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

Waste Package and Drip Shield Degradation

Presented to:
Nuclear Waste Technical Review Board

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YUCCA MOUNTAIN PROJECT

Process Model Factors Affecting Waste Package Lifetime - Waste Package Degradation

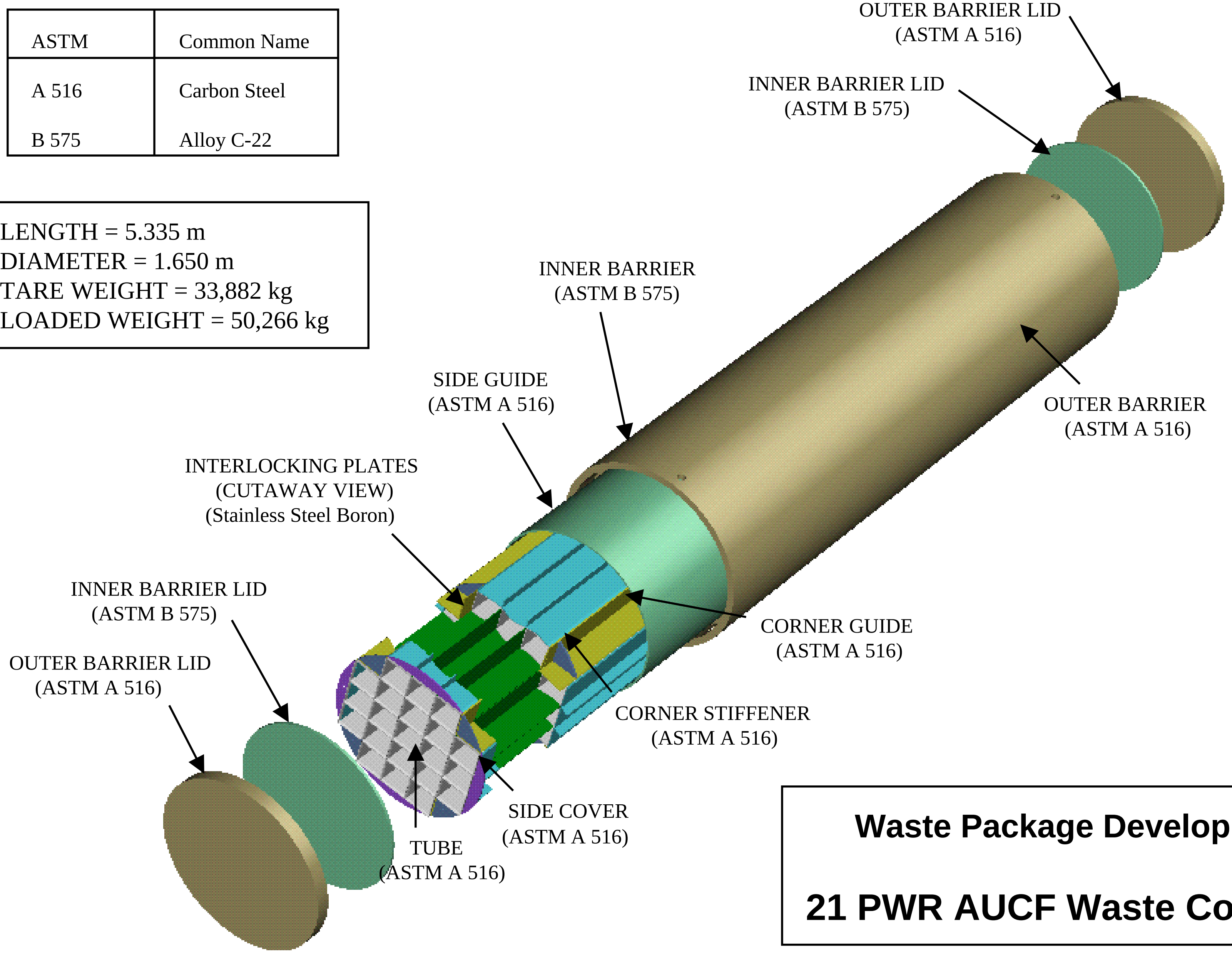
Key Attributes of Performance	Process Model Factor	TSPA-SR Input Parameters
Waste Package Lifetime	Drip Shield Degradation and Performance	• Probability of material and manufacturing defect flaws in drip shield • Size of material and manufacturing defect flaws in drip shield • Probability and size of rockfall induced by seismic activity • Threshold for general corrosion initiation • General corrosion rate under drip and no-drip conditions • Crevice corrosion initiation threshold • Probability (or area) of crevice formation on drip shield • Stress and stress intensity factor profile in drip shield • SCC initiation threshold • SCC crack growth rate • Effect of material and manufacturing defects on SCC initiation and crack growth rate • Effect of rockfall damage on SCC initiation and crack growth rate • Hydrogen concentration profile in drip shield • HIC initiation threshold • Penetration opening size by general corrosion, localized corrosion and SCC
	Waste Package Degradation and Performance	• Probability of material and manufacturing defect flaws in waste package • Size of material and manufacturing defect flaws in waste package • Threshold RH for general corrosion initiation under drip and no-drip conditions • General corrosion rate under drip and no-drip conditions • Crevice corrosion initiation threshold of WP outer barrier • Penetration opening size by general corrosion, localized corrosion and SCC • Stress and stress intensity factor profile at closure welds • SCC initiation threshold • SCC crack growth rate • Effect of material and manufacturing defect on SCC initial and crack growth rate • MIC factor on corrosion rate • Kinetics phase instability processes in base metal and weld • Aging factor on corrosion rate

Waste Package Design

- **Waste Package design has changed significantly since TSPA-VA**
  - **Carbon steel corrosion allowance barrier eliminated**
  - **Alloy 22 retained as corrosion resistant material but moved to outer barrier position**
  - **316 stainless steel added as structural material inside Alloy 22**
  - **Drip shield made of Ti added for defense in-depth**

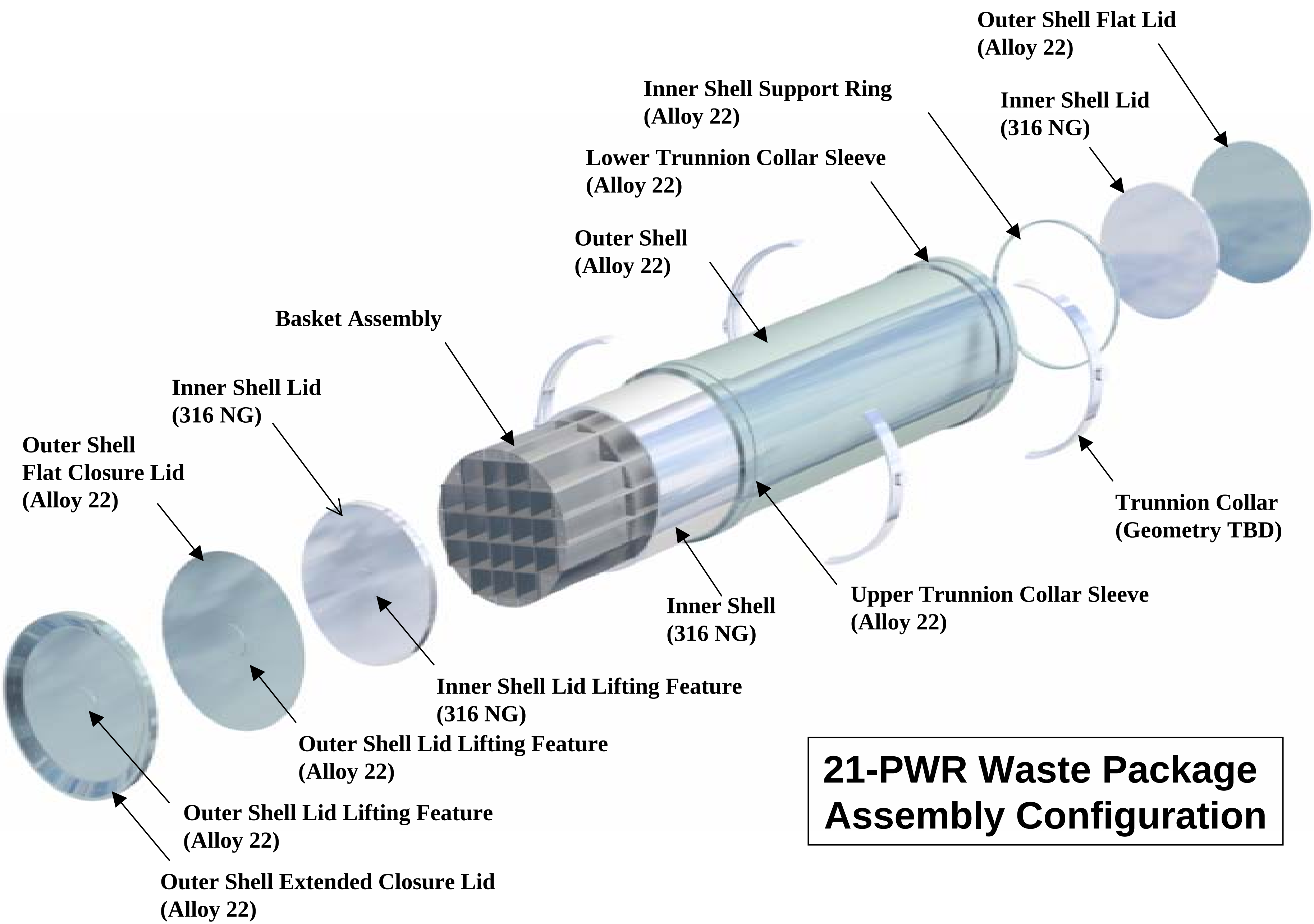
ASTM	Common Name
A 516	Carbon Steel
B 575	Alloy C-22

LENGTH = 5.335 m
DIAMETER = 1.650 m
TARE WEIGHT = 33,882 kg
LOADED WEIGHT = 50,266 kg



Waste Package Development

21 PWR AUCF Waste Container



21-PWR Waste Package Assembly Configuration

Waste Package Degradation Models for TSPA-VA and TSPA-SR

- As a result of design changes, several new degradation models added for TSPA-SR
- Waste package process models in TSPA-SR now includes:
  - Stress corrosion cracking, including effects of manufacturing flaws
  - Aging and phase stability effects for Alloy 22
  - Microbiologically influenced corrosion (MIC) effects
  - Potential effects of radiolysis
  - Bounding environmental conditions on waste package and drip shield

Comparison of Degradation Models

Corrosion Allowance Material (CAM) Corrosion

TSPA-VA

- **Included both general and localized corrosion including humid air corrosion**
  - **Corrosion rates based on published data (RH, T, and pH)**
  - **Spatial and temporal variations in exposure conditions included**

TSPA-SR

- **CAM is not part of SR design**

Comparison of Degradation Models

General and Localized Corrosion

TSPA-VA

- Included general and localized corrosion
- A range of water chemistry in the crevice was assumed with the most aggressive being due to Ferric chloride
- Model parameters and corrosion rates based on expert elicitation and published data (not relevant to the repository conditions)

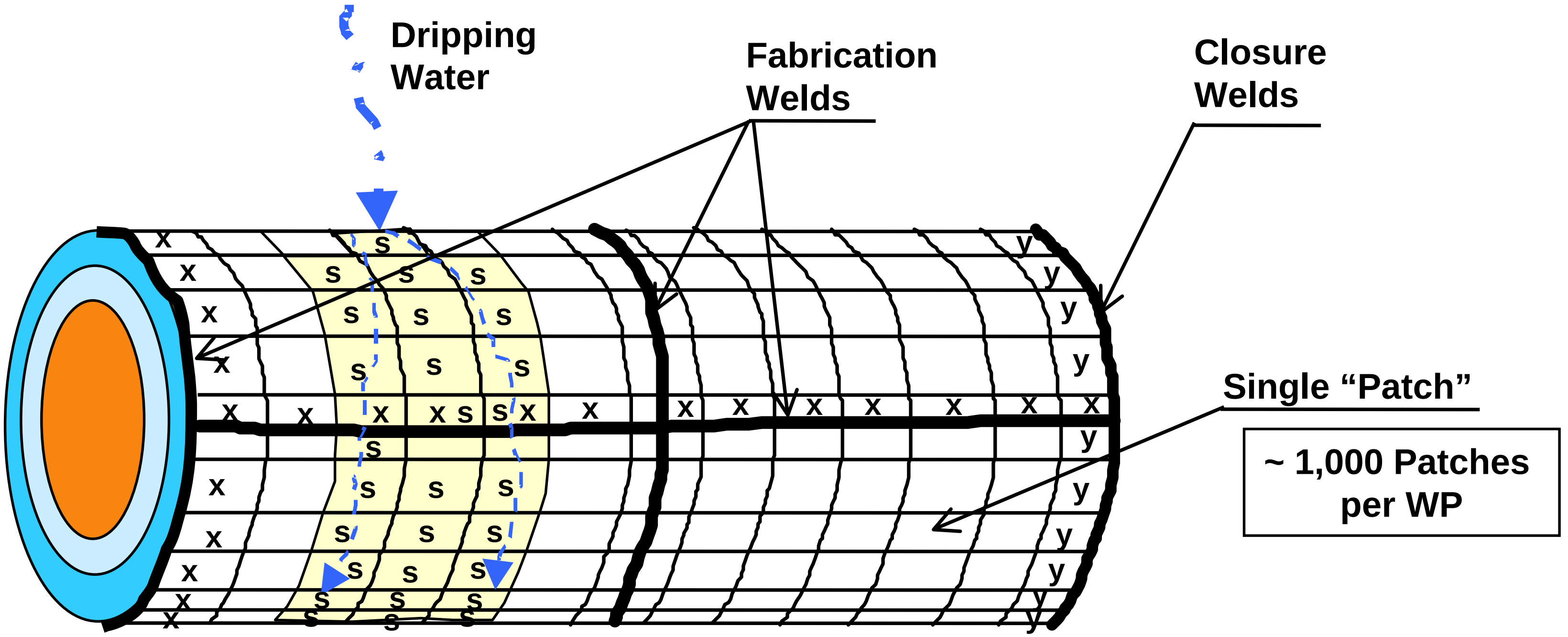
TSPA-SR

- Addresses dry oxidation, humid air corrosion, aqueous phase corrosion
- Environment on the surface based on evaporative concentration of J-13 type water
- Based on experimental data from the long-term corrosion test facility (LTCTF) and short-term cyclic polarization data

Schematic of the Conceptual Model of Stochastic WP Degradation Model (WAPDEG) for TSPA-SR

* T, RH, in-drift water dripping from multi-scale T-H and UZ model abstraction

* pH, [Cl-] of water contacting WP & DS from EBS chemical environment model abstraction



s - Patches with drips; Potential salt deposits; potential localized corrosion

x - Patches with fabrication welds

y - Patches with closure welds; potential SCC

Comparison of Degradation Models

General and Localized Corrosion

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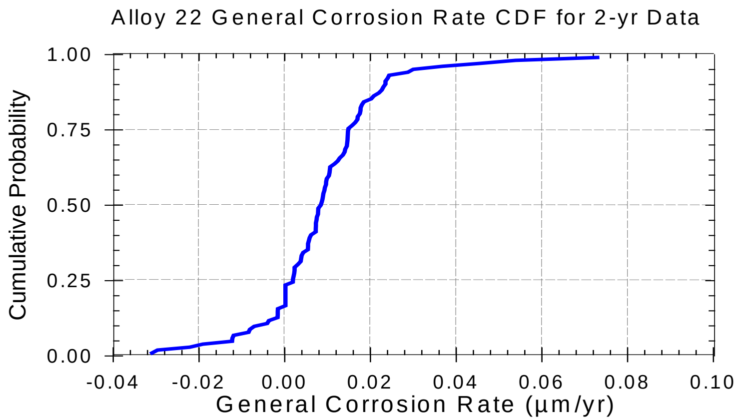
TSPA-VA

- Waste package surface divided into about 1000 patches
- Did not include drip shield



TSPA-SR

- Waste package surface divided into about 1000 patches
- Maximum general corrosion rate for Alloy 22 assumed is 0.073 microns/yr. (upper bound of 2- year data). For Titanium, the general corrosion rate of 0.325 microns/yr is used based on measured data

Comparison of Degradation Models

General and Localized Corrosion

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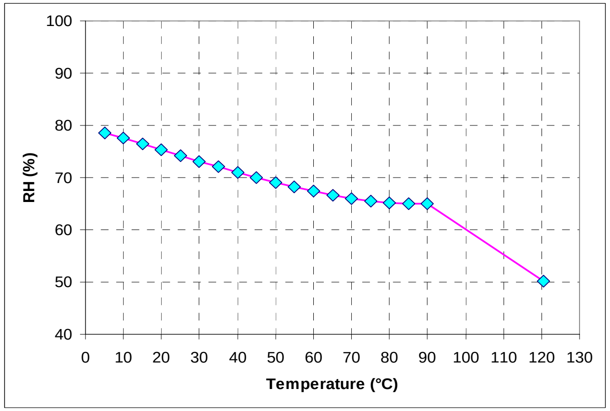

TSPA-SR

- As an added conservatism, a bias (of up to 0.063 microns/yr.) was added for silica deposits
- Specimens with crevice geometry in the LTCTF showed no evidence of localized corrosion
- Cyclic polarization tests showed that potentials for the localized corrosion of both Alloy 22 and Ti will not be exceeded under repository conditions

Microbiologically influenced Corrosion (MIC) - Alloy 22 and Drip Shield

TSPA-VA

- Did not consider MIC - Alloy 22 was assumed to be immune

TSPA-SR

- MIC effects were evaluated using electrochemical techniques
- Samples tested in sterile and inoculated test media (J-13 based)
- A corrosion rate enhancement factor in the range of 1 to 2 was determined as appropriate from the data
- Additional experiments are on-going
- Titanium is assumed to be immune to MIC

Radiolysis Effects

TSPA-VA

– Did not consider radiolysis effect

TSPA-SR

– Short-term cyclic polarization tests were conducted

– Hydrogen peroxide (up to 72 ppm) was added to simulate the effects of gamma radiolysis

– Effects on corrosion potentials were not significant enough to affect corrosion rates of either materials

– Radiolysis effects screened out for both materials from TSPA

Aging and Phase Stability

TSPA-VA

- No aging effects were assumed

TSPA-SR

- Aging and phase stability model addresses grain boundary precipitation and long range ordering
- A functional relationship between temperature and fraction of grain boundary coverage has been developed
- Limited data shows that aging and phase stability will not be important if the surface temperatures stay below 260°C

Aging and Phase Stability
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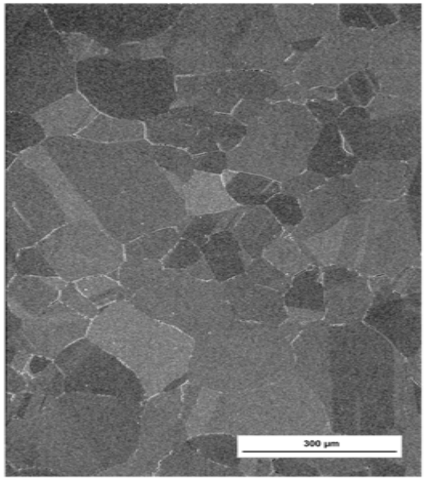

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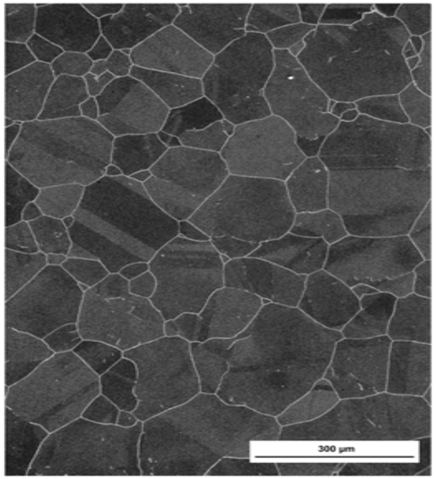

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TSPA-SR

- An enhancement factor up to 2.5 was conservatively determined from cyclic polarization tests on fully aged specimens
- No aging effects are assumed for titanium drip shield

Early failures

TSPA-VA

- 1 waste package failure at 1,000 years for base case
  - Probabilistic cases used uniform distribution from 1 - 10
  - Upper bound based on British pressure vessel data: 17 defect-related failures in 20,000 vessels (8.5 in 10,000)
  - Lower bound based on conservative interpretation of Midland reactor vessel estimate: 6×10^{-6} per WP
  - Time of occurrence arbitrary

TSPA-SR

- Approach for SR is more thorough and defensible
  - Review early failure literature on welded metallic containers
  - Identify types of defects that can occur and the subset applicable to waste packages
  - For each defect type, estimate probability of occurrence per waste package and consequences
  - Manufacturing and handling induced errors/defects can impact performance, leading to early failure

Manufacturing Defects Including Welding

Waste Package Defect Type	Probability per Waste Package
Weld Flaws - Surface Breaking and embedded	$< 2X10^{-4}$ for flaws larger than 4 mm $< 10^{-8}$ for flaws larger than 9 mm
Base Metal Flaws	Flaw Rate in Non-Inspected Welds $\times 10^{-4}$
Improper Weld Material	$3.0x10^{-5}$
Improper Heat Treatment	$2.2x10^{-5}$
Surface Contamination	$4.5x10^{-4}$
Handling Damage	$5.1x10^{-6}$
Thermal Misload of Waste Package	$1.2x10^{-5}$ (with thermal output verification)
Drip Shield Emplacement Error	$9x10^{-5}$

Only weld flaws have the potential to lead to early failures by SCC

Stress Corrosion Cracking (SCC)

TSPA-VA

- Not addressed - but acknowledged as a possible degradation mechanism in VA. It was deferred to later analyses due to a lack of an appropriate model and relevant data

TSPA-SR

- Two different models were adopted for SCC of Alloy 22
- SCC of Titanium drip shield was not considered because of planned annealing of the drip shield and the use of backfill. Model development for Ti is underway and will be included
- SCC model for Alloy 22 includes manufacturing defects present in the closure lid welds
- Slip dissolution/film rupture model used
- This model assumes a stress threshold for the initiation of the SCC cracks

Stress Corrosion Cracking (SCC)
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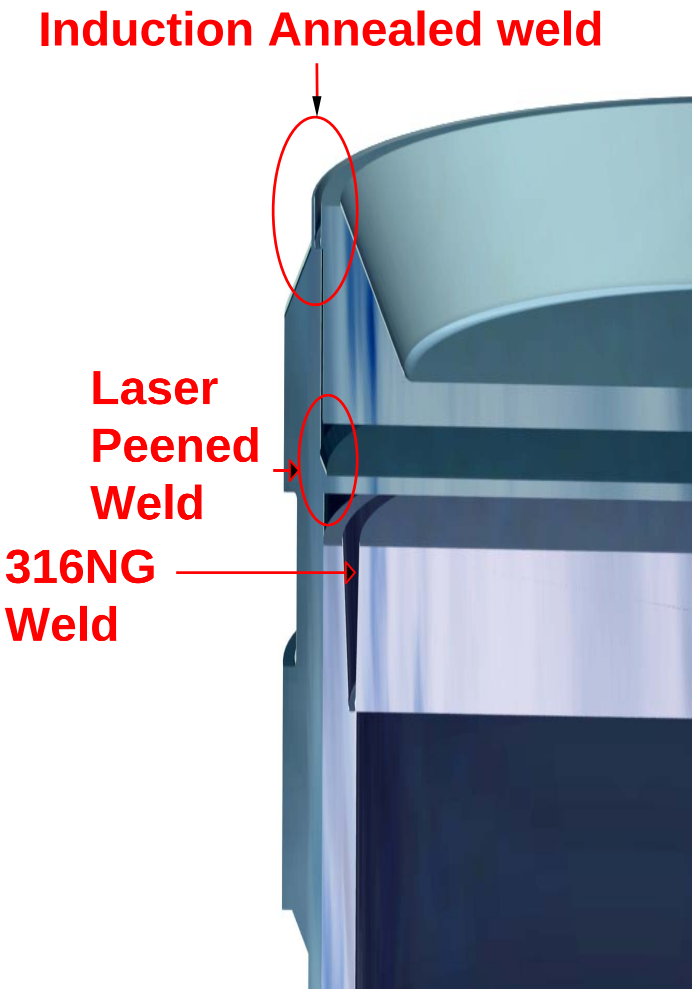
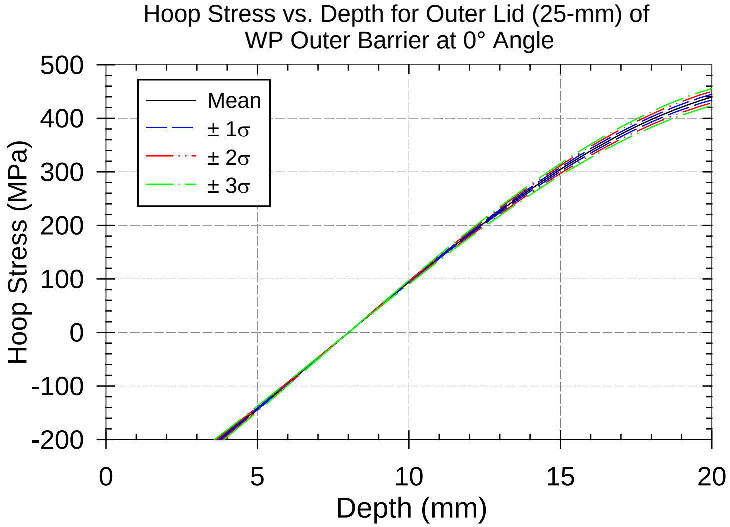
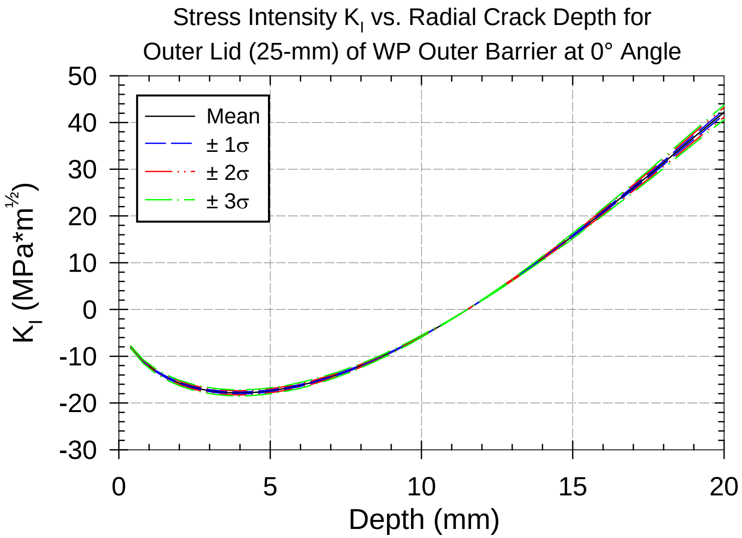


TSPA-SR

- Recent data from SCC tests show that both Alloy 22 and Ti are susceptible to SCC
- Mitigation of weld residual stresses is a necessary step to eliminate or delay SCC
- A second lid has been added to the design for additional margin
- The residual stress distribution resulting from the mitigation step is incorporated into the SCC model

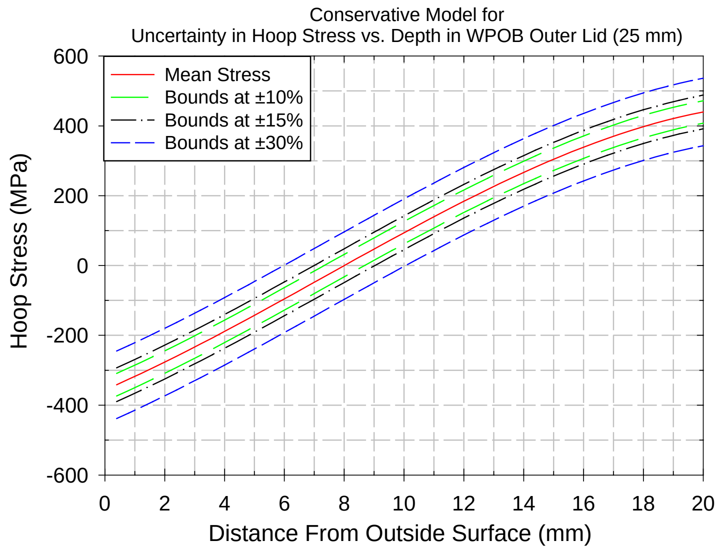
Stress Corrosion Cracking – Solution Annealing of Outer Closure Lid

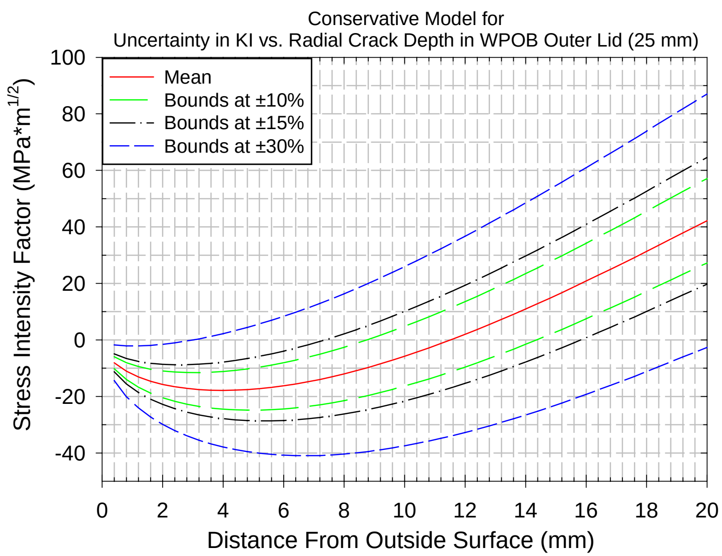




- **Hoop stress is the dominant stress driving radial SCC cracks in outer closure-lid weld**
- **Assume normal distribution bounded at 3 standard deviations for the uncertainty range**
- **Stress must exceed threshold stress for crack to initiate**
  - **Assume uniform distribution between 20 and 30% of yield strength**
- **Stress intensity factor (K_I) must be positive for crack to propagate**
- **Weld must be corroded to ~12 mm before SCC cracks propagate**

Alternative Conservative Model for Stress and Stress Intensity Factor Uncertainty in Outer Closure-Lid Weld





TSPA-SR

- Modify stress and stress intensity factor uncertainty distributions to include wider ranges based on present uncertainty
- Assume triangular distribution between the bounds and with the mode at the mean
- Conservative because weld stress can be controlled in design process
- Decreases minimum thickness of compressive zone to ~6 mm with ±30% uncertainty bounds
- The mitigated layer is allowed to corrode away by general corrosion and the SCC is initiated when the stress levels exceed the threshold

Waste Package Lifetime

TSPA-VA

- First failure of waste package was due to localized corrosion of the two barriers
- First failure occurred at about 2700 years after emplacement

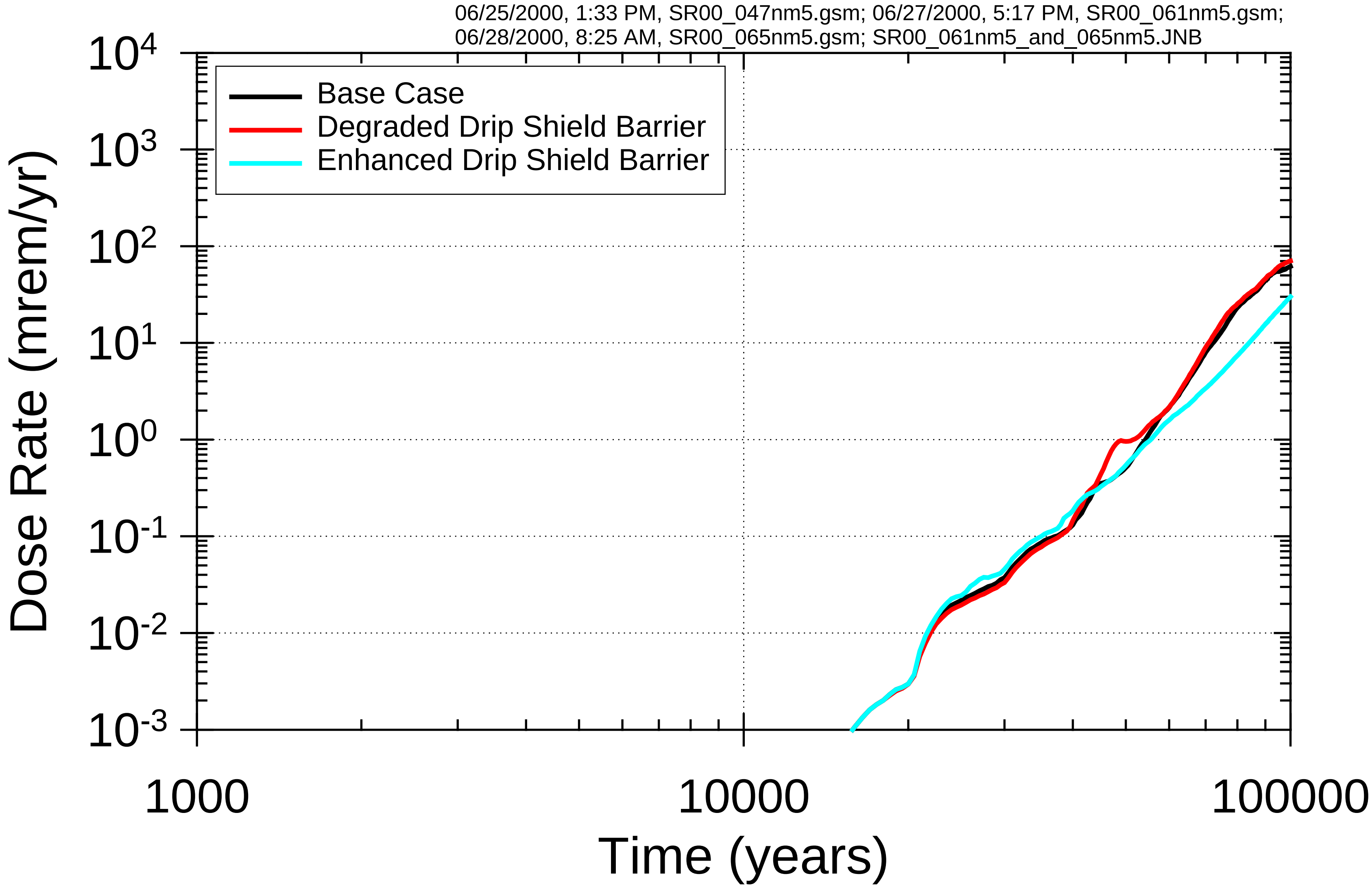
TSPA-SR

- Significant model enhancements incorporated to account for changed design and to include new repository relevant data
- First failure of waste package is conservative estimate at about 11,000 years. This failure time has a very low probability and represents the earliest possible first failure time for the worst case scenario

Drip Shield Barrier Sensitivity

- **Degraded Barrier**
  - 95th %tile Titanium Median General Corrosion Rate
  - 5th %tile Uncertainty-Variability Partition (i.e., high variability/low uncertainty)
- **Enhanced Barrier**
  - 5th %tile Titanium Median General Corrosion Rate
  - 95th %tile Uncertainty-Variability Partition (i.e., low variability/high uncertainty)

Preliminary
Drip Shield Barrier Sensitivity



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Waste Package Barrier Sensitivity

- **Degraded Barrier**
  - 95th %tile SCC Outer and Inner Lid Stress Profile Indices (+/- 30% uncertainty range)
  - 95th %tile Alloy 22 Median General Corrosion Rate
  - 5th %tile Uncertainty-Variability Partition (i.e., high variability/low uncertainty)
  - 95th %tile manufacturing defect probability (or defect number per WP)
  - 95th %tile aging enhancement factor
  - 95th %tile MIC enhancement factor

Waste Package Barrier Sensitivity

(Continued)

- **Enhanced Barrier**
  - 5th %tile SCC Outer and Inner Lid Stress Profile Indices (+/- 30% uncertainty range)
  - 5th %tile Alloy 22 Median General Corrosion Rate
  - 95th %tile Uncertainty-Variability Partition (i.e., low variability/high uncertainty)
  - 5th %tile manufacturing defect probability (or defect number per WP)
  - 5th %tile aging enhancement factor
  - 5th %tile MIC enhancement factor

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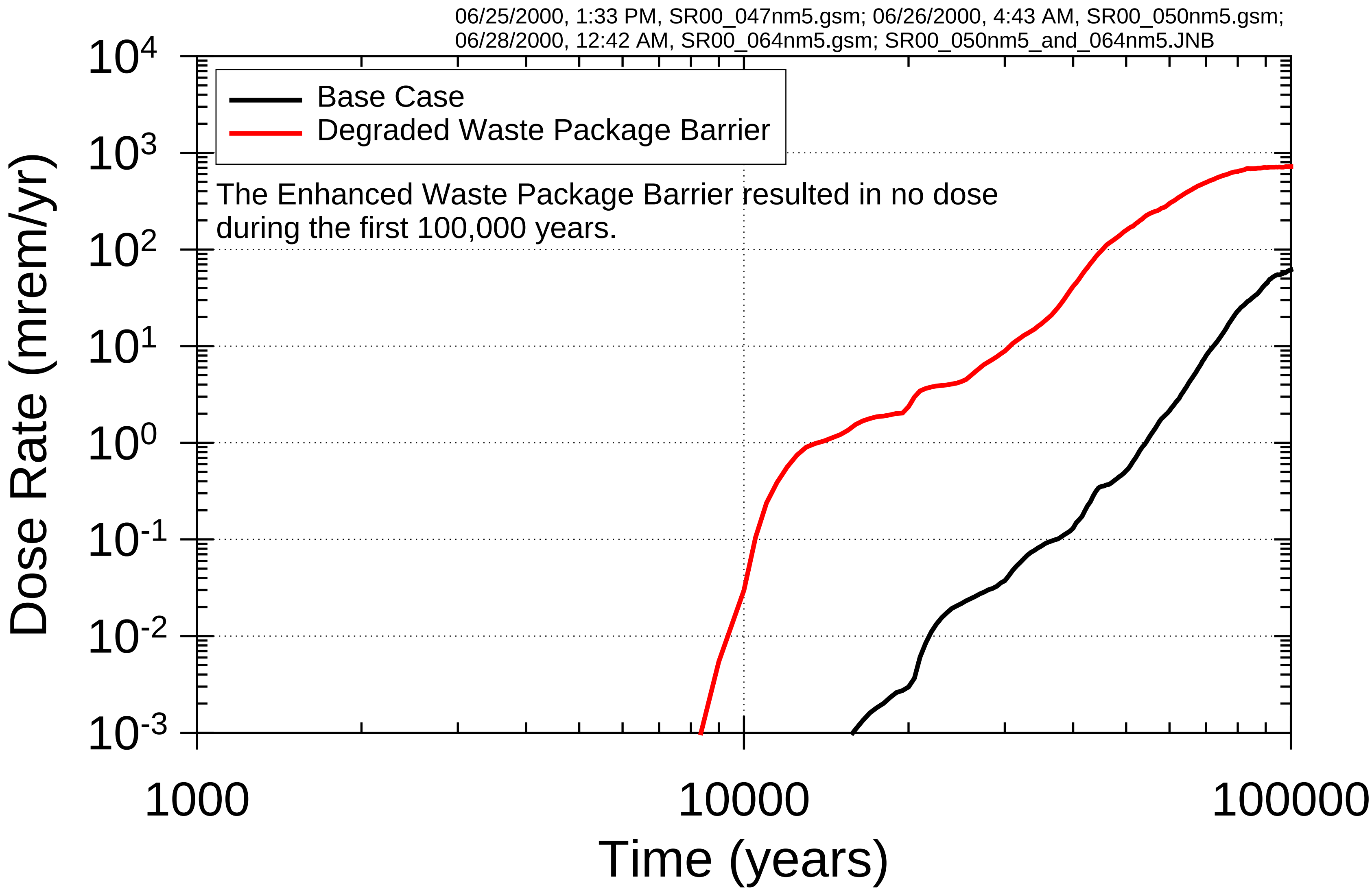
Waste Package Barrier Sensitivity



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