U.S. DEPARTMENT OF ENERGY
OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT

NUCLEAR WASTE TECHNICAL REVIEW BOARD
JOINT PANELS ON HYDROGEOLOGY & GEOCHEMISTRY AND STRUCTURAL GEOLOGY & GEOENGINEERING

SUBJECT: TOTAL SYSTEM PERFORMANCE ASSESSMENT UPDATES

PRESENTER: ROBERT W. ANDREWS

PRESENTER'S TITLE AND ORGANIZATION: PERFORMANCE ASSESSMENT DEPARTMENT MANAGER
CRWMS M&O/INTERA
LAS VEGAS, NEVADA

PRESENTER'S TELEPHONE NUMBER: (702) 794-7380

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Outline

- Review key elements of isolation argument and potential effects of alternate thermal loads
- Summarize fundamental thermo-hydrologic assumptions affecting TSPA-1993 results
- Present additional sensitivity analyses of TSPA-1993 results
- Describe revisions to TSPA-1993 using preliminary drift-scale thermo-hydrologic analyses
- Present plans for TSPA-1995

Key Components of Waste Isolation Argument at Yucca Mountain

- Dry environment within engineered barriers
- Robust engineered materials for those packages contacted by liquid water/humid air
  - Waste package and zircaloy cladding
- Slow dissolution of waste matrix due to limited availability of water and low solubility of radionuclides
- Slow release of radionuclides through the engineered barrier due to limited water
- Slow release of radionuclides through the geosphere

[modified from NWTRB briefing by J. Younker October 12, 1994]

Potential Effects of Thermal Load on Key Components of Waste Isolation Argument

- Thermo-hydrologic regime within drifts
  - "Dryness" of environment around engineered barriers
- Initiation of aqueous corrosion
  - Dependent on temperature and humidity environment
- Rate of aqueous corrosion
  - Dependent on temperature and humidity environment
- Rate of waste-form dissolution
  - Dependent on temperature and liquid saturation
- Radionuclide solubilities in liquid water
  - [Depends more on geochemical environment]
- Advective and diffusive flux rates
  - Dependent on temperature and liquid saturation

Fundamental Thermo-Hydrologic Assumptions Affecting Waste-Package Failures in TSPA-1993

- **Near-field temperatures and saturations based on panel-scale T-H model**
  - Represents "average" T-H response
  - Accounts for spatial variability in T-H response
  - Under-predicts expected waste-package temperature
  - Over-predicts expected drift-scale saturations
- **Either temperature or liquid saturation criterion assumed to initiate corrosion**
  - Neglects drift-scale T-H response
  - Initiates aqueous corrosion conservatively early
- **Pitting corrosion rates considered to be temperature-dependent**
  - Leads to very conservative (high) corrosion rates for saturation initiation

Other Fundamental Assumptions Affecting Waste Package Failures in TSPA-1993

- Pitting corrosion rate of mild steel evaluated with two different models:
  - One (Stahl) assumed rate increased with increasing temperature and decreased with time
  - Other (Lamont) assumed rate independent of time and was a maximum at about 70°C
  - For assumed saturation initiation, leads to very conservative (high) corrosion rates

Other Fundamental Assumptions Affecting Waste Package Failures in TSPA-1993

(continued)

- **Pitting corrosion rate of corrosion-resistant material evaluated with two different models**
  - Deterministic model (Stahl) assumed extremely high rates
  - Stochastic model (Lamont) assumed high rates at high temperatures (~96°C) and 100x decrease at 70°C
  - Stochastic model combined with very high corrosion rate of mild steel
  - Combined effects led to very conservative corrosion rates for most packages
- **Degradation of cladding assumed to be congruent with corrosion-resistant material**

Fundamental Thermo-Hydrologic Assumptions Affecting Waste Package/EBS Release in TSPA-1993

- Waste package (+cladding) failure distribution
- Entire waste package surface assumed to be degraded at time of failure
  - Failure conservatively defined by first pit penetration
  - Increased surface area allows greater diffusive releases
- Thermally perturbed advective fluxes evaluated at panel scale
  - Considered spatial distribution
  - Neglects capillary barrier effect in the drift
- Entire waste-form surface assumed to be exposed and contacted by liquid water film at time of failure
  - Neglects capillary barrier effect in the drift

Fundamental Thermo-Hydrologic Assumptions Affecting Waste Package/EBS Release in TSPA-1993

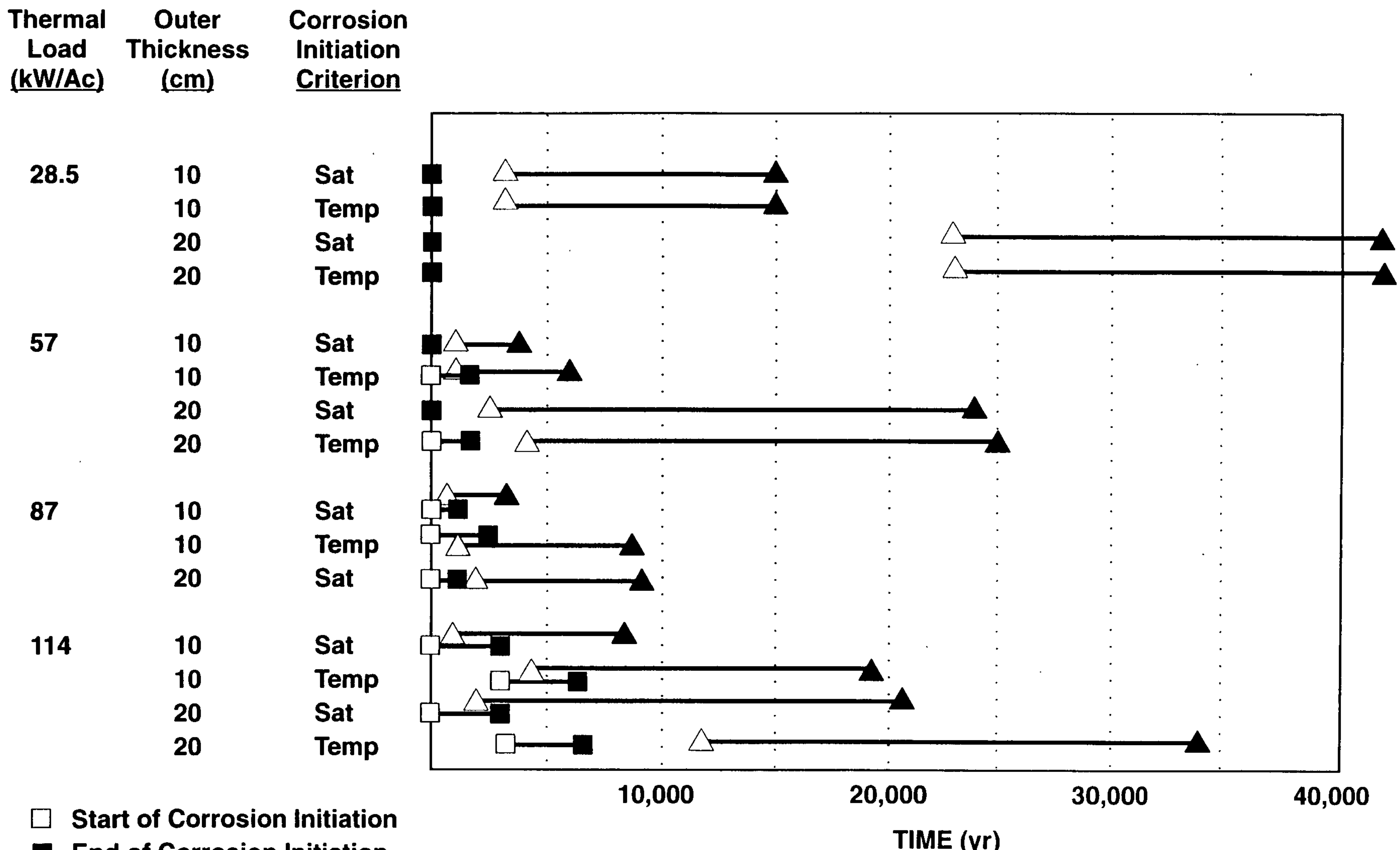
(Continued)

- **Dissolution rates and solubility limits considered to be temperature-dependent**
  - Based on laboratory observations at PNL/LLNL and LBL/LANL
- **Diffusion coefficients through waste package and backfill (invert) based on average rock water contents from panel-scale T-H model**
  - Neglects capillary differences between rock and backfill

Objectives of Additional Sensitivity Analyses on TSPA-1993

- Complete sensitivity analyses of temperature-based corrosion initiation criterion
- Correct advective flux through waste package for 114 kW/acre case
- Evaluate effect of a different thermal load
  - 87 kW/acre
- Compare HLW versus spent fuel releases
- Compare alternate waste package designs
  - SCP, 6 PWR MPC, 21 PWR MPC
- Initiate sensitivity analyses of peak EBS release rates
- Initiate evaluation of drift-scale T-H analyses
- Prepare for TSPA-1995

Summary of TSPA-1993 Waste Package Failures*: Sensitivity to Thermal Load, Waste Package Thickness, and Corrosion Initiation Criterion



□ Start of Corrosion Initiation
■ End of Corrosion Initiation
△ Start of Waste Package Failures
▲ End of Waste Package Failures

*Correspond to failure of corrosion-allowance barrier
Based on panel-scale thermo-hydrology

Summary of TSPA-1993 Cumulative Waste Package ^{237}Np and ^{99}Tc Releases Normalized to Table 1 of 40 CFR 191: 10,000 and 100,000 Years

Thermal Load (kW/Ac)	Outer Thickness (cm)	Corrosion Initiation Criterion	10,000 Yr.		100,000 Yr.		Percent of Release from HLW
			^{237}Np	^{99}Tc	^{237}Np	^{99}Tc	
28.5	10cm	Sat.	1.2	0.14	11.7	1.06	0.1%
	10 cm	Temp.	1.2	0.14	11.7	1.06	0.1%
	20 cm	Sat.	0.0	0.0	8.4	0.7	0.1%
	20 cm	Temp.	0.0	0.0	8.4	0.7	0.1%
57	10 cm	Sat.	3.7	0.43	13.4	1.3	3%
	10 cm	Temp.	3.0	0.33	13.3	1.3	3%
	20 cm	Sat.	1.9	0.21	13.1	1.2	3%
	20 cm	Temp.	0.35	0.04	12.7	1.2	3%
87	10 cm	Sat.	1.3	0.48	13.9	1.3	
	10 cm	Temp.	1.1	0.25	13.7	1.3	
	20 cm	Sat.	1.2	0.31	13.8	1.3	
	20 cm	Temp	*	*	*	*	
114	10 cm	Sat.	0.1	0.31	14.2	1.4	6%
	10 cm	Temp.	0.03	0.02	14.0	1.3	6%
	20 cm	Sat.	0.06	0.06	14.0	1.3	6%
	20 cm	Temp.	0.0	0.0	14.0	1.3	6%

Summary of Relevant TSPA-1993 Conclusions

- Waste-package failures dependent on model for corrosion initiation
  - Saturation-dependent occur earlier
- Spatial variability (due to edge effects) in corrosion initiation and rates affects distribution of failures
- Assumed corrosion model affects distribution of failures
- Diffusive releases from waste package/engineered barrier system generally dominate advective releases
- No significant waste-package cumulative release differences occur during 100,000 years

Preliminary TSPA Analyses Using Drift-Scale Thermo-Hydrologic Model: Objectives

- Directly evaluate T-H response at drift scale
  - Temperature, liquid saturation and flux, relative humidity
- Evaluate range of designs for Systems Study
  - Two thermal loads: 25 and 87 kW/acre
  - Two backfill alternatives: none and gravel
  - Two waste package spacings: 39 x 39 m and 16 x 93 m
  - Three corrosion-allowance thicknesses: 10, 20 and 45 cm
- Evaluate sensitivity (waste-package failures) to corrosion initiation criterion
  - Relative humidity > 70% or temperature < 96°C
- Evaluate sensitivity (waste-package release) to release initiation criterion
  - Saturation > residual saturation of backfill
- Evaluate sensitivity (AE release and dose) to limited range of designs

Preliminary TSPA Analyses Using Drift-Scale Thermo-Hydrologic Model: Approach/Assumptions

- **Analyze drift-scale T-H response**
  - 2-D vertical section: surface to 1000 m below water table
  - Refined mesh in vicinity of drift
  - TOUGH2 and FEHM compared
  - Calculate temperature, saturation, flux, and humidity
  - Humidity determined from Kelvin relationship
  - Evaluate sensitivity to ambient percolation flux
    - » 0.0, 0.1 and 0.2 mm/yr
  - Sensitivity to rock and backfill properties <u>not</u> evaluated
- **Determine corrosion initiation**
  - Humidity > 70% <u>or</u> temperature < 96°C

Preliminary TSPA Analyses Using Drift-Scale Thermo-Hydrologic Model: Approach/Assumptions

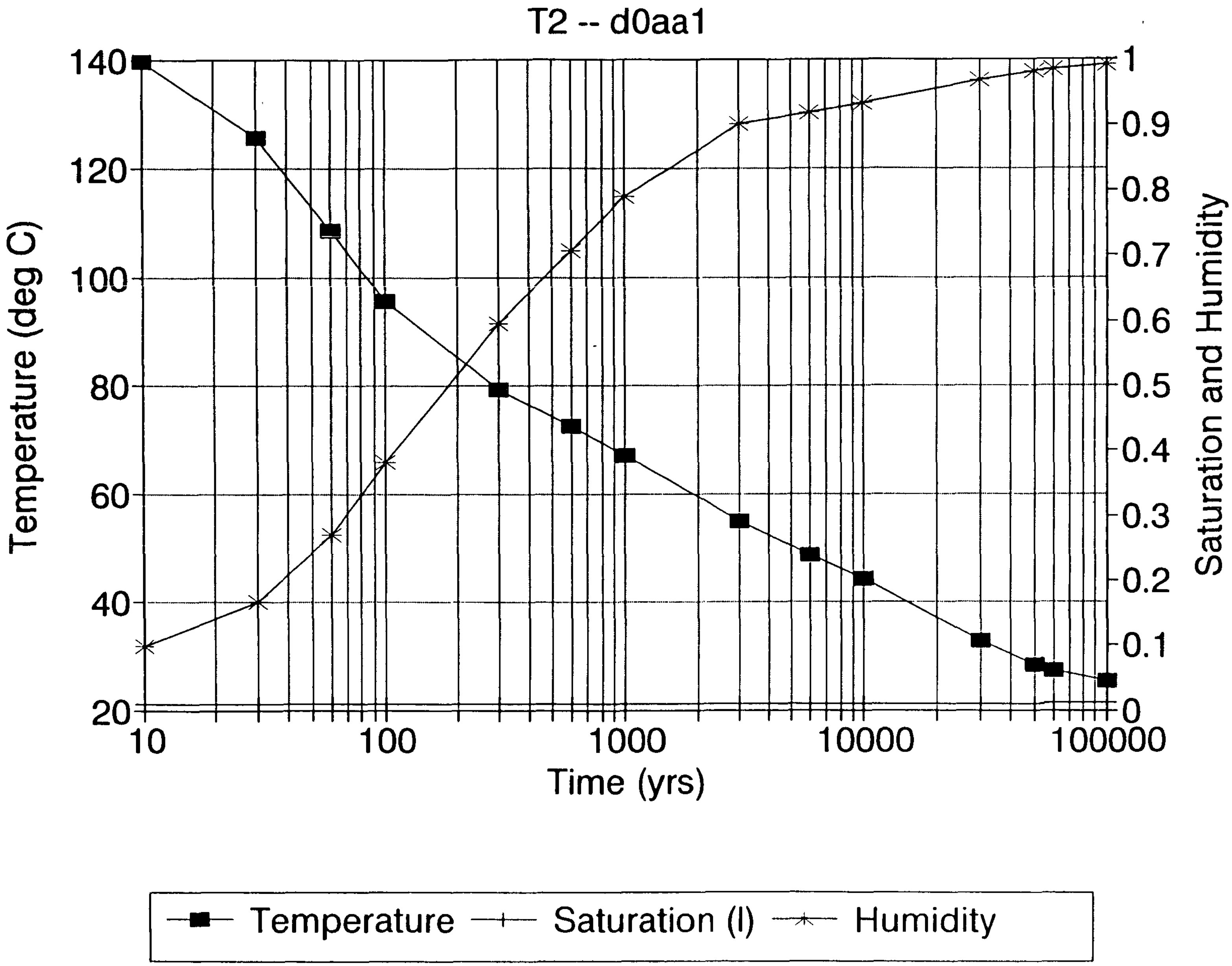
(Continued)

- Corrosion rates assuming Stahl (1993) with pitting
  - Not spatially variable
  - Spread of failures using two alternate models
    - » +/- 25% of mean failure time
    - » +/- 25% of time exponent
- Corrosion-resistant barriers (including cladding) fail congruently with corrosion allowance
- Entire waste-form surface exposed to water
  - Evaluate sensitivity to wetting criteria
- Dissolution rates and solubilities from TSPA-1993
- Diffusion coefficient from Conca
  - Minimum of 1.0E-06 m^2/yr

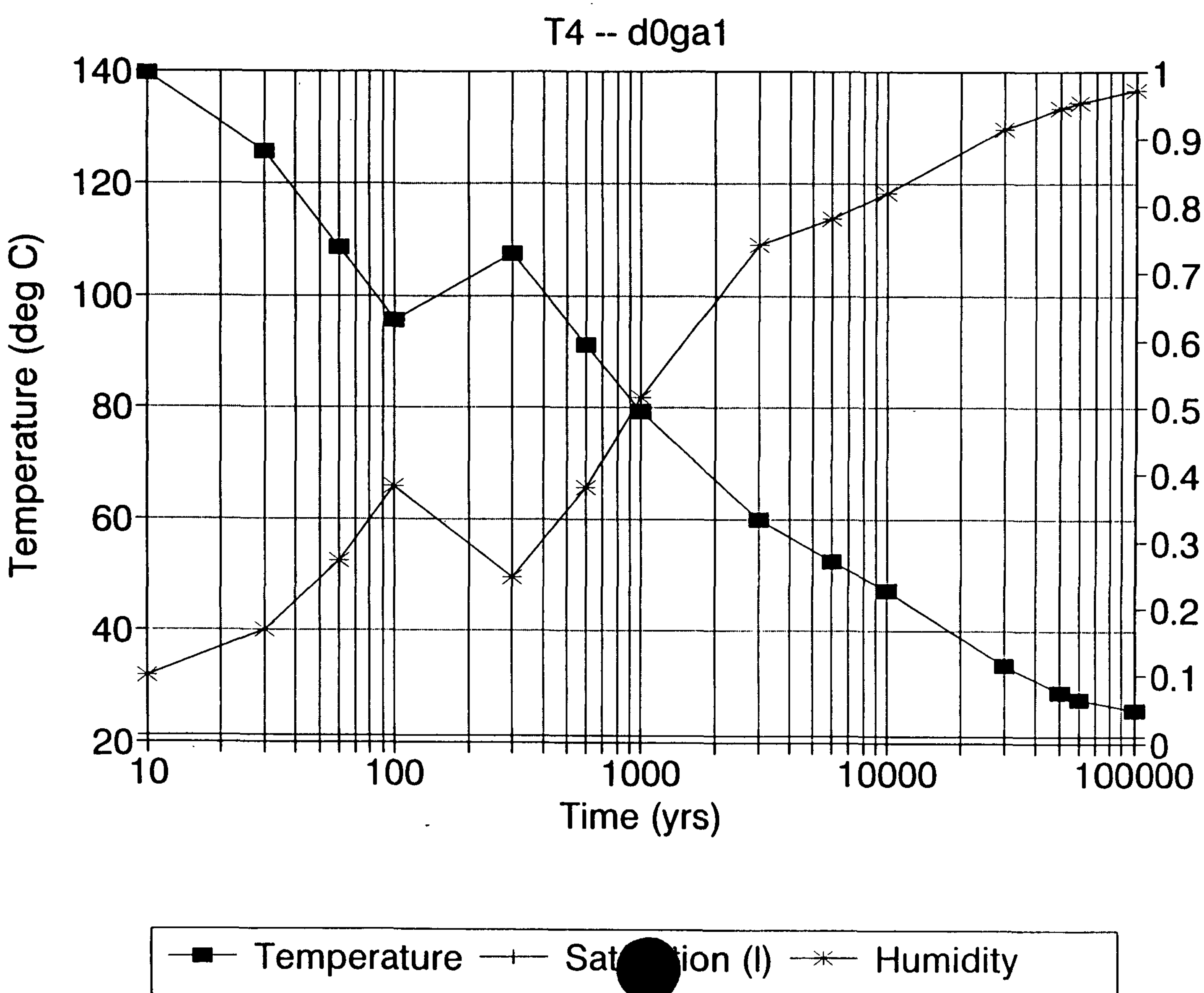
Preliminary TSPA Analyses Using Drift-Scale Thermo-Hydrolgic Model Principal Results

- Representative drift-scale T-H responses
- Waste package failure distributions
- Waste package cumulative releases
  - 10,000 year
  - 100,000 year

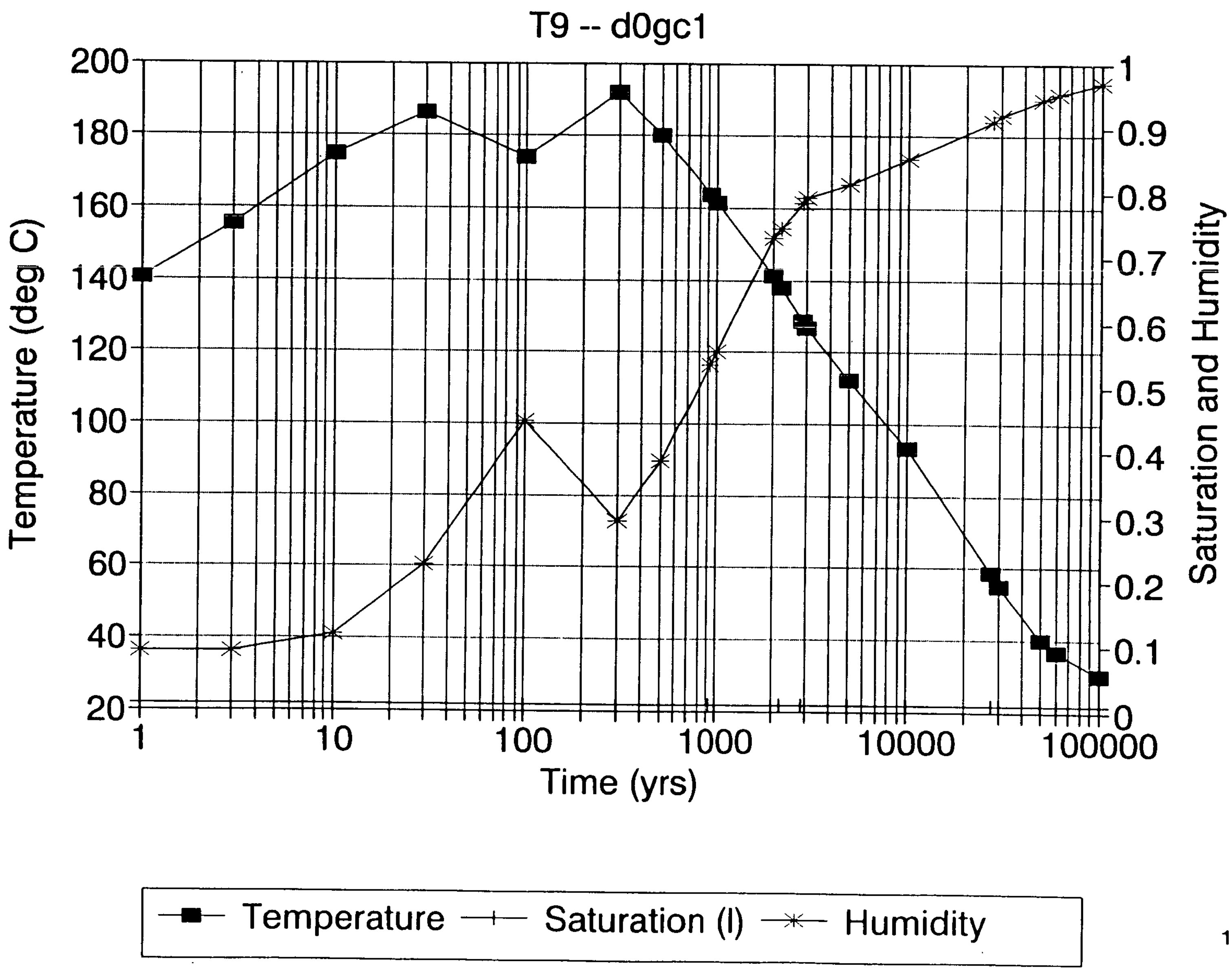
In-Drift Distribution of Temperature, Saturation and Humidity:
25 kW/Acre; gravel backfill; rectangular spacing



In-Drift Distribution of Temperature, Saturation and Humidity:
25 kW/Acre; no backfill; rectangular spacing

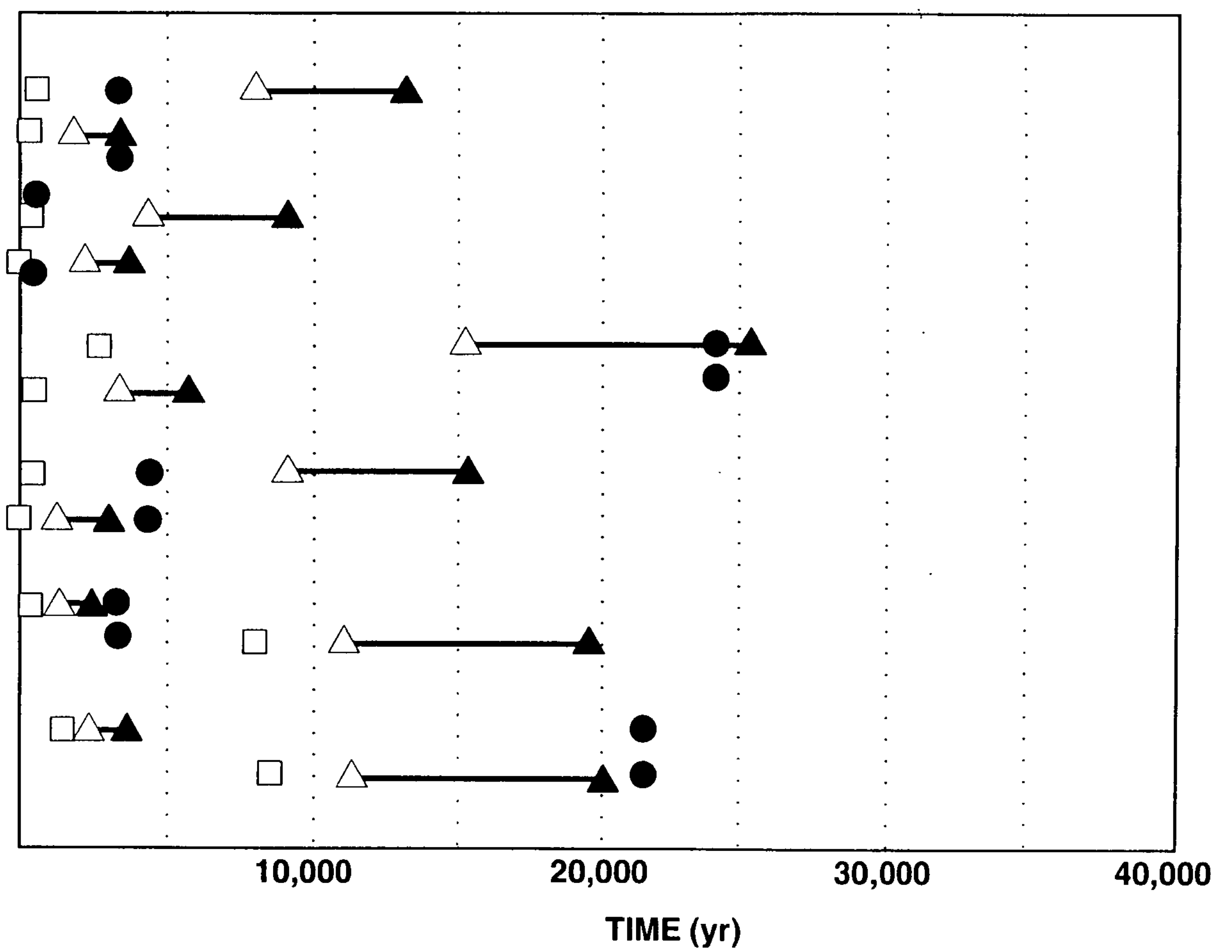


In-Drift Distribution of Temperature, Saturation and Humidity:
87 kW/Acre; gravel backfill; rectangular spacing



Summary of Waste Package Failures Using Drift-Scale Thermo-Hydrology: Sensitivity to Thermal Load; Backfill; Spacing; Corrosion Initiation--10cm Outer Barrier; 0.1 mm/yr Percolation Flux

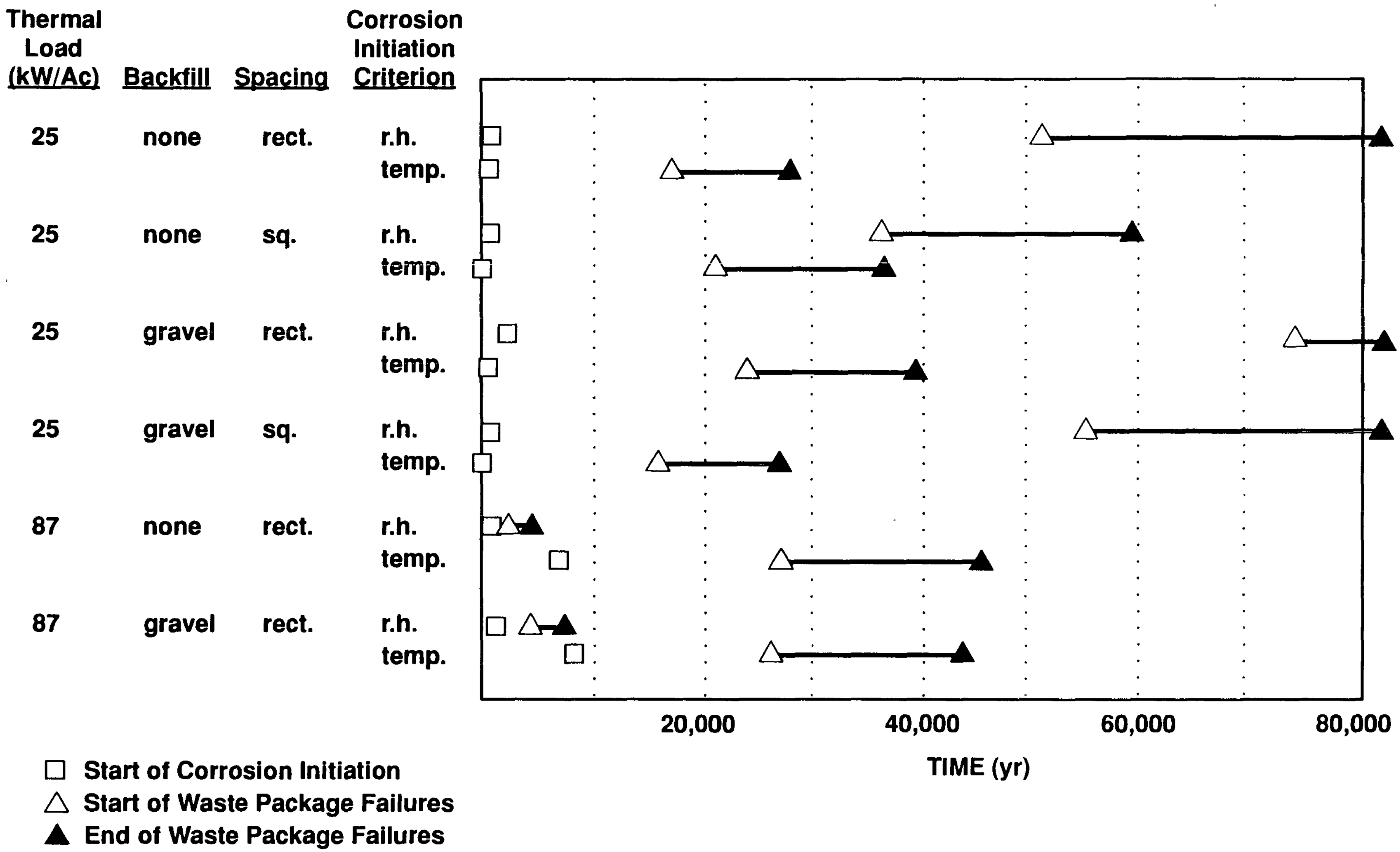
Thermal Load (kW/Ac)	Backfill	Spacing	Corrosion Initiation Criterion
25	none	rect.	r.h.
			temp.
25	none	sq.	r.h.
			temp.
25	gravel	rect.	r.h.
			temp.
25	gravel	sq.	r.h.
			temp.
87	none	rect.	r.h.
			temp.
87	gravel	sq.	r.h.
			temp.



□ Start of Corrosion Initiation
△ Start of Waste Package Failures
▲ End of Waste Package Failures
● Time: Sat > Sres

1) rect. = rectangular: 92.7 m spacing between drifts, 16m opening along drift
sq. = square: 38.5m spacing between drifts, 38.5m opening along drift
2) r.h. = relative humidity > 70%
temp. = temperature < 96° C

Summary of Waste Package Failures Using Drift-Scale Thermo-Hydrology: Sensitivity to Thermal Load; Backfill; Spacing; Corrosion Initiation--20cm Outer Barrier; 0.1 mm/yr Percolation Flux



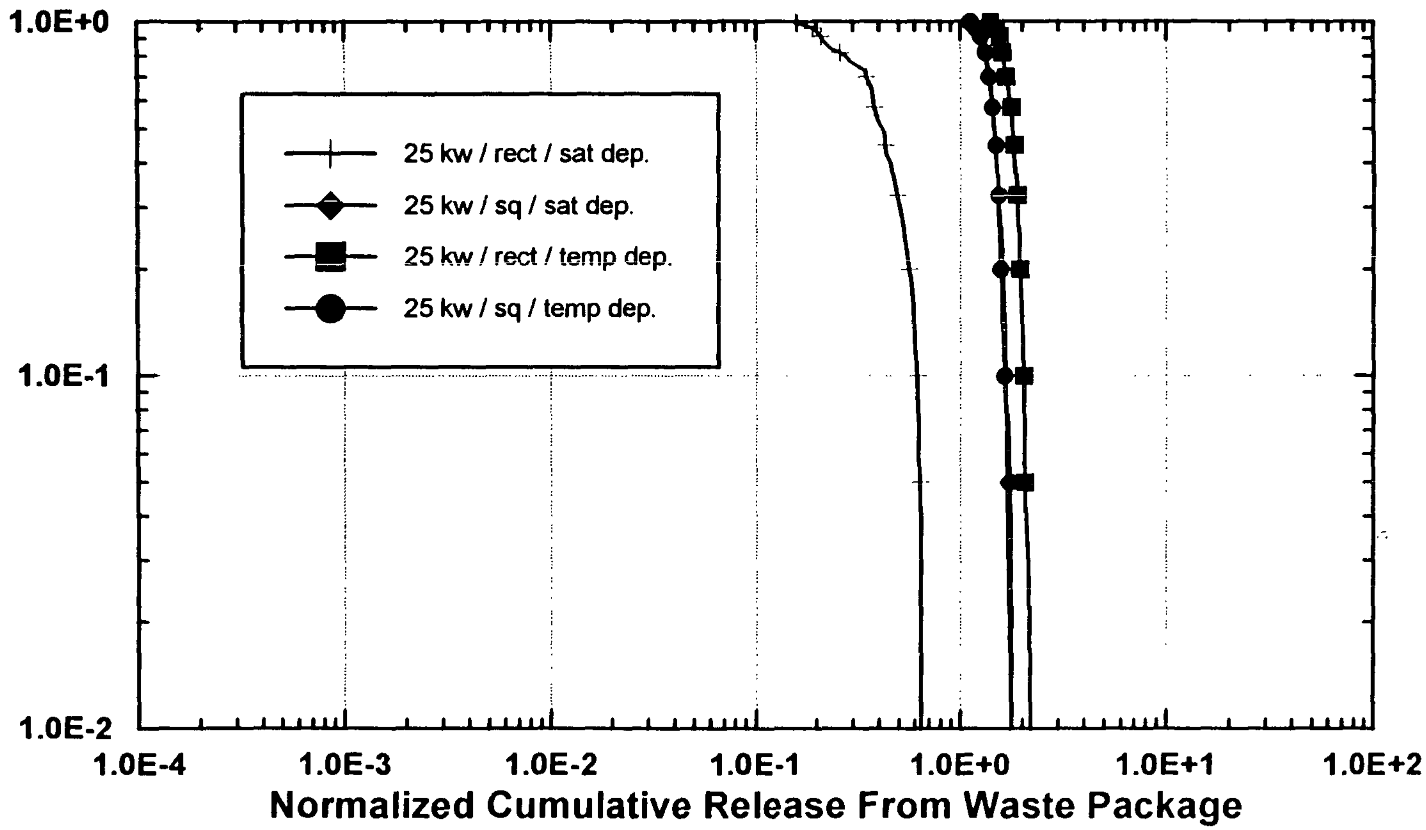
Summary of Revised Thermo-Hydrologic Analyses on Cumulative Waste Package ^{237}Np and ^{99}Tc Releases Normalized to Table 1 of 40 CFR 191 (Temperature Corrosion Initiation Criterion, 10 cm Outer Barrier)

Thermal Load (kW/Ac)	Backfill	Spacing	Release Dependent**	Waste Package 10,000 Yr. Np	Waste Package 10,000 Yr. Tc	Waste Package 100,000 Yr. Np	Waste Package 100,000 Yr. Tc
25	None	Rect.	Sat.	3.5 E-5	1.3 E-4	4.19	0.92
			Temp.	4.9 E-3	4.9 E-2	4.21	1.01
25	None	Sq.	Sat.	5.2 E-3	5.2 E-2	11.0	1.0
			Temp.	5.2 E-3	5.2 E-2	11.0	1.01
25	Gravel	Rect.	Sat.	0.0	0.0	2.7 E-2	0.58
			Temp.	3.2 E-2	2.7 E-2	4.4 E-2	0.81
25	Gravel	Sq.	Sat.	3.7 E-5	1.3 E-4	4.8 E-2	0.83
			Temp.	4.9 E-3	5.0 E-2	5.5 E-2	0.92
87	None	Rect.	Sat.	0.0*	0.0*	7.4	1.11
			Temp	0.0*	0.0*	5.9	1.11
87	Gravel	Rect.	Sat.	0.0*	0.0*	3.0 E-2	0.42
			Temp.	0.0*	0.0*	5.0 E-2	0.77

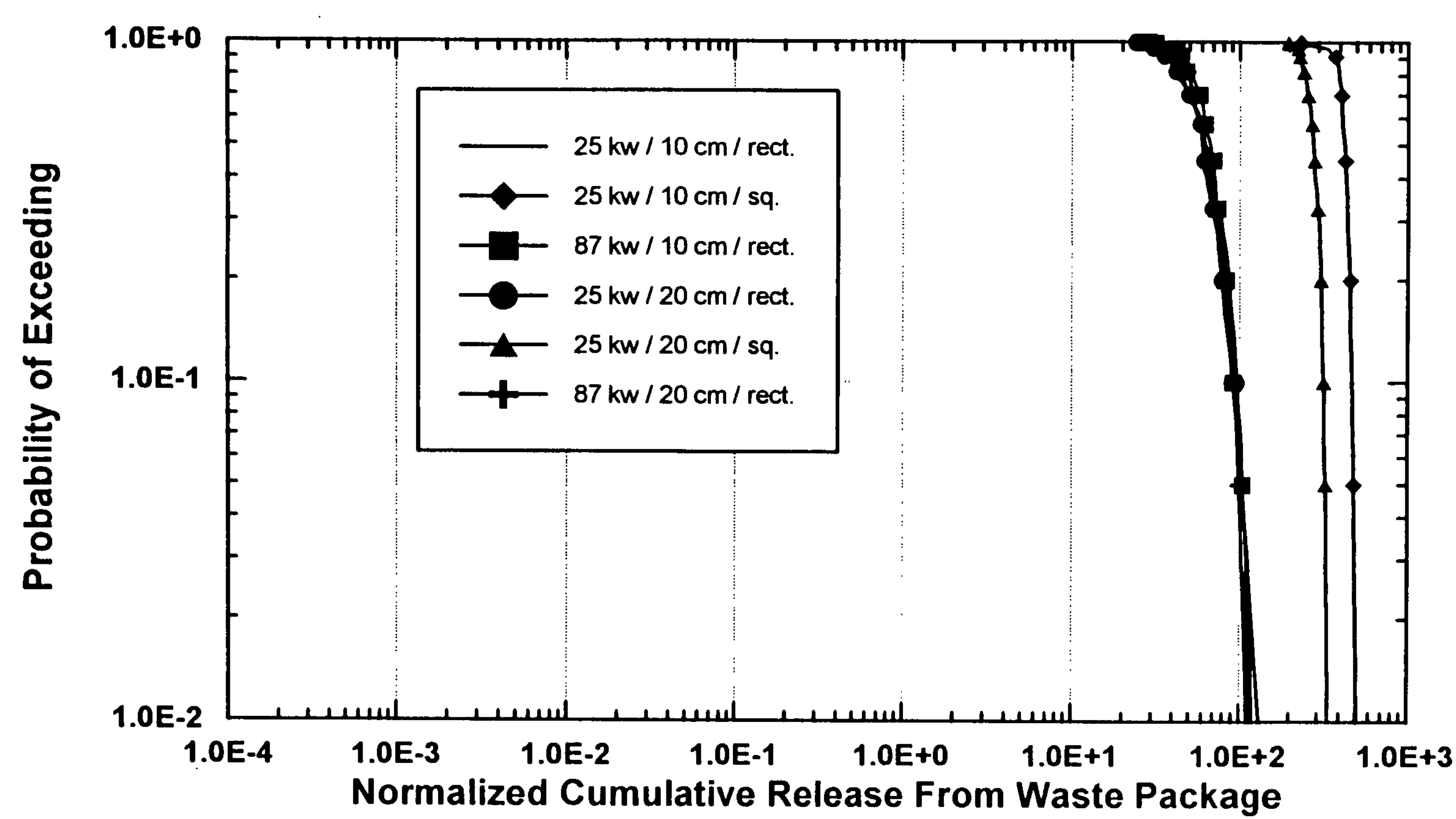
* No Failures for 87 kW/Ac for 10,000 years assuming temperature corrosion initiation.

** Sat. = Saturation in drift> residual saturation of gravel (0.01) before waste is wet.
Temp. = Temperature in drift<96°C before waste is wet

CCDF of Total Normalized Waste Package Release for 10,000 Years: Effect of Spacing and Release Initiation



CCDF of Total Normalized Waste Package Release for 10,000 Years: Effect of Thermal Load, Spacing, and Outer Barrier THickness



Summary of Initial TSPA Results Based on Preliminary Drift-Scale Thermo-Hydrologic Model

- Humidity-initiated corrosion can lead to earlier failures at higher thermal loads
  - [Not accounting for humidity effects on corrosion rates]
- Backfill leads to slightly higher failure times
  - Depends on corrosion initiation criterion
- Rectangular spacing leads to slightly higher failure times
- 20 cm outer barrier leads to increased failure times
  - [Conservative treatment of inner barrier and cladding]
- Although differences occur in waste package and AE release, their significance is strongly affected by assumptions in waste package/engineered barrier system model

Thermally Related Issues to be Addressed in TSPA-1995

- **Revised drift-scale thermo-hydrologic model**
  - Alternate backfill characteristics
  - Alternate thermal loads
  - Evaluate effect of rock property uncertainty
  - Direct prediction of humidity
  - Indirect prediction of spatial variability
- **Revised model(s) for initiation of aqueous corrosion**
- **Drift-scale liquid saturations used to define**
  - Percent of waste-form surface exposed to water
  - Percent of waste package and EBS with diffusive pathway

Other Issues to be Addressed in TSPA-1995

- Revised unsaturated zone hydrologic model
  - Spatially variable infiltration
  - Fracture-matrix flow and transport
  - Heterogeneity and scaling effects
- Revised waste-package corrosion rate models
  - Corrosion-allowance materials
  - Corrosion-resistant materials and cathodic protection
  - Cladding

Other Issues to be Addressed in TSPA-1995

(Continued)

- Revised radionuclide mobilization and EBS release model
  - Percent of waste package degraded
    - » Probabilistic pit generation and growth model
  - Percent of cladding surface degraded
  - Percent of waste-form exposed to water
    - » Based on water content fn(time)
  - Percent of continuous water film for diffusion
    - » Based on water content fn(time)
  - Revised waste-form dissolution model
  - Revised solubilities
    - » Colloidal mobilization and transport

Key Information Needs for TSPA-1995

- Unsaturated Zone Hydrology
  - Infiltration and percolation rate (and variability and uncertainty)
  - Fracture-matrix coupling
    - » Matrix imbibition and diffusion
  - Bulk rock characteristic curves in TSw2 (and variability and uncertainty)
- Waste Package/Engineered Barrier System
  - Backfill and invert thermo-hydrologic properties
  - Corrosion initiation criteria (and uncertainty)
  - Corrosion model and parameters (and uncertainty)
    - » Corrosion allowance
    - » Corrosion resistant
    - » Cladding
  - Effective diffusion coefficient at low liquid saturation
  - Spent fuel dissolution model for expected thermo-hydrologic conditions

Conclusions

- Additional sensitivity analyses confirm conclusions made in TSPA-1993 and illustrate importance of assumptions made in waste-package degradation and EBS release
- Preliminary drift-scale thermo-hydrologic analyses indicate importance of
  - Criteria for initiation of corrosion
  - Criteria for initiation of dissolution and release
- Planning for TSPA-1995 is underway, with focus on key components of waste-isolation argument