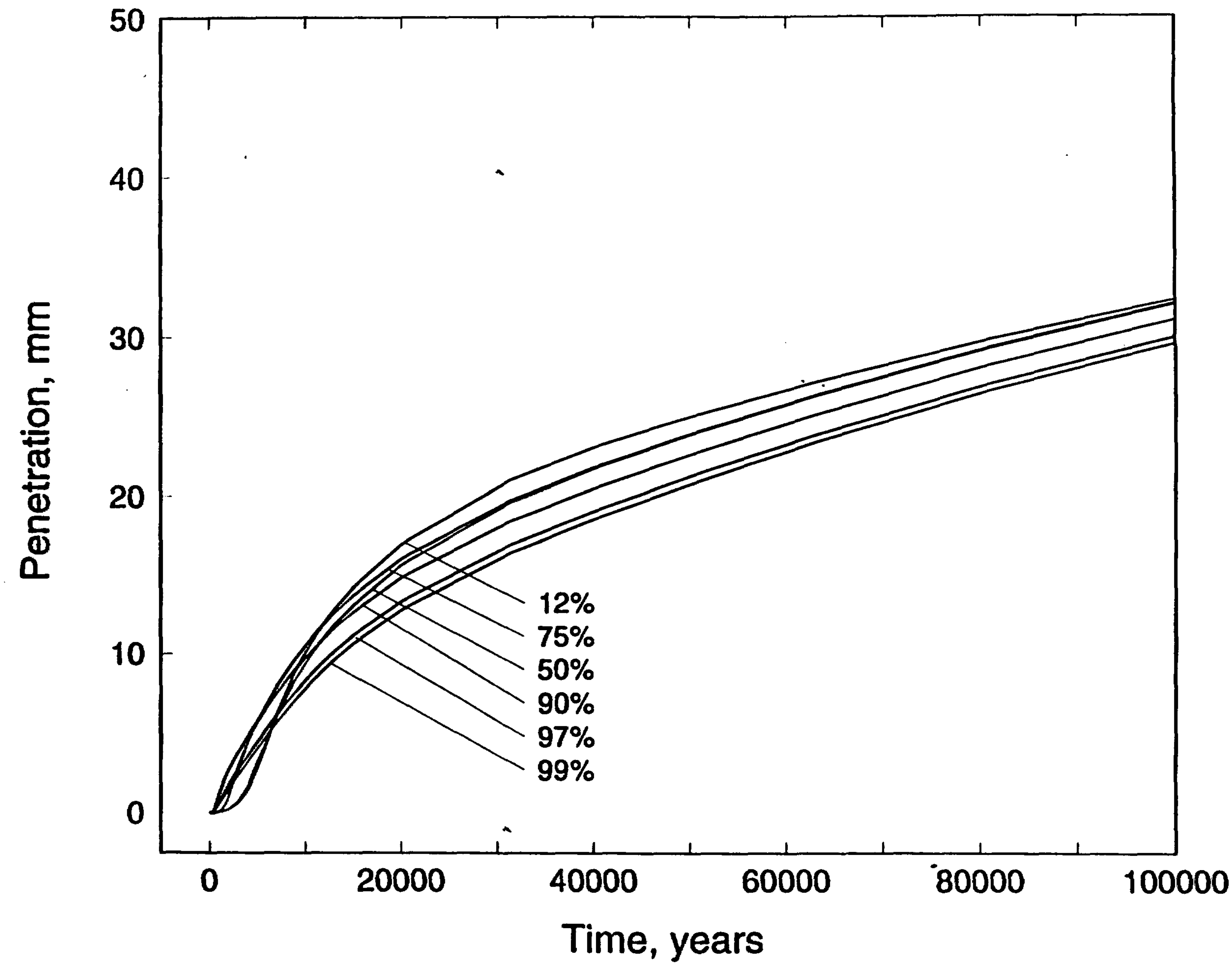
Calculated Depth of Penetration as a Function of Time for 6.0 kg U/m^2 (24.2 MTU/acre) for Various Percentages of Repository Area



Calculated Depth of Penetration as a Function of Time for 6.0 kg U/m^2 (24.2 MTU/acre) for Various Percentages of Repository Area



Calculated Depth of Penetration as a Function of Time for 13.7 kg U/m^2 (55.3 MTU/acre) for Various Percentages of Repository Area



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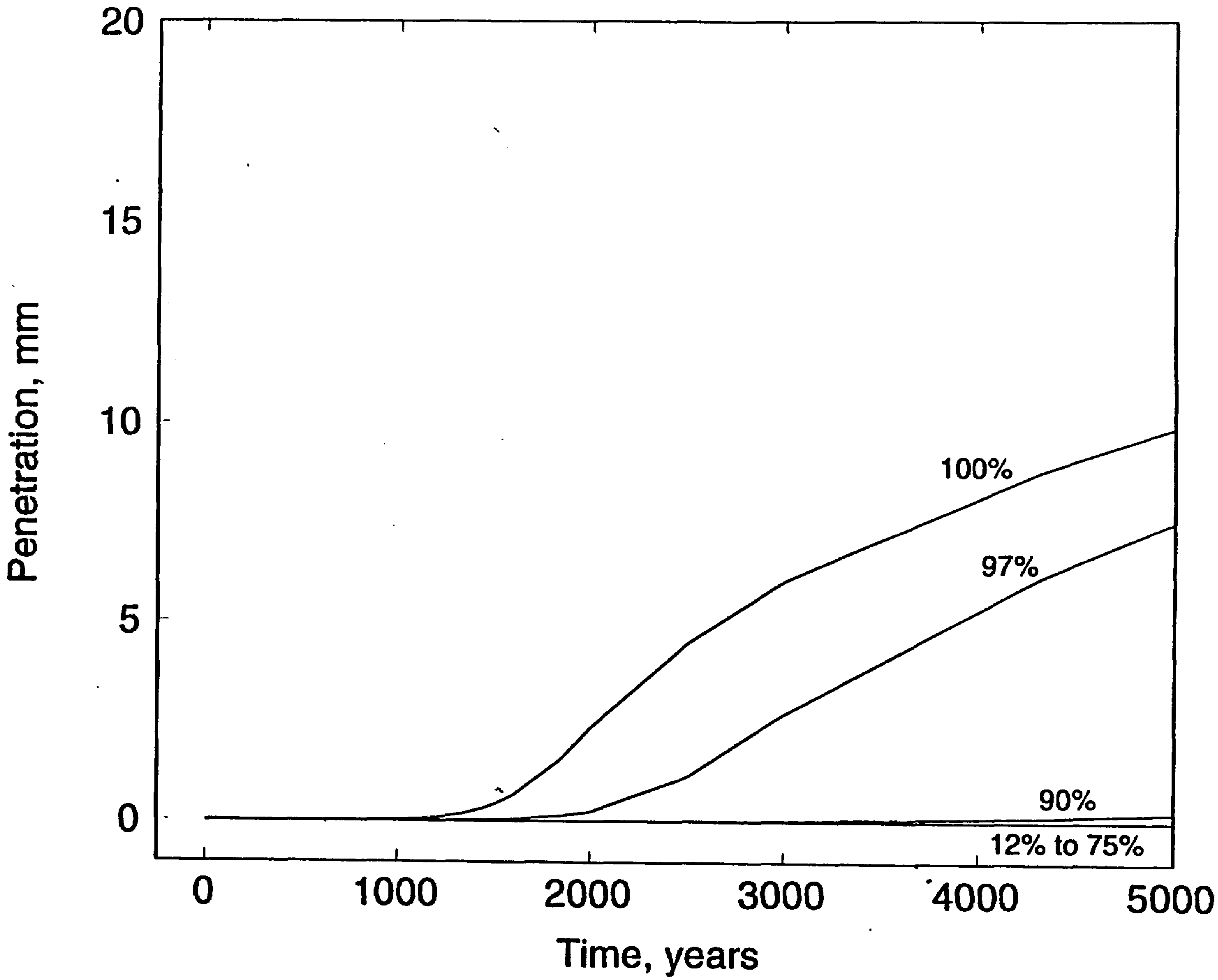
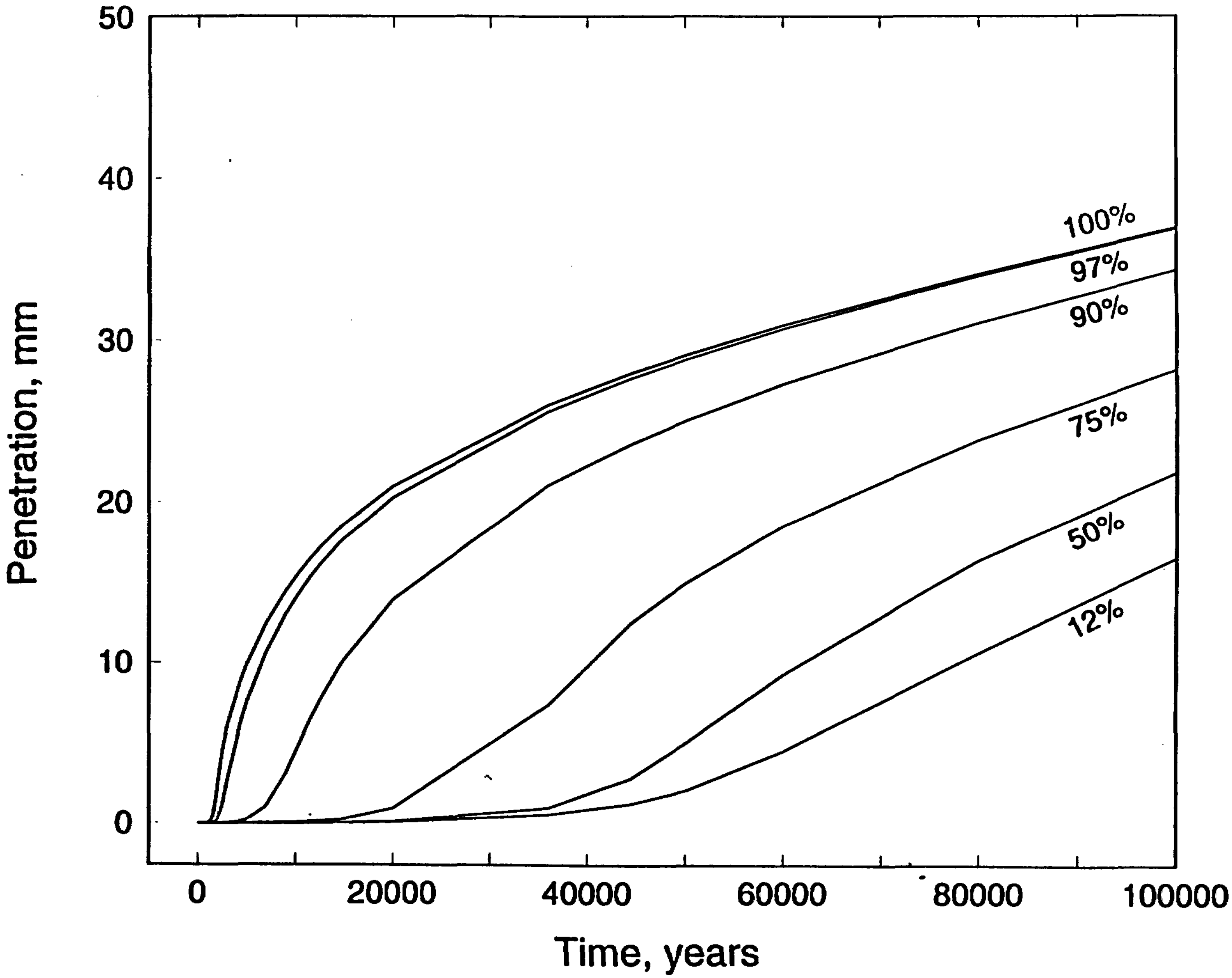


Calculated Depth of Penetration as a Function of Time for 27.3 kg U/m^2 (110.5 MTU/acre) for Various Percentages of Repository Area



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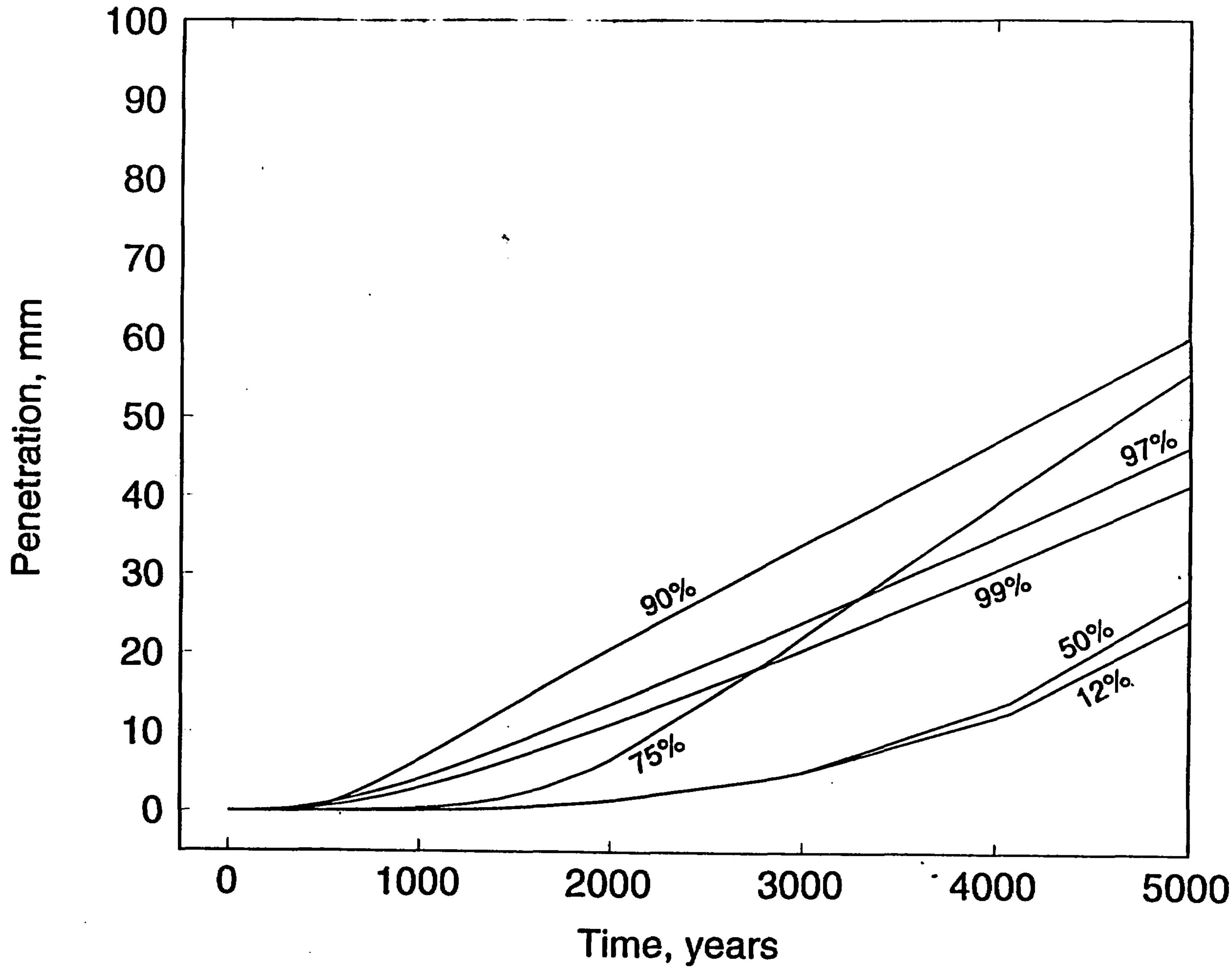
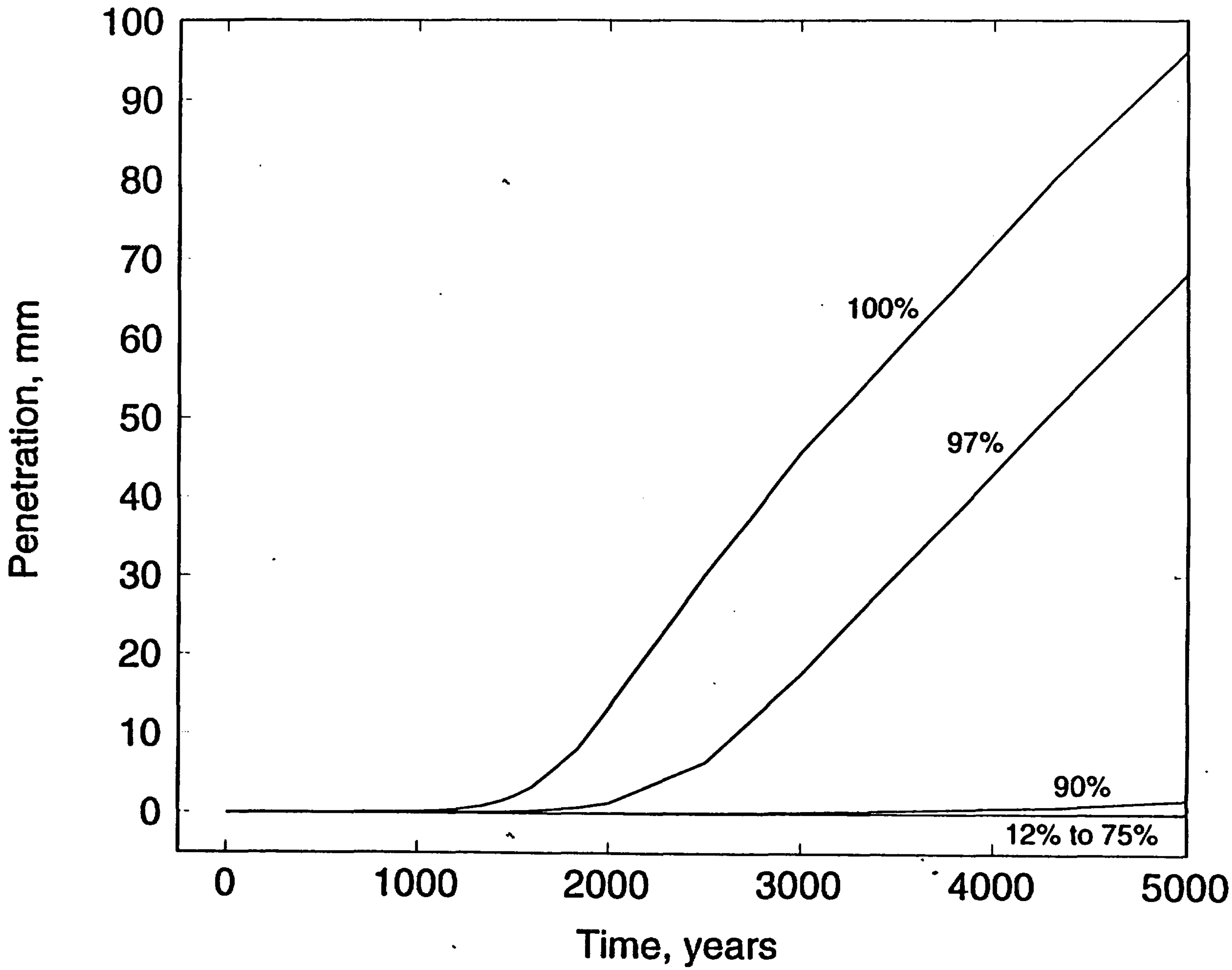


Calculated Depth of Penetration as a Function of Time for 13.7 kg U/m^2 (55.3 MTU/acre) for Moderate Loss of Protectiveness (c = 0.75)



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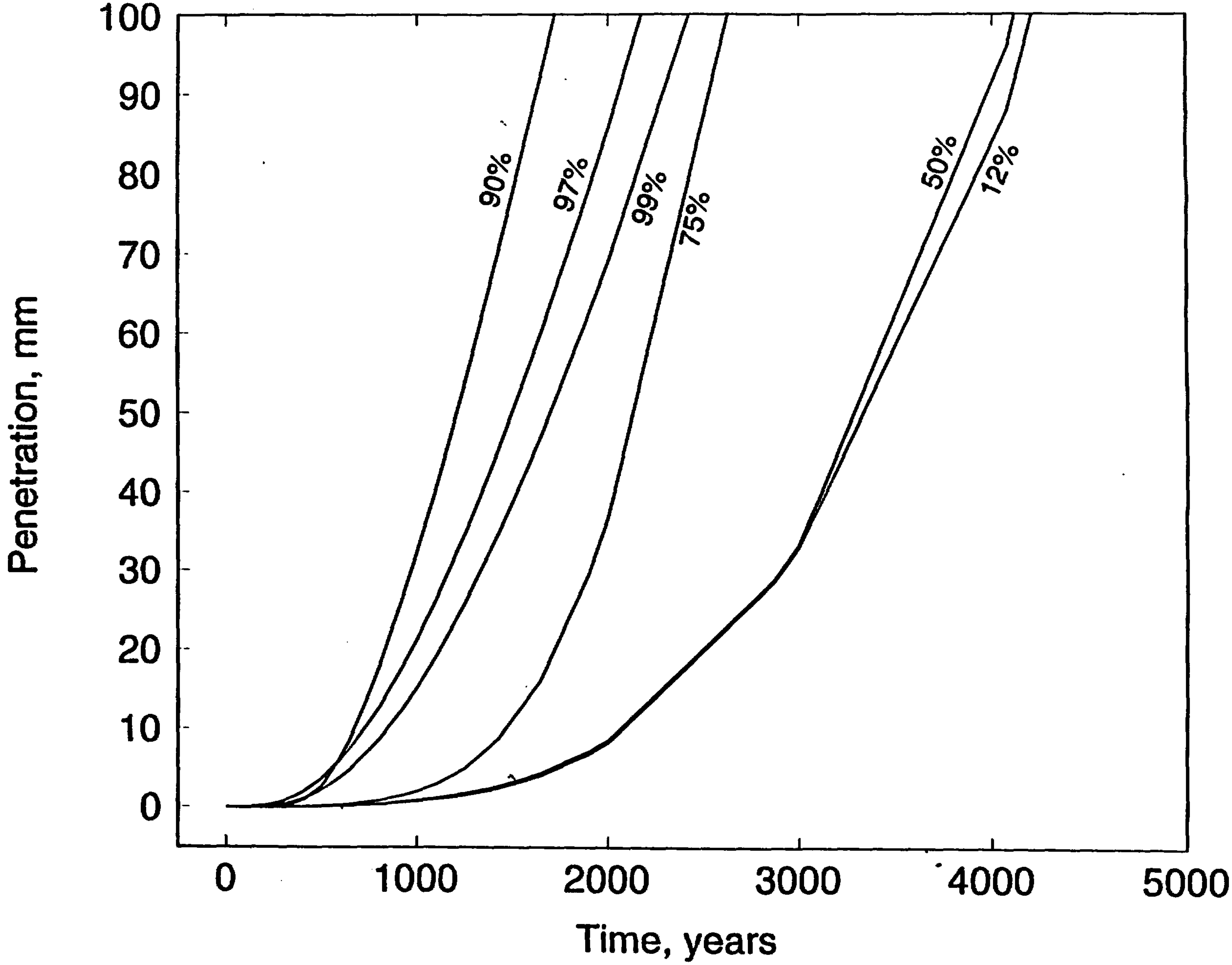
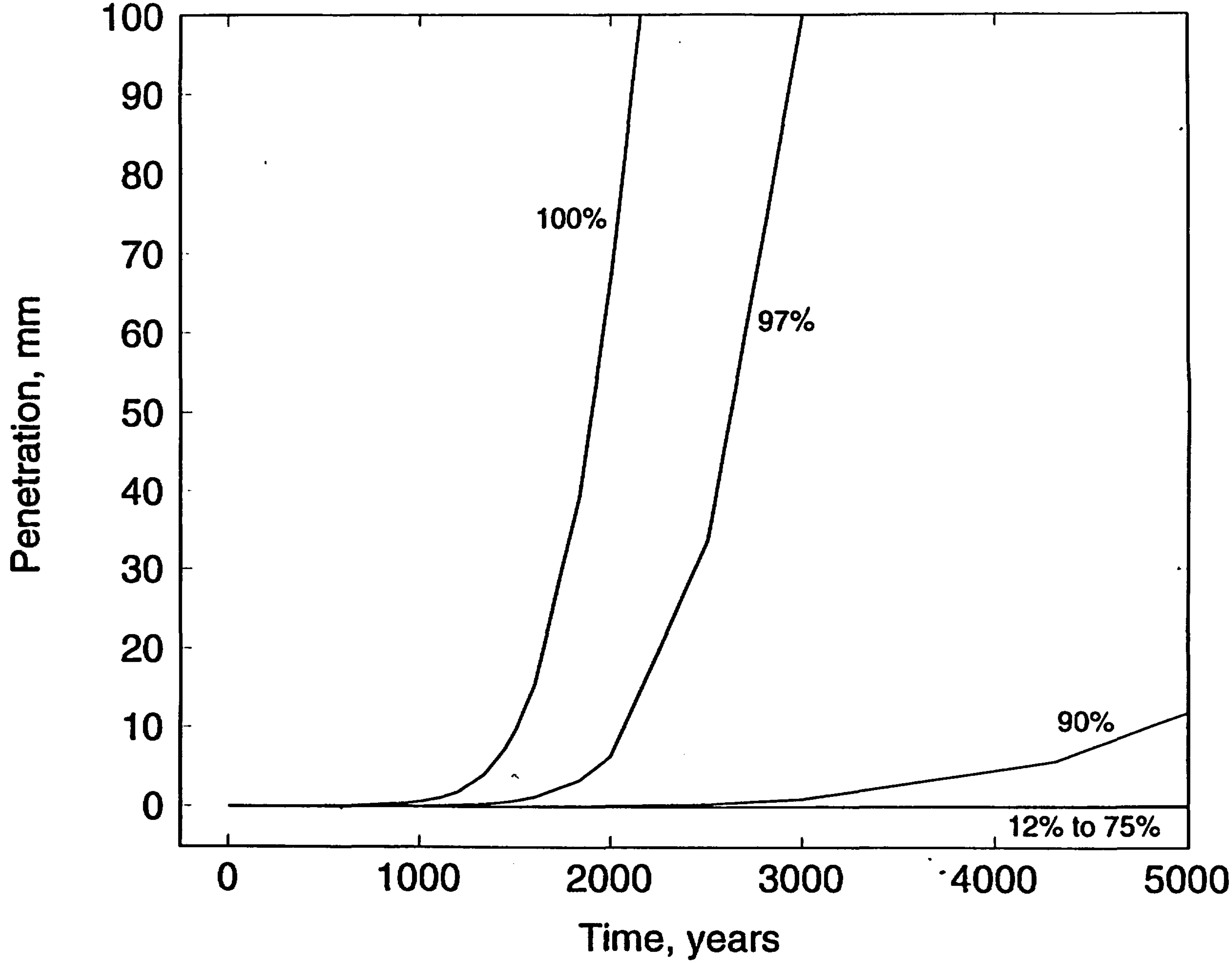


Calculated Depth of Penetration as a Function of Time for 13.7 kg U/m^2 (55.3 MTU/acre) for Complete Loss of Protectiveness (c = 1.00)



Calculated Depth of Penetration as a Function of Time for 27.3 kg U/m^2 (110.5 MTU/acre) for Complete Loss of Protectiveness (c = 1.00)

Table I. Containment lifetime in years for a waste package with a 100 mm wall for various mass loadings and time exponents *c*. Effects of MIC are not considered.

Mass Loading, kgU/m²	$c = 0.47$		$c = 0.75$		$c = 1.00$	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
6.0	> 100000	> 100000	12000	16000	2900	4400
13.7	> 100000	> 100000	7900	10000	1700	4200
27.3	> 100000	> 100000	5200	65000	2200	36000

Table II. Containment lifetime in years for a waste package with a 100 mm wall for various mass loadings and MIC factors. The time exponent *c* is taken to be 0.47.

Mass Loading, kgU/m²	MIC factor = 4		MIC factor = 10		MIC factor = 100	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
6.0	86000	97000	18000	24000	1900	3500
13.7	50000	72000	9300	14000	920	3400
27.3	33000	> 100000	5100	78000	1700	41000

Conclusions

- Simple kinetic equations were utilized to determine the depth of penetration for the corrosion-allowance barrier.
- For the case where the oxide film is protective (time exponent is about one-half), the <u>full range</u> of thermal loads will yield depths of penetration which are less than the proposed thickness of the outer container (100 mm) and lifetimes of many tens of thousands of years.
- For low and intermediate thermal loads, if the time exponent is higher, if MIC or pitting is active, or the pH drops, the minimum barrier lifetime is on the order of a few thousand years.
- For the high thermal load, the depth of penetration does not exceed the container thickness for tens of thousands of years, except for the extreme edge of the repository. This yields very long barrier lifetimes.

Demonstrating Compliance with the SCC Requirement

PRESENTED TO
DOE-NRC Technical Exchange

PRESENTED BY
Dr. David Stahl
Manager
Waste Package Materials & Performance Analysis
M&O/Las Vegas, Nevada

December 7, 1994

Outline

- Background
- Current Approach
- Status of SCA Open Items
- Supplemental Response to Comment 80
- Supplemental Response to Question 47
- Supplemental Response to Question 35
- Summary

Background

- 10 CFR 60.113(a)(1)(ii)(A)

  "Containment of HLW within the waste packages will be substantially complete for a period to be determined by the Commission taking into account the factors specified in 60.113(b) provided, that such period shall not be less than 300 years nor more than 1,000 years after permanent closure of the geologic repository;"

- NRC Staff Position 60-001

  "The requirement in 10 CFR 60.113(a)(1)(ii)(A) for substantially complete containment of high-level waste ... is a minimum performance requirement which is not intended, and should not be interpreted, as a cap on the waste package lifetime or a limitation on the credit that can be taken (in engineered barrier system and overall repository system performance assessments) if the waste package is designed to provide containment in excess of 1,000 years."

Background
(Continued)

- Issue Resolution Working Group established to address SCC
- New goal for waste package performance developed that meets the intent of SCC
- Technical Exchange held with the NRC on the current direction of waste package designs and position on SCC
- Responses to open SCA items transmitted to the NRC

Current Approach

- The focus of the new design concepts is on containment and the integrity of the waste package during the containment period, which is consistent with the NRC SCA comments

- A specific containment performance goal has been developed to guide the design effort

- The revised performance goal is a waste package design with a mean lifetime well in excess of 1,000 years

- This is reflected in the barrier performance assumption that the fraction of container failures in 1,000 years will be less than 1% [ln]

Current Approach
(Continued)

- Current design concepts are based on double-walled waste packages

- Emphasis is on corrosion-resistant inner container and a thick-walled, corrosion-allowance outer container which provide confidence that the performance goal and the SCC requirement will be met

- The M&O design effort, materials evaluations and environmental studies conducted by LLNL, fabrication studies, performance analyses, and performance assessments are directed toward achieving a long-lived waste package that will demonstrate that the SCC requirement has been met

Current Approach
(Continued)

- For corrosion-resistant materials, the dominant degradation mode is localized corrosion

  - Initiation is usually a random process
  - Performance prediction is difficult
  - Rates are usually rapid after the process is initiated
  - Degradation mode surveys have been performed for the six candidate alloys plus titanium alloys

- For corrosion-allowance materials, the dominant degradation mode is general corrosion (atmospheric and aqueous)

  - Permits performance prediction
  - Rates are usually parabolic (protective)
  - Some rates are linear (non-protective)
  - Degradation mode surveys have been performed for copper-based alloys and for iron-based materials

Status of NRC SCA Open Items
Related to Substantially Complete Containment

Open Item	Description	Action	Status
Comment 5	Technological limitations and uncertainties and the impact on demonstration of compliance with 60.113	Supple-mental response provided	Resolved

Status of NRC SCA Open Items Related to Substantially Complete Containment
(Continued)

Open Item	Description	Action	Status
Comment 80	DOE performance goals were inconsistent among themselves and intent of the SCC requirement	Supplemental response provided	Resolved
	Potential inconsistency exists between new DOE performance goal and the SCC requirement	Supplemental response provided	Open

Status of NRC SCA Open Items Related to Substantially Complete Containment
(Continued)

Open Item	Description	Action	Status
Question 46	Release of isotopes with long half-lives controlled at a stricter standard during the containment period Note: concerns for releases of radionuclides better addressed in response to Comment 80	Supplemental response provided	Resolved -see note

Status of NRC SCA Open Items Related to Substantially Complete Containment
(Continued)

Open Item	Description	Action	Status
Question 47	Relation of container failure to compliance demonstration and definition of failure	Supple-mental response provided	Open
Question 35	Basis for helium leak test acceptance criteria	Supple-mental response provided	Open

Supplemental Responses to Comment 80

- Has DOE allowed for waste package failure mechanisms in the containment period other than those discussed in NUREG-0804 when the SCC requirement was promulgated?

  - DOE is considering a variety of failure mechanisms. These include:

    * Oxidation, general and localized corrosion, stress corrosion cracking, hydrogen attack, galvanic attack, microbiologically-influenced corrosion, as well as mechanical failures due to rock fall and tectonic events

    * The activities that evaluate these failure mechanisms have been described in the Waste Package Implementation Plan, the Metallic Barrier Scientific Investigation Plan, and the Study Plan on Waste Package Rupture due to Tectonic Processes and Events

Supplemental Responses to Comment 80
(Continued)

- What are DOE's plans concerning a comparative analysis of the alternatives to the major design features of waste packages that would provide greater containment during the containment period?
  - The DOE has developed a plan for the development of alternate metallic barriers and non-metallic barriers that would provide enhanced waste isolation
  - The non-metallic barrier effort produced an assessment of industrial capability in FY 94. However, this effort is unfunded in FY 95.
  - The comparative analysis of alternatives will be performed utilizing existing codes such as the Yucca Mountain Integrating Model (YMIM) from LLNL and the Repository Integrating Program (RIP) from Golder Associates

Supplemental Responses to Comment 80
(Continued)

- What will be the expected distribution, with respect to time, of these predicted failures and the expected mean waste package lifetime?
  - DOE has determined the failure time for the corrosion-allowance outer container as a function of temperature, relative humidity and time
  - A sensitivity study was also performed that evaluated the affect of pitting and MIC factors and the time exponent
  - Under expected conditions, the failures times greatly exceeded the SCC requirement
  - A similar approach will be applied to the corrosion-resistant barrier when experiment data are available

Supplemental Responses to Comment 80
(Continued)

- What are the expected consequences (in terms of estimated radionuclide releases) of waste package failures that occur during the containment period?

  - A bounding calculation of both gaseous and aqueous releases was performed assuming 1% of the waste packages failed during the containment period

  - For gaseous release of C-14 as carbon dioxide, the fractional release per year was found to be 10% of the controlled release rate limit

  - For aqueous release of the soluble species such as cesium and strontium, the fractional release per year was found to be 2% of the controlled release rate limit

  - Better estimates will be generated when the waste package design is better defined.

Supplemental Responses to Question 47

- What definition of failure will be used with DOE's new performance goal?
  - The same definition of failure will be retained with the new performance goal
  - The DOE intends to use the American National Standards Institute (ANSI) Standards for Radioactive Materials - Leakage Tests on Packages for Shipment, ANSI N 14.5, as the basis for waste package failure

Supplemental Responses to Question 35

- What is the basis for the helium leak test criteria?
  - The DOE provided a response regarding the basis for the helium leak test acceptance criteria.
  - The NRC staff considered the question closed regarding the basis for the acceptance criteria, but open as to whether the criteria are consistent with 10 CFR 60.113.

Supplemental Responses to Question 35
(Continued)

- What are the consequences of this level of leakage in terms of radionuclide release and the demonstration of consistency with the performance requirements for the engineered barrier system?

  - The DOE response addressing this further question was inadvertently left out of the supplemental response.

    * Conservatively assumed that all waste packages leak at the acceptance criteria rate

    * Conservatively assumed that leak is made up of only C-14 as carbon dioxide

    * Calculated release rate of 4.3×10^{-6} per year for small waste packages is well below the 1×10^{-5} per year limit of 10 CFR 60.113 for the post containment period

Summary

- The NRC has agreed, in principle, that the new DOE performance goal is an acceptable approach to demonstrating compliance with the SCC requirement

- The DOE has provided supplemental responses to SCA open items related to SCC

- The waste package design and material testing programs will provide the information required for demonstrating compliance with the SCC requirement

SCC AND WASTE PACKAGE DESIGN TECHNICAL EXCHANGE

NRC/CNWRA TECHNICAL PROGRAM

Presented at
Two White Flint North
December 7, 1994

by

CNWRA Participants

P. Nair
N. Sridhar

SCC AND WASTE PACKAGE DESIGN TECHNICAL EXCHANGE

- **TOPICS OF REVIEW**
  - SCC Technical Activities
  - Modeling for Containment
  - Testing and Research Program

SUBSTANTIALLY COMPLETE CONTAINMENT EXAMPLE PROBLEM

- Thermal Loading Effects Are Assumed To Be Dominated by Heat Conduction
- Conceptual Model for Waste Package Environment Considering the Effect of Water Evaporation, Diffusive Transport of Vapor, and Dripping of Liquid Water on Container Surface
- Corrosion Potential and Critical Potentials for Specific, Localized Corrosion Processes as Key Parameters for Modeling of Container Corrosion
- Consideration of Mechanical Failure Processes (simplified buckling, yield and fracture models)

ENGINEERING EXPERIENCE ON RELIABILITY OF COMPONENTS APPLICABLE TO DESIGN, FABRICATION, AND PERFORMANCE OF HLW CONTAINERS

- What Levels of Reliability Can Be Expected for Fabricated Components Involved in Critical Operations, and, therefore, for a WP Component?

- What Design Processes and Quality Control Procedures Can Be Implemented to Attain the Reliability Required for Meeting Performance Requirements With Reasonable Assurance?

RELIABILITY OF FUEL RODS

Country	Reliability	Remarks
United States	99.2% (1970) 99.97% (1985–89)	Improved with time Leveled off recently
Japan	99.999% (1984–90)	Similar to U.S. in recent years
Europe		
• Belgonucleaire	99.992%	–
• Fragema	99.994% (1983) 99.998% (1986–90)	Improved with time Leveled off recently
• CEGB	99.88% (up to 1973)	Six-fold failure reduction for 1982–85 w.r.t. pre-1982

ENGINEERING EXPERIENCES REPORT SUMMARY

- Well Documented Information Directly Applicable to WP Design and Fabrication Is Limited

- For Fuel Rods and Pressure Vessels

  - Reliability Improvements Have Been Incorporated Into Design and Fabrication of Specific Components through Operational Experience

  - Reliability Has Increased, and Eventually Leveled Off, through Identification of Degradation Processes, Improvement of Design and Fabrication Methods, Followed By Development of Standards and Appropriate Inspection Procedures

- For Buried Structures

  - No Adequate or Sufficient Data Exist To Assign Reliability Values

ENGINEERING EXPERIENCES REPORT SUMMARY (CONT'D)

- Highly Reliable Components Can Be Designed and Fabricated
  - Accurate Prediction of Failure Mechanisms
  - Ability to Relate Design and Manufacturing Parameters to the Potential Failure Mechanisms
  - Ability to Control Design and Manufacture Parameters to Provide Adequate Life

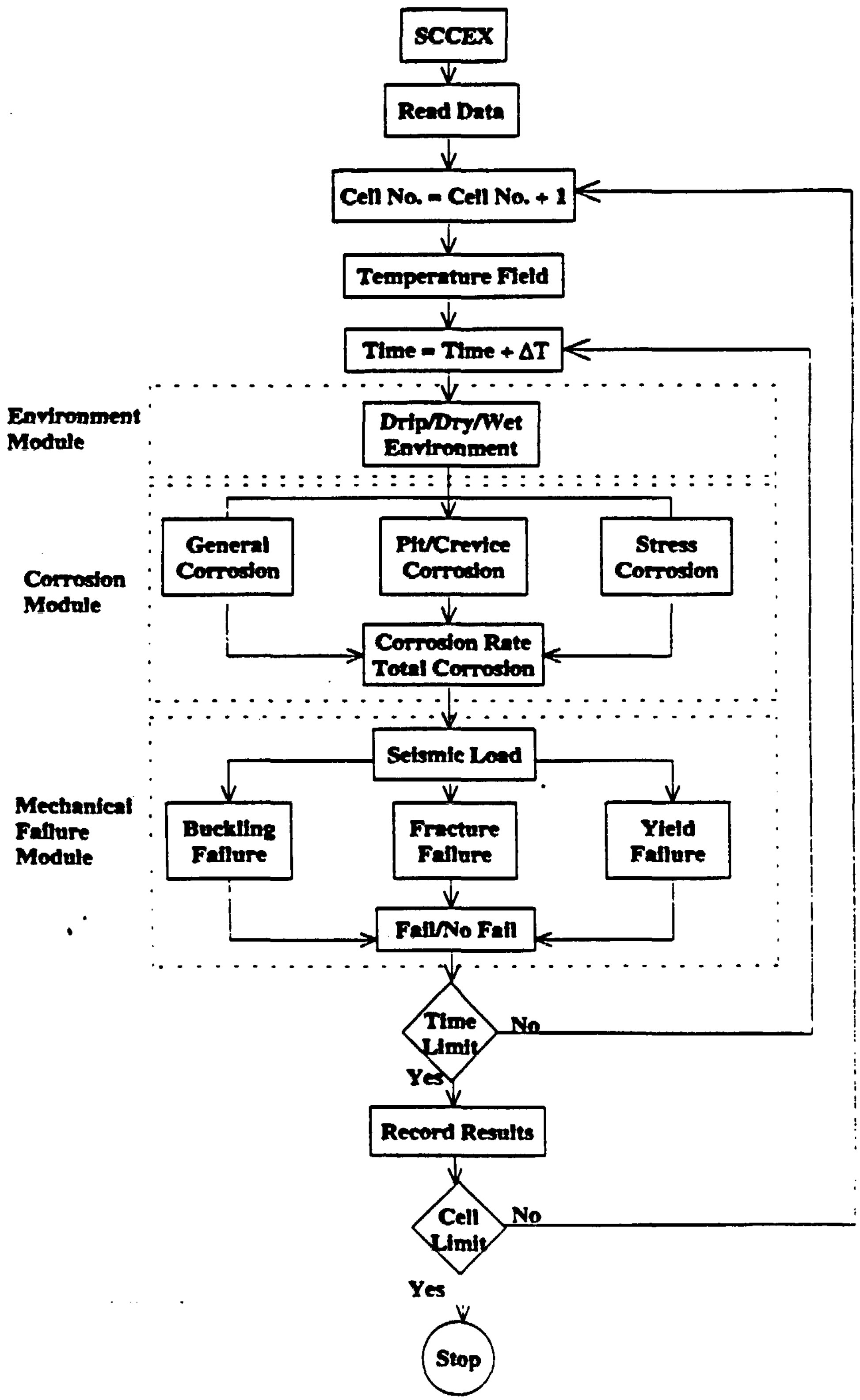
BASELINE PARAMETERS FOR DETERMINISTIC ANALYSIS

- SCP Design: Vertical Emplacement in Borehole with Air Gap (No Backfill)
- Container Material: Type 304L SS
- Thermal Loading: 57 kW/acre (4.4×10^8 J/m^2/yr)
- Spent Fuel: 70,000 MTU (60% PWR and 40% BWR); 2.3 MTU per container
- Standard Burn-Ups: 33,000 MWd/MTU for PWR and 27,500 MWd/MTU for BWR
- Fuel Age: 10 yr
- Simulation Time: 1,000 yr

SCOPE OF DETERMINISTIC ANALYSIS

- Parametric Study of Thermal Power Density
- Parametric Study of Other Input Parameters (16 Thermo-Environmental Parameters and 9 Corrosion-Related Parameters)
- Alternative Material/Environment Cases (Type 304L SS [Reference], Alloy 825 and Materials, X, Y, and Z)

SCCEX CODE STRUCTURE



SUMMARY OF EXAMPLE PROBLEM TEST CASES

Cases	Objective	Material	Environment	Deterministic Analysis	Probabilistic Analysis
Baseline	Reference material. Uncontrolled environment.	Type 304L stainless steel	Uncontrolled Cl^- concentration. High, intermediate and low thermal power density	10-yr fuel age. Parametric study of thermal power density and others	10- to 60-yr fuel age. 100 vectors. CDF and PDF for failure time vectors
Alt-1	Alternative material. Uncontrolled environment.	Alloy 825	Uncontrolled Cl^- concentration. Intermediate thermal power density	10-yr fuel age. Baseline case for input parameters	10- to 60-yr fuel age. 100 vectors. CDF and PDF for failure time vectors
Alt-2	Reference material. Uncontrolled environment.	Type 304L stainless steel	Controlled Cl^- (< 100 ppm) concentration. Intermediate thermal power density	10-yr fuel age. Baseline case for input parameters	10- to 60-yr fuel age. 100 vectors. CDF and PDF for failure time vectors
Alt-3	Alternative material. Controlled environment.	Alloy 825	Controlled Cl^- (< 100 ppm) concentration. Intermediate thermal power density	10-yr fuel age. Baseline case for input parameters	10- to 60-yr fuel age. 100 vectors. CDF and PDF for failure time vectors
Alt-4	Highly designed material. Uncontrolled environment.	X	Uncontrolled Cl^- concentration. Intermediate thermal power density	10-yr fuel age. Baseline case for input parameters	10- to 60-yr fuel age. 100 vectors. CDF and PDF for failure time vectors
Alt-5	Highly designed material. Uncontrolled environment.	Y	Uncontrolled Cl^- concentration. Intermediate thermal power density	10-yr fuel age. Baseline case for input parameters	10- to 60-yr fuel age. 100 vectors. CDF and PDF for failure time vectors
Alt-6	Super designed material. Uncontrolled environment.	Z	Uncontrolled Cl^- concentration. Intermediate thermal power density	10-yr fuel age. Baseline case for input parameters	30-yr fuel age. 100 vectors. CDF and PDF for failure time vectors

Status of NRC/CNWRA Waste Package Research Efforts

Participants

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Presented by

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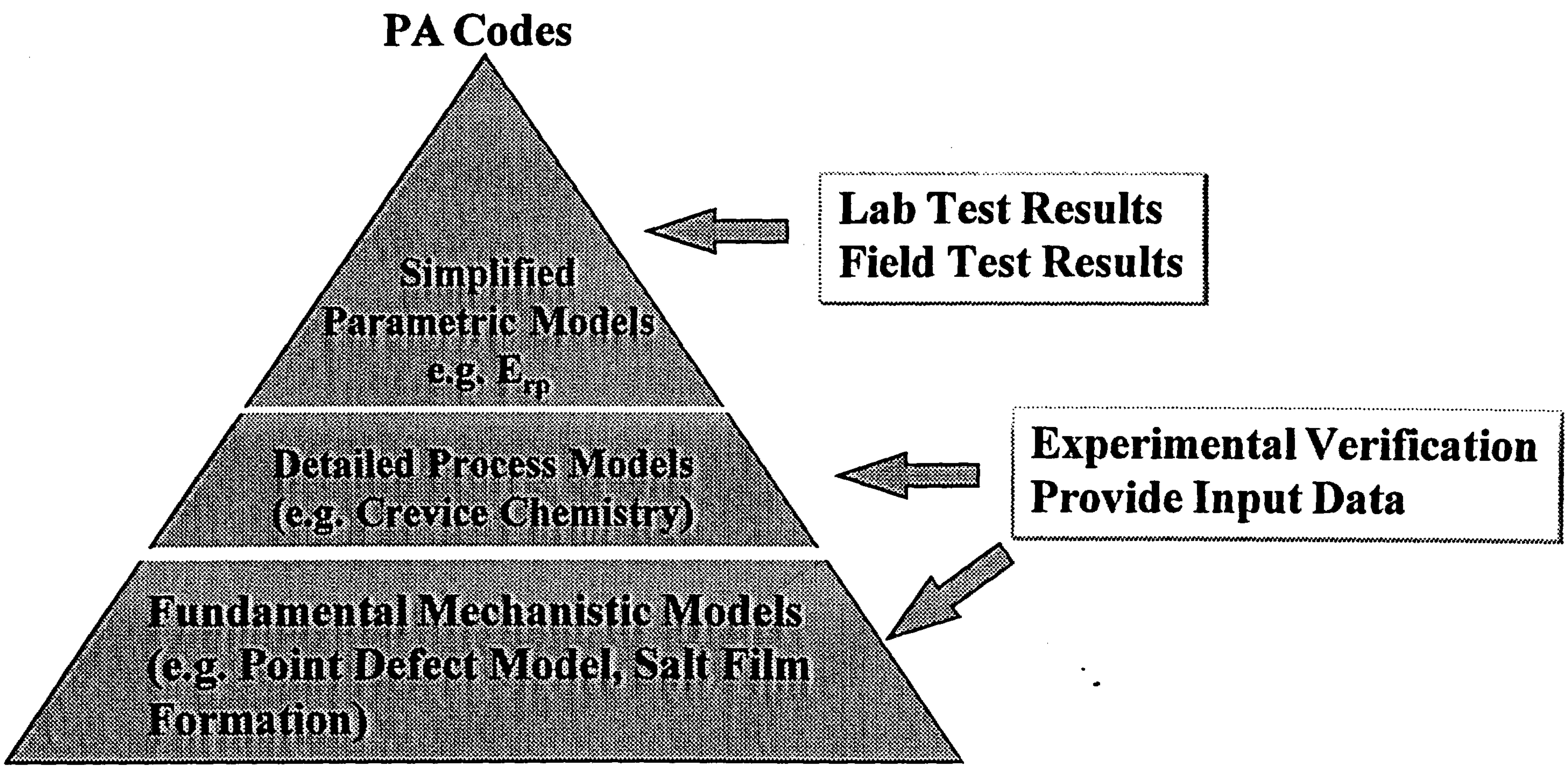
Contents

- **License Application Review Plan**
  - Key Technical Uncertainties
- **Overall Approach to Waste Package Performance Assessment**
- **Specific Areas of Research Activities**
  - Experimental Investigations
  - Model Development
  - Review of ACD Materials and Designs
- **Future Plans**

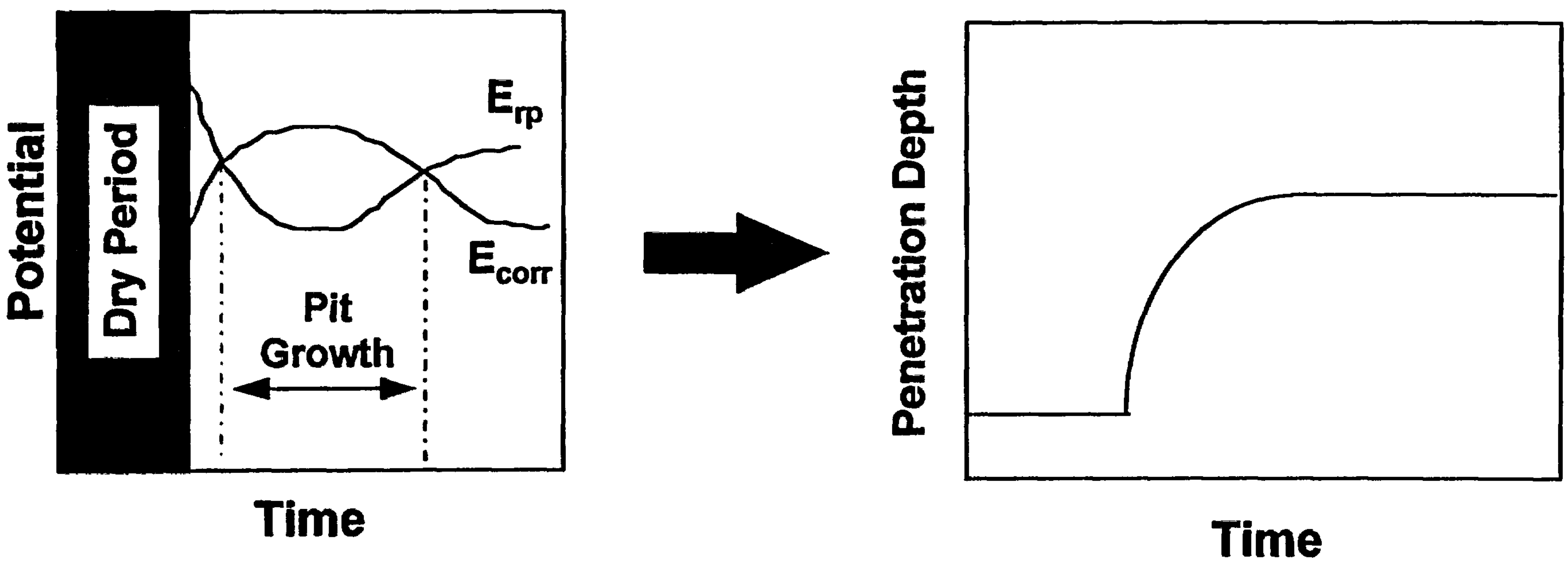
KEY TECHNICAL UNCERTAINTIES

- ❑ Characterizing the chemistry of groundwater in the partially saturated hydrologic zone
- ❑ Prediction of environmental effects on the performance of waste packages and the EBS
- ❑ Extrapolation of short-term test results to predict long-term performance of waste packages and EBS
- ❑ Prediction of thermomechanical effects on the performance of waste packages and the EBS
- ❑ Prediction of release rate parameters (size, shape distribution of penetrations of waste packages)

Overall Approach

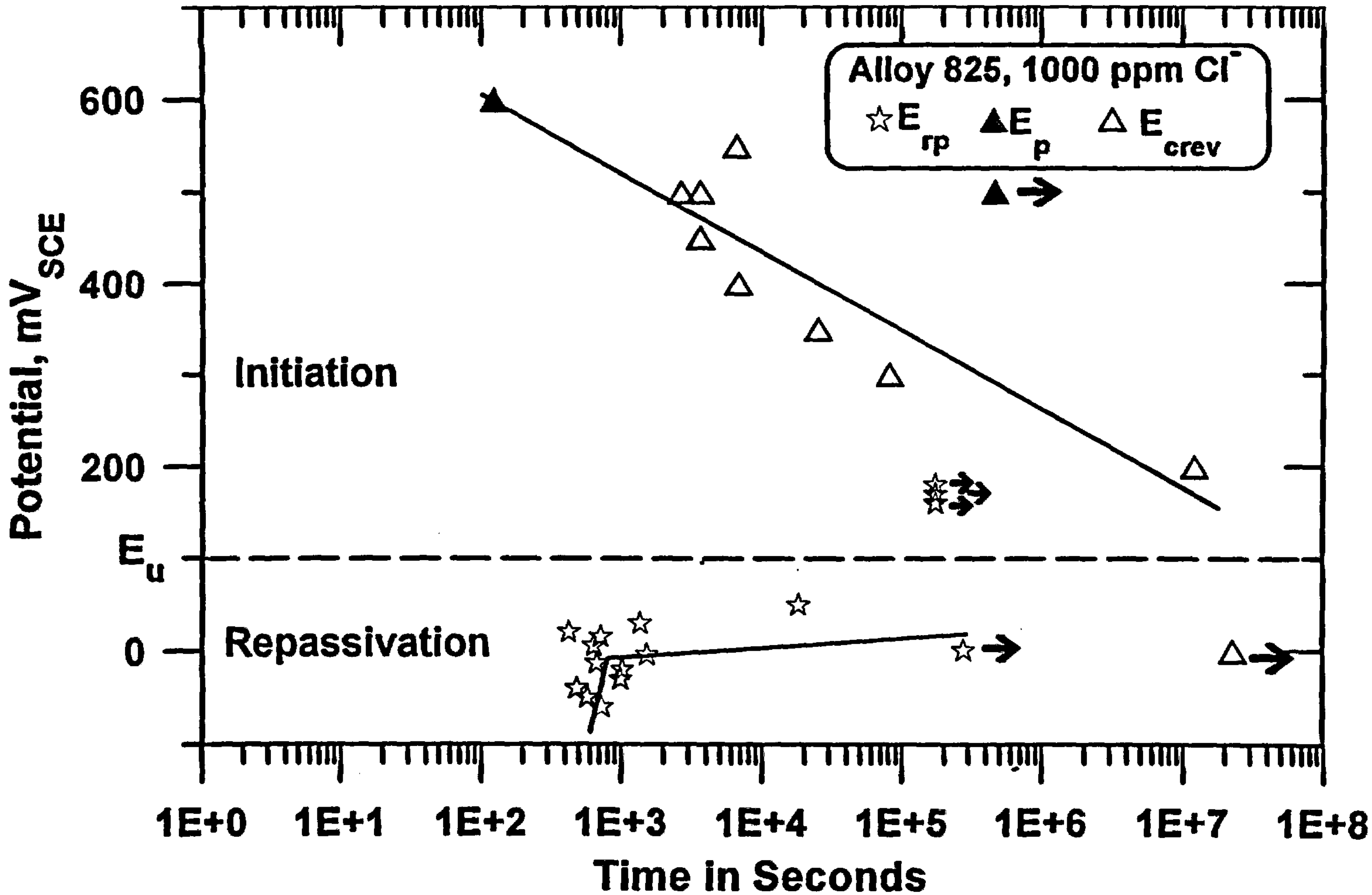


EXTRAPOLATION OF SHORT-TERM DATA

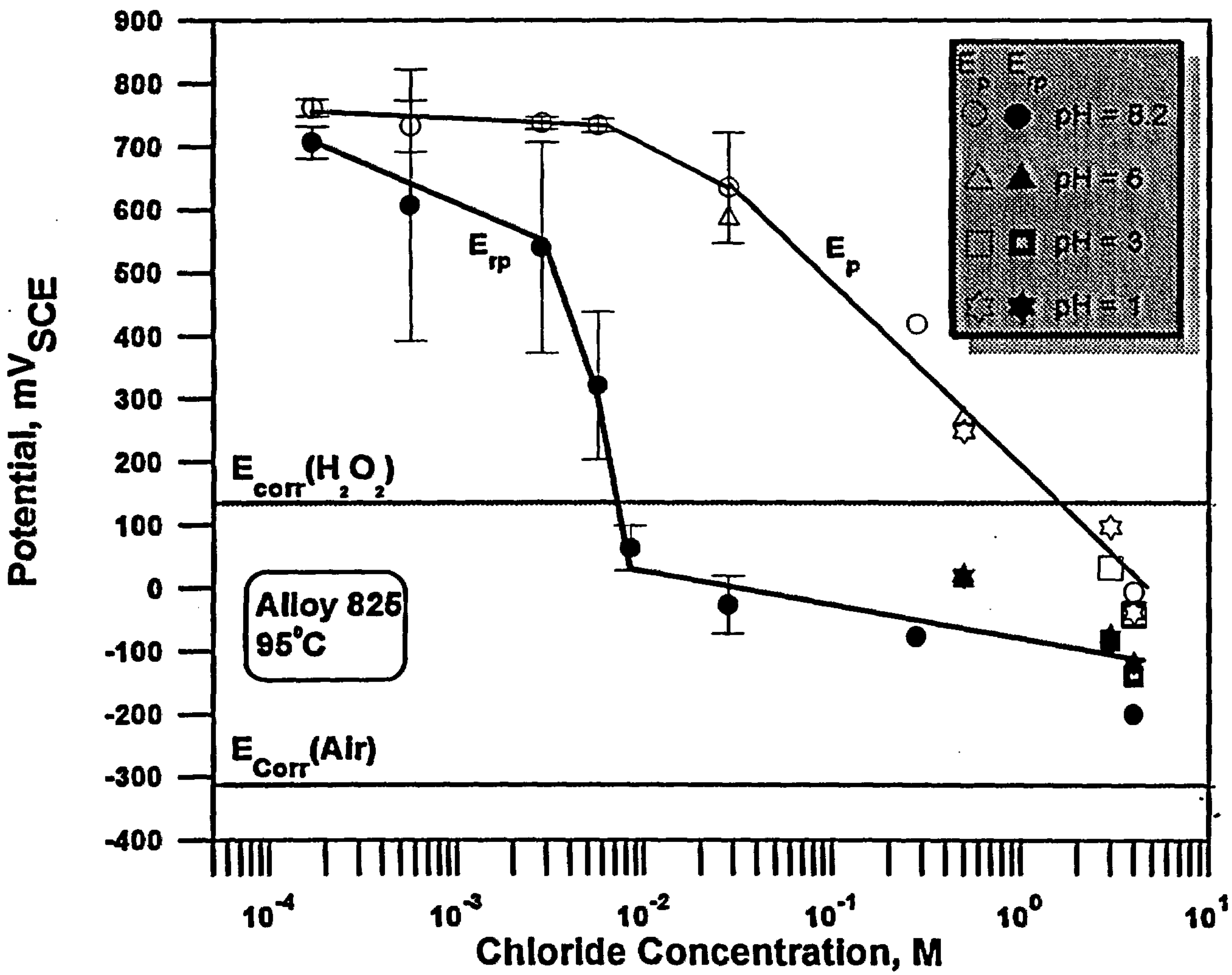


- The approach is flexible - can accommodate design changes, bimetallic containers, and environmental variations
- Both E_{rp} and E_{corr} are amenable to mechanistic interpretation

Extrapolation of Short-Term Data
Repassivation Vs. Initiation

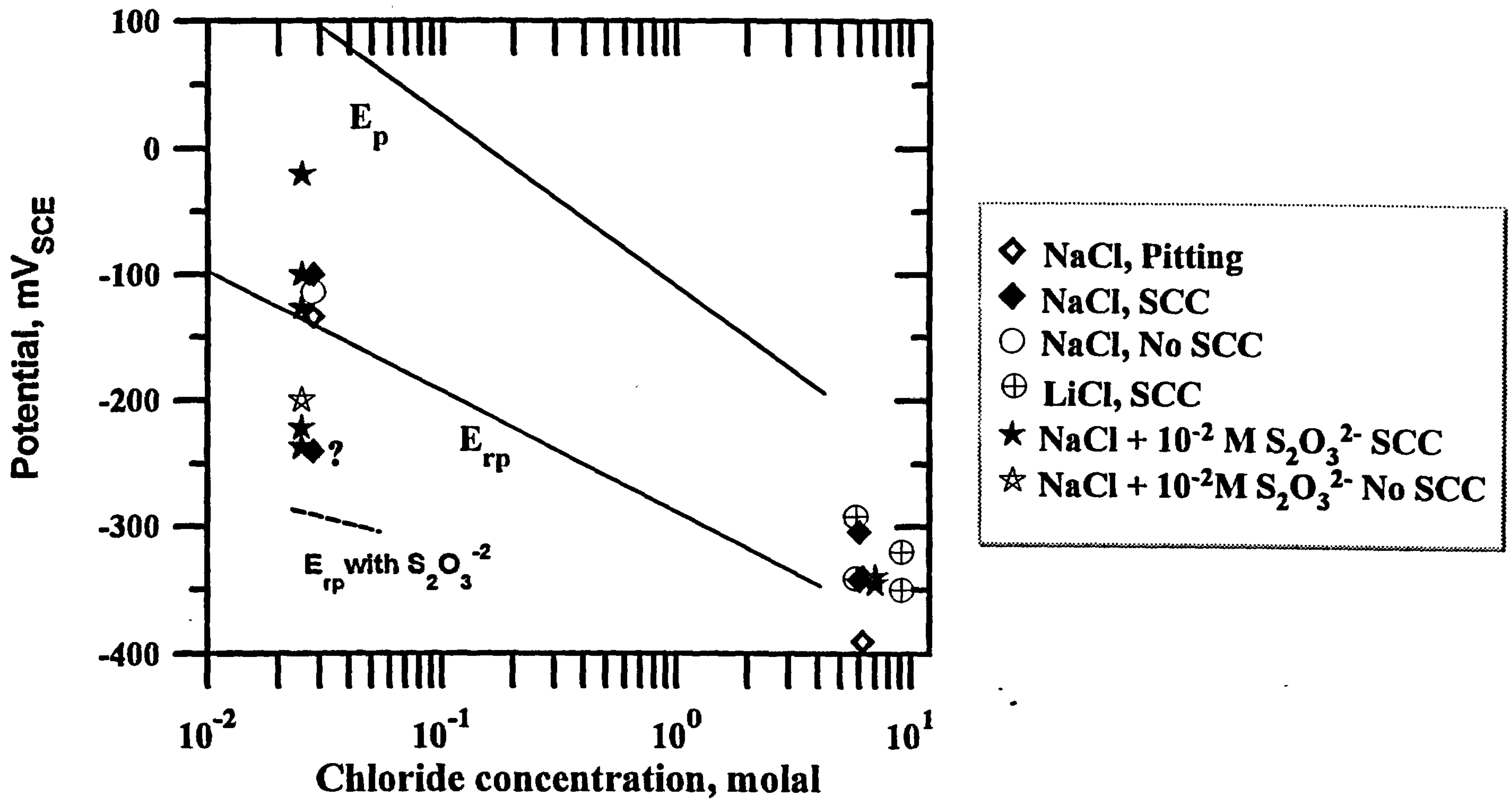


Effect of Environmental Species on Localized Corrosion (Alloy 825)

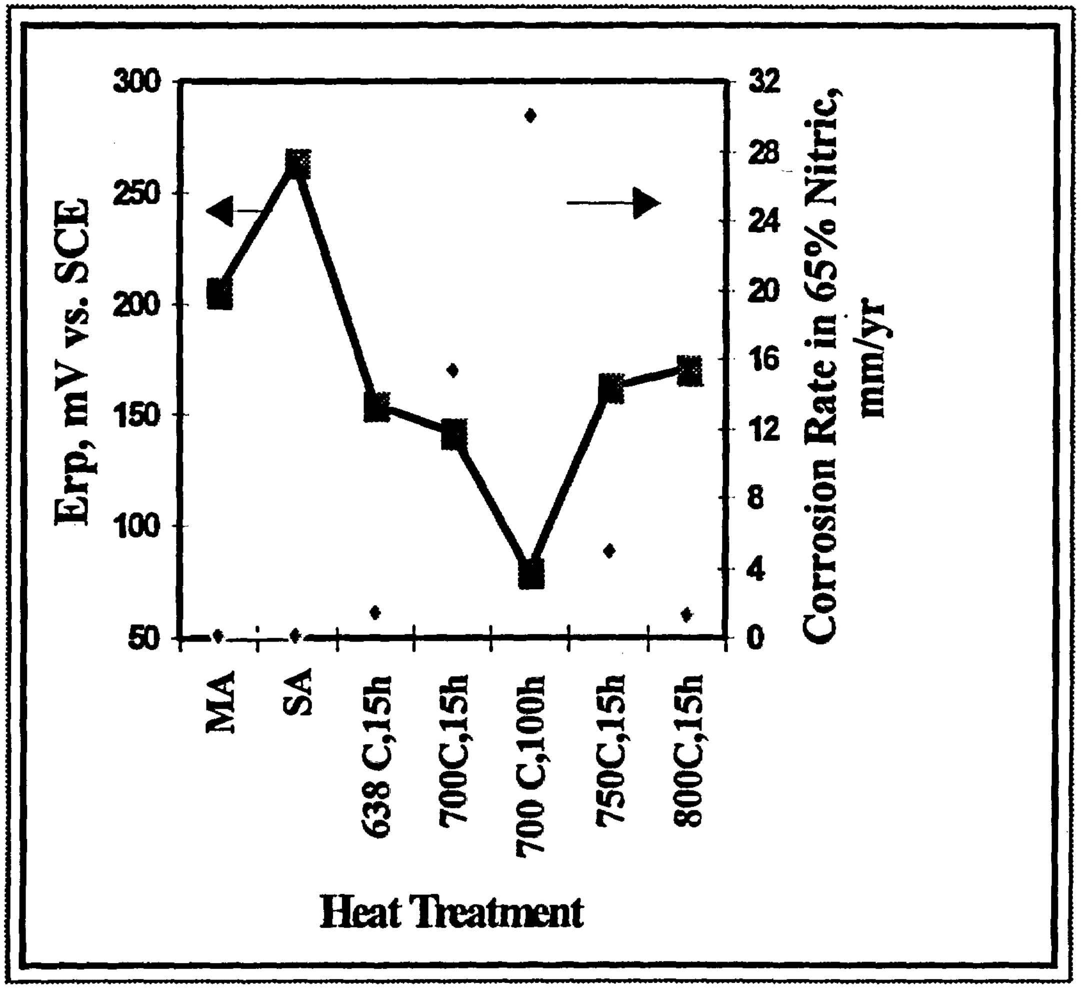


- Chloride is the most detrimental species
- Nitrate inhibits localized corrosion
- Critical potentials are relatively insensitive to pH at high chloride
- Critical potentials decrease with increase in temperature

Use of Repassivation Potential for SCC (316L SS)



Effect of Sensitization on Localized Corrosion of Alloy 825



- Sensitization lowers E_{rp} in 100 ppm chloride solution.
- E_{rp} is more sensitive than ASTM test
- Pitting intergranular for sensitized specimens
- The effect insignificant at higher chloride for IG pitting

Extrapolation of Short-Term Data (Localized Corrosion)

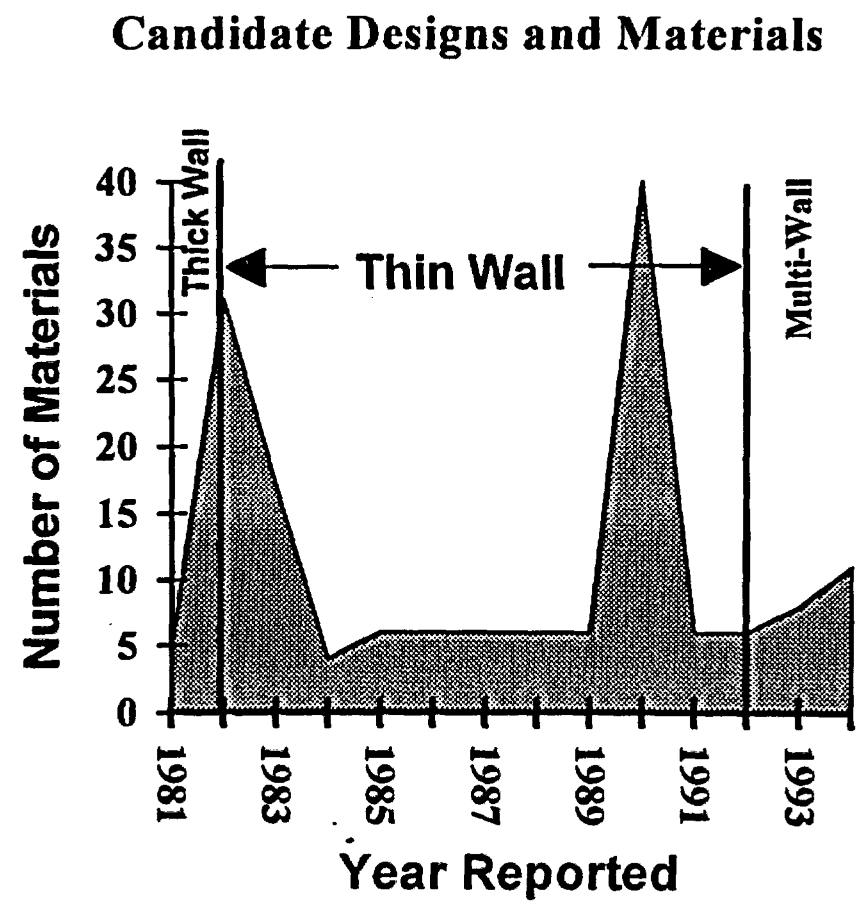
- **Pit initiation potentials measured by short-term tests are non-conservative**
- **Stochastic modeling of pit initiation, while fundamentally important, has many limitations for long-term prediction**
  - Sample size at low potentials
  - Extrapolation of nucleation rate to low potentials
  - Existence of a minimum potential
  - Surface sensitivity
- **Extrapolation of long-term tests can be performed reliably only if the corrosion potential is measured.**

Extrapolation of Short-Term Data (Contd.)

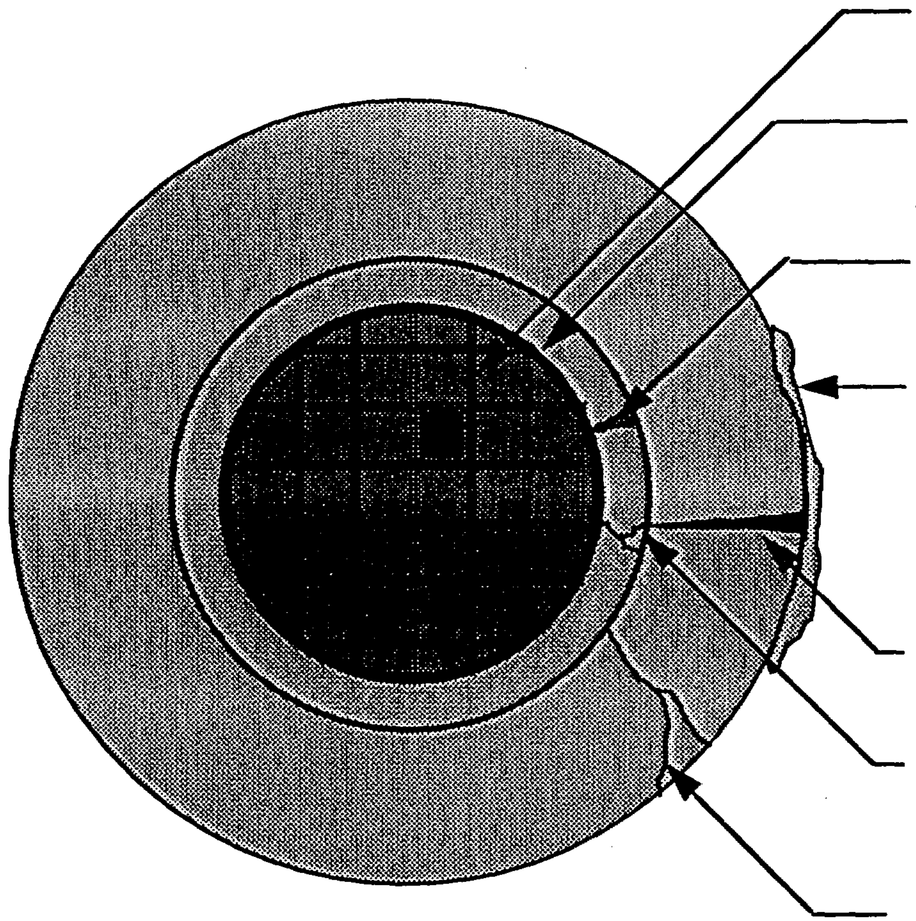
- Repassivation potential is a robust and conservative parameter - but not too conservative if measured properly
- Repassivation potential for localized corrosion can be used to predict the occurrence of stress corrosion cracking (for austenitic stainless steels)
- Several instances of field failures (marine, pulp and paper) can be correlated to repassivation potential
- Long-term tests to verify the applicability of repassivation potential are continuing

Need for Focus on Designs and Materials

- **Rigor Vs. Flexibility in Choice of Design or Materials**
  - Too many candidate materials in the ACD
  - Rigorous investigation on fewer materials
  - Model parameters and long-term data can be developed for fewer materials



Some Factors in the Performance of the New ACD Waste Package Design



Summary

- **Predictive approaches ought to be defensible mechanistically, conservative, robust, flexible, and simple computationally**
  - Repassivation potential approach fulfills these requirements
- **Long-term aqueous corrosion tests must measure corrosion potential to do extrapolation reliably**
- **Number of materials in the ACD phase are too large to permit in-depth generation of relevant parameters**
- **Some of the factors that may affect the performance of the ACD phase materials have been identified**