

PRELIMINARY DRAFT
User's Guide to
Waste Package Degradation (WAPDEG) Simulation Code
Version 1.0

WAPDEG was developed for
Yucca Mountain Site Characterization Project
Office of Civilian Radioactive Waste Management
United States Department of Energy

by

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September 9, 1996

[WAPDEG Version 1.0 was originally developed to simulate waste package degradation as part of the total system performance assessment-1995 (TSPA-1995) for the potential Yucca Mountain repository. This **PRELIMINARY DRAFT** user's guide is provided to the U.S. Nuclear Regulatory Commission to facilitate the NRC's detailed review of the waste package degradation simulation results conducted for TSPA-1995.]

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1. INTRODUCTION

The current design concept for a multi-barrier waste container provides the primary component of the engineered barrier system (EBS) for containment and isolation of spent nuclear fuel (SF) and vitrified defense high-level waste (DHLW) in the potential repository at Yucca Mountain. Fulfillment of the requirements for substantially complete containment and subsequent controlled release of radionuclides into the geosphere will rely upon a robust waste container design, among other EBS components. Failure of the waste container will most likely occur in the form of 'holes' created by localized corrosion of the container materials. An additional 'small' fraction of waste containers may fail prematurely due to material and/or manufacturing defects or damage during handling. Even if perforated with holes and cracks, the waste container should still be able to provide a substantial barrier to release of radionuclides (Pigford, 1993).

WAPDEG (Waste Package DEgradation) Version 1.0 was originally developed to simulate waste package degradation as part of the total system performance assessment-1995 (TSPA-1995) (M&O, 1995) for the potential repository at Yucca Mountain. As outputs, WAPDEG provides the failure time of waste packages (defined as having at least one pit penetration) and subsequent pitting degradation history of the waste packages. This **PRELIMINARY DRAFT** user's guide was prepared to facilitate the detailed review of the TSPA-1995 waste package degradation simulations by the United States Nuclear Regulatory Commission.

2. CORROSION MODELS

The current version of WAPDEG simulates a waste package with two layers of metal barrier: the first layer is carbon steel (corrosion-allowance barrier) and the second layer is Alloy 825 (corrosion-resistant barrier). For a nominal waste package design, the thickness of the first layer is 100 mm, and that of the second layer is 20 mm.

The corrosion models presented in this chapter result from synthesis and analysis of literature data to capture and represent the major parameters in the corrosion degradation processes. More detailed discussions of the models are given elsewhere (M&O, 1995; Lee, et al. 1996a and 1996b). The site-relevant corrosion testing and model development programs currently underway in this program should enable incorporation of detailed electrochemical and other physicochemical processes associated with waste container corrosion for future analysis (Henshall, et al., 1993; McCright, 1994).

As discussed in Sections 2.1 and 2.2, carbon steel undergoes active corrosion both in humid-air and aqueous environments. In the potential repository, it is expected that the waste container will be exposed to both humid-air and aqueous conditions at elevated temperatures for extended periods of time. The term "humid-air corrosion" is used to refer to corrosion which takes place under a 'thin' film of water that forms on the container surface above a certain critical humidity threshold. Such a water film is not thick enough to behave as bulk water. The term "aqueous corrosion" is used to refer to corrosion of metal in contact with bulk water.

2.1 Humid-Air Corrosion Models for Carbon Steel

A total of 166 atmospheric corrosion data (up to 16 years of exposures) of cast irons and carbon steels which have similar corrosion behaviors to the candidate corrosion-allowance materials were collected from literature. The data are from various exposure conditions in tropical, rural, urban, and industrial test locations (Lee, et al 1996a). Important testing parameters considered in the data compilation included test duration, average exposure temperature, average relative humidity, and average sulfur dioxide content of the test atmosphere. The test exposure conditions for the collected data range from 5 to 27°C average temperature, 63 to 85% average relative humidity (RH), and 2 to 406 $\mu\text{g SO}_2/\text{m}^3$ average SO_2 content. Although no considerable SO_2 -level is expected in the potential repository, it was necessary to include the SO_2 -content term in the model fitting.

General Corrosion Model

The following dependencies of general corrosion on exposure conditions in humid-air were obtained from the literature data and incorporated into the model development.

$$D_g \propto A_1 t^{A_2} \quad (1)$$

$$\frac{dD_g}{dt} \propto B_1 e^{\frac{B_2}{RH}} \quad (2)$$

$$\frac{dD_g}{dt} \propto C_1 e^{\frac{C_2}{T}} \quad (3)$$

$$\frac{dD_g}{dt} \propto D_1 e^{D_2 [SO_2]} \quad (4)$$

where D_g is general corrosion depth (μm), dD_g/dt is general corrosion rate ($\mu\text{m}/\text{yr}$), t is exposure time (years), RH is relative humidity (%), T is temperature (K), and $[SO_2]$ is sulfur dioxide content in the testing atmosphere ($\mu\text{g}/\text{m}^3$). A 's, B 's, C 's, and D 's are constants. By combining equations (1) through (4), the humid-air general corrosion model can be expressed as follows:

$$\ln D_g = a_0 + a_1 \ln t + \frac{a_2}{RH} + \frac{a_3}{T} + a_4 [SO_2] + \varepsilon \quad (5)$$

where a_0 , a_1 , a_2 , a_3 and a_4 are constants to be determined from fitting equation (5) to the transformed corrosion data. ε is a term representing uncertainties not explained by the model and has a normal distribution with a mean of zero and a standard deviation of 0.38. Linear regression was used to fit the model in equation (8), giving the following parameter values: $a_0 = 16.9865 \pm 2.8736$, $a_1 = 0.6113 \pm 0.0295$, $a_2 = -893.76 \pm 231.04$, $a_3 = -833.53 \pm 381.97$, and $a_4 = 0.002637 \pm 0.000377$.

Pitting Corrosion Model

A stochastic pitting corrosion model for the corrosion-allowance barrier in humid-air was developed by utilizing a pitting factor that is defined as the ratio of the maximum pit depth to the general corrosion depth at a given exposure time. The results from the extensive corrosion testing programs in inland tropical environments in Panama indicate that the pitting factor for carbon steels and cast irons exposed to 'normal' atmospheric conditions (i.e. in the absence of highly aggressive conditions such as in acidic or concentrated salt conditions) ranged from 2 to 6 (Southwell and Bultman, 1982; Southwell et al, 1976). The distribution may be similar to a normal distribution but with a long tail to the right (Marsh and Taylor, 1988; Marsh et al, 1988; Strutt et al, 1985). Accordingly, the pitting factor was assumed to be normally distributed with a mean of 4 and a standard deviation of 1. In addition, the pitting factor was constrained to be greater than or equal to 1, i.e. with the pitting factor equal to 1, the pit depth is equal to the

general corrosion depth. The pitting factor was sampled randomly and used as a multiplier to the general corrosion depth. Thus, the pitting corrosion model of corrosion-allowance material in humid-air is expressed as follows:

$$D_p = f_p \cdot D_g = \begin{cases} \text{normal}(4,1) \cdot D_g & \text{if } \text{normal}(4,1) \geq 1 \\ D_g & \text{if } \text{normal}(4,1) < 1 \end{cases} \quad (6)$$

where D_p is pit depth (μm) and f_p is the pitting factor. In the stochastic pitting modeling, pit initiation was not explicitly considered. Instead, all the pits that can form on the waste container were assumed to start growing at the same time when the humid-air general corrosion initiates.

2.2 Aqueous Corrosion Models for Carbon Steel

General Corrosion Model

An aqueous general corrosion model for carbon steel was developed using long-term corrosion data for a suite of carbon steel and cast iron, which were obtained from literature. The following aqueous general corrosion dependencies on exposure conditions were obtained from the literature data and incorporated into the model development:

$$D_g \propto A_3 t^{A_4} \quad (7)$$

$$\frac{dD_g}{dt} \propto C_3 e^{\left(\frac{C_4}{T} + C_5 T^2\right)} \quad (8)$$

where A 's and C 's are constants, and other symbols were defined in equations (1) to (4). By combining equations (7) and (8), the aqueous general corrosion model is expressed as follows:

$$\ln D_g = b_0 + b_1 \ln t + \frac{b_2}{T} + b_3 T^2 + \varepsilon \quad (9)$$

where b_0 , b_1 , b_2 and b_3 are constants to be determined from fitting equation (9) to the aqueous general corrosion data. ε is a term representing uncertainties not accounted for in the model and has a normal distribution with a mean of zero and standard deviation of 0.19. Parameter values for the corrosion rate constant (b_0) and the time-dependence term (b_1) were determined from long-term corrosion data (up to 16 years) in polluted river water (Larrabee, 1953; Coburn, 1978) and in tropical lake water (Southwell et al, 1970). The data include the potential effects of various chemical species dissolved and of microbial activity in the waters. Parameter values for

the temperature dependence terms (b_2 and b_3) were determined from a set of short-term (100 days) corrosion data of mild steel in distilled water at temperatures from 5 to 90°C (Brasher and Mercer, 1968; Mercer et al, 1968). The parameter values are: $b_0 = 111.506 \pm 10.804$, $b_1 = 0.532 \pm 0.0272$, $b_2 = -23303.2 \pm 2296.2$, and $b_3 = -3.193 \times 10^{-4} \pm 3.526 \times 10^{-5}$.

Pitting Corrosion Model

As in the humid-air pitting corrosion model, aqueous pitting corrosion of corrosion-allowance material was modeled stochastically by assuming the pitting factor is normally distributed with a mean of 4 and a standard deviation of 1 (Southwell et al, 1970), and equation (6) is also applicable to aqueous pitting corrosion of corrosion-allowance material.

2.3 Pitting Model for Alloy 825

The pitting corrosion model for Alloy 825 (corrosion resistant inner barrier) was developed from an elicitation discussed in the previous TSPA (Andrews et al, 1994). The elicitation provides a range of "constant" (time-independent) pit growth rates in aqueous conditions at 70 and 100°C. In the elicitation, the pit growth rate ranges are presented as the median, 95th percentile and 5th percentile growth rates. Since pits grow at a decreasing rate with time, the "constant" pit growth rates given in the elicitation are conservative. For the pit growth rate ranges at other temperatures, these values were extrapolated as a function of temperature in an Arrhenius-type functional form. The resulting functional form for the median pit growth rate is given as follows:

$$\ln R_p = 50.373 - \frac{19655.85}{T} \quad (10)$$

where R_p is the constant pit growth rate (mm/yr), and T is temperature (K). The pit growth rate decreases exponentially with decreasing temperature, and the rate at room temperature is about 6 orders of magnitude less than the rate at 100°C (373 K). In WAPDEG, pit growth rates for the Alloy 825 inner barrier are sampled randomly, based on the 95th and 5th percentile pit growth rate ranges.

3. OVERVIEW OF WAPDEG

An overview of WAPDEG is shown in Figure 1. The humid-air and aqueous general and pitting corrosion models (with uncertainties) for the carbon steel outer barrier, and the aqueous pitting corrosion model (with uncertainties) for the Alloy 825 inner barrier are incorporated into the stochastic waste package degradation simulation module. The drift-scale temperature and humidity profiles at the waste container surface are fed into the waste package degradation simulation module as a lookup table. The waste package degradation simulation module calls on appropriate corrosion model(s) depending on the near-field environment and the waste container degradation at a given time step. The simulation module provides as output the "failure" time for each waste package, which corresponds to the time for the initiation of waste form alteration (or radionuclide mobilization) inside the waste package. The simulation module also provides the pitting history of a "failed" waste container in terms of the number of pit penetrations as a function of time. A total number of pit penetrations at a given time gives an area on the waste container that is available for transport of mobilized radionuclides through the waste container. The waste package "failure" time and subsequent pitting history of the container are incorporated into the EBS transport model.

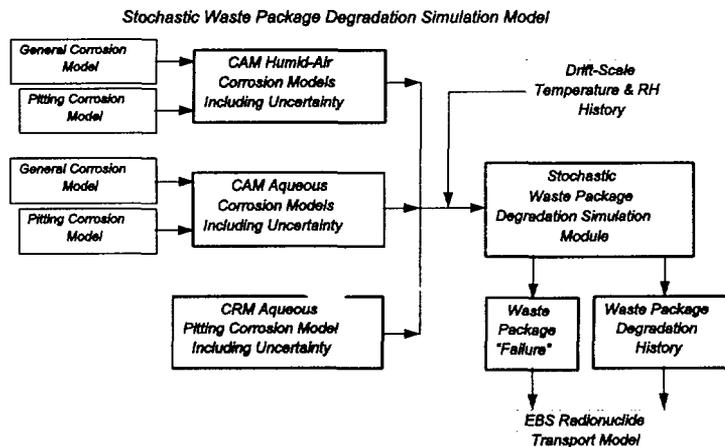


Figure 1 An Overview of WAPDEG Code.

4. ASSUMPTIONS IN WAPDEG SIMULATION

This chapter discusses the major assumptions made in the WAPDEG simulations. Reference(s) for the basis of the assumptions are given when available.

- 1) Humid-air general and pitting corrosion of the carbon steel outer barrier initiate at a threshold RH which is uniformly distributed between 65 and 75 %. This threshold is independently chosen for each waste package. This assumption is based on numerous data found in the literature (Haynie, et al, 1978; Phipps and Rice, 1979; Vernon, 1933).
- 2) Aqueous general and pitting corrosion of the carbon steel outer barrier initiate at a threshold RH which is uniformly distributed between 85 and 95 % RH. Visual observations indicating that steel coupon surfaces were covered with a thin film of water at about 85 % RH in a controlled environment chamber have been reported (Haynie, et al., 1978).
- 3) For each waste package, complete and positive correlation of the humid-air corrosion initiation threshold and the transition threshold from humid-air corrosion to aqueous corrosion is assumed. That is, if humid-air corrosion initiates at 65 % RH, aqueous corrosion initiates at 85 % RH.
- 4) Corrosion-allowance outer barrier material (carbon steel) is subjected to general and pitting corrosion both in humid-air and aqueous conditions. The uncertainties in the humid-air and aqueous general corrosion models (equations (5) and (9)) were utilized to account for pit to pit variability and waste package to waste package variability. In the post-closure repository, about 12,000 waste packages will be spread over the repository area, and a local corrosion environment in one part of the repository may be different from that in another part. This variability of the local corrosion environment is referred to here as waste package to waste package variability. Also, since a waste container has a relatively large surface area (about 37 m²), the general corrosion rate on one part of the waste package may be different from that on another part of the waste package. This variability in corrosion rate on a waste package is referred to here as pit to pit variability. Because information on the degree of the variability among waste packages and among pits is not available currently, the variabilities are accounted for by equally splitting the uncertainties in the humid-air and aqueous general corrosion models into the variability among waste packages and the variability among pits.
- 5) Corrosion resistant inner barrier material (Alloy 825) is subjected to aqueous pitting corrosion only (not to general corrosion). The time-independent pit growth rate distributions (equation (10)) were utilized to represent pit to pit variability and waste package to waste package variability. The same reasoning given in item (4) is applied also to account for the variability among waste packages and among pits.

- 6) When pits reach the inner barrier through the outer barrier, aqueous conditions are assumed there. This assumption is based on the observations that the capillary condensation of moisture by gel-like porous corrosion products of the outer barrier covering the inner barrier surface (Vernon, 1933) and the hygroscopic nature of many corrosion products (Fyfe, 1994; Haynie et al. 1978) would provide an aqueous corrosion condition at the surface of the inner barrier.
- 7) Pits form uniformly over the entire waste container surface. It is known that pits are most stable when growing in the direction of gravity because the dense, concentrated solution within a pit is necessary for its continuing activity (Fontana, 1986, pp. 64-69). Elongation of pits growing in the direction of gravity has been observed (Ruijini, et al, 1989). However, there is an uncertainty regarding crevice corrosion at the bottom of the waste container contacting the invert. Additionally, over the containment and isolation periods, rock may fall on the waste container, or backfill may be introduced. In these cases, there may be crevice corrosion occurring at the contact points between the rocks and waste container surface. Because of the uncertainty of the possibility of crevice corrosion at the side and bottom of waste containers, it is assumed that pits form uniformly over the entire waste container surface.
- 8) All pits have a uniform area of 1 mm^2 which corresponds to a pit radius of 0.56 mm. This may be large for the pits forming in Alloy 825, which tend to be much narrower (Szklaarska-Smialowska, 1986, pp. 127-141).
- 9) The waste container surface has a pit density of 10 pits/cm^2 (Marsh, and Taylor, 1988; Marsh et al, 1988; Strutt et al, 1985), and the same pit density is also assumed for the inner barrier.
- 10) Taking the pit density (10 pits/cm^2), the uniform pit area (1 mm^2) and the nominal surface area (about 37 m^2) of the waste package container, the total number of pits that can form on the waste container is about 4 million. This corresponds to about 10 % of the total surface area.
- 11) All the pits on a waste package start to grow at the same time when the threshold humidity discussed in items (1) and (2) is reached. That is, pit initiation is not explicitly considered in WAPDEG.

5. IMPLEMENTATION OF WAPDEG

The algorithm for the waste package degradation simulations in WAPDEG is described in the flow chart shown in Figure 2. In the simulations, the time steps are discretized such that within any time step, both the relative humidity and the temperature are relatively constant (e.g., within 2% difference in a given time step). A total of 400 waste packages are simulated for the nominal case. For each simulated waste package, random values were selected to represent the mean values on that particular waste package of each of the parameters in the corrosion models. This selection process is represented by the second box in the flow chart in the figure.

A total of 250,000 pits per waste package (instead of 4 million pits as indicated in Item #10 in Chapter 4) are used in the simulations. The choice of this number is discussed below. Based on the mean values already selected for each waste package, random values were sampled for each pit to represent the parameters in the corrosion models. This is represented by the third box in the flow chart in Figure 2.

Once the parameter values for the corresponding corrosion model are known for a given pit, the depth of that pit is tracked through each time step. Within each time step, the average relative humidity and temperature are calculated. These are used to determine whether humid-air or aqueous corrosion is occurring, and at what rate corrosion is occurring. Based on this information, the model calculates how much corrosion occurs during that time step, and checks if the pit penetrates the waste package. If the pit penetrates the waste package during that time step, the time when the pit penetrates the waste package is also calculated. This is illustrated in the fourth through seventh boxes of the flow chart in Figure 2.

As mentioned above, the WAPDEG simulation for a nominal case is conducted with a reduced number of waste packages (400 waste packages) and pits (250,000 pits per waste package) primarily because of constraints in computing resources. Considering various sources of uncertainties embedded in conceptual models and process-level models (thermal-hydrologic model, corrosion model, etc.), the results based on the smaller number of waste packages and pits should not be significant in light of the overall uncertainty range of the analyses. Also, test simulations were conducted with waste package numbers from 50 to 500 and pit numbers per waste package from 100,000 to 4,000,000 to evaluate the effect of using smaller values to represent the larger system. It was generally found that the number of waste packages used did not influence the results noticeably. For example, in the 83 metric tons of uranium (MTU)/acre case (the example problem case discussed in Chapter 7), when the number of pits was increased from 100,000 to 4,000,000 per waste package, the reduction in the time for the first pit penetration was on the order of 200 years for most waste packages.

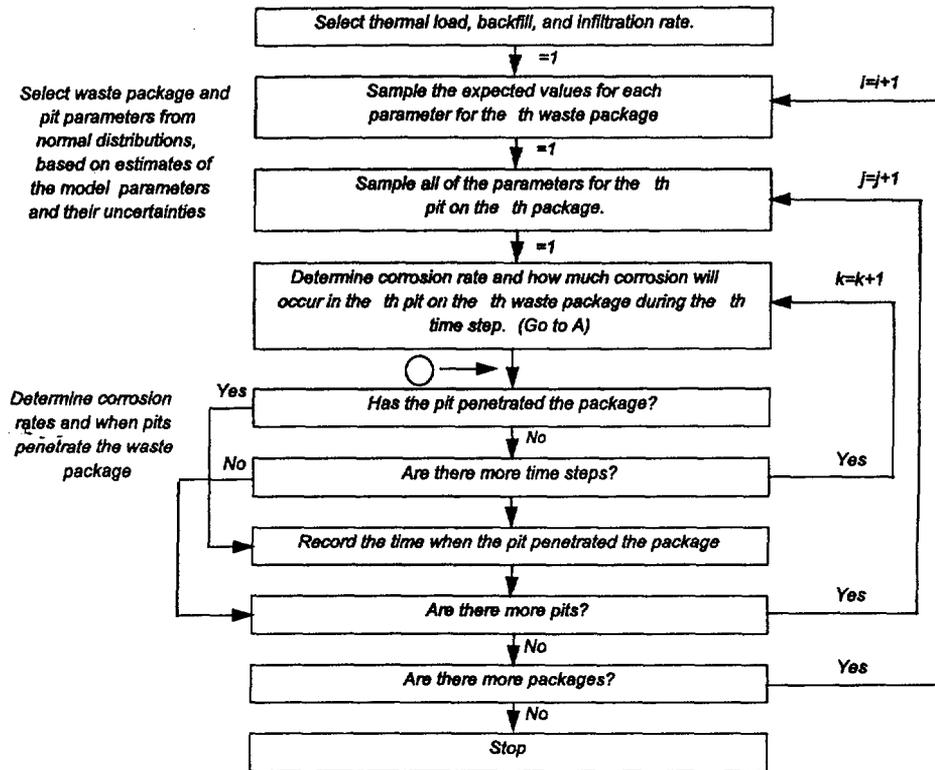


Figure 2 Flowchart of the stochastic waste package degradation simulation in WAPDEG.

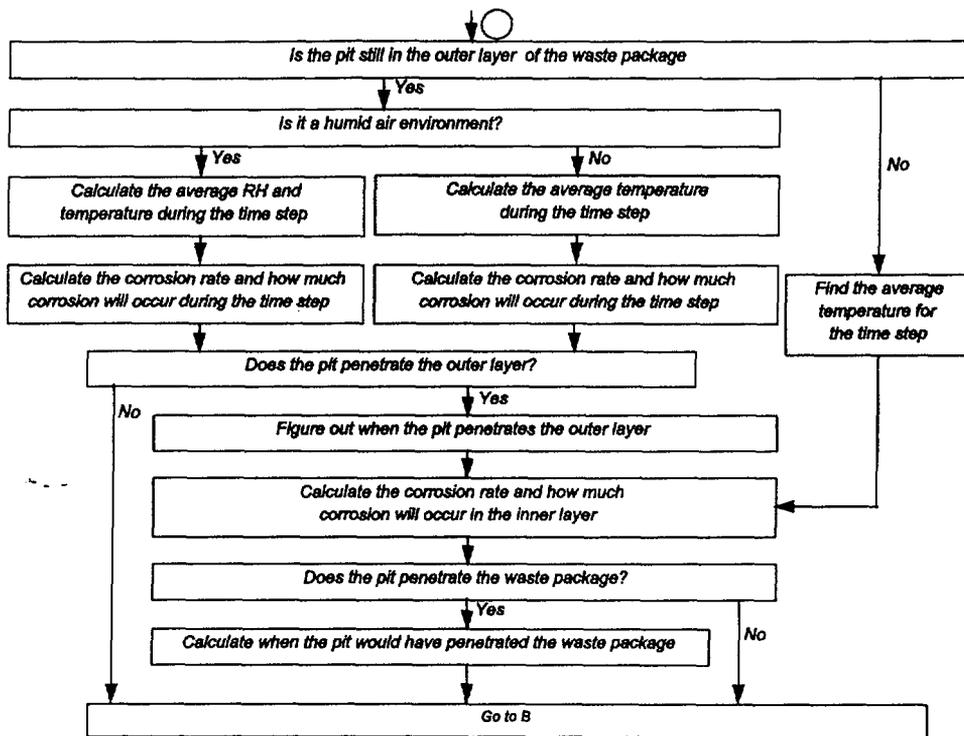


Figure 2 (continued).

6. Cathodic Protection

It is generally agreed that in the current waste package design, some degree of cathodic protection of the Alloy 825 corrosion-resistant inner barrier will be provided by the carbon steel outer barrier. The cathodic protection mechanism will become active when the outer barrier is breached and a galvanic couple is formed between the outer barrier and the inner barrier. Proper cathodic protection is ensured if the two metals maintain an intimate contact. However, no published data are available that are readily applicable to the current stochastic waste package degradation simulation. An elicitation was provided to account for the cathodic protection of the corrosion-resistant inner barrier in the waste package (McCright, 1995). The elicitation indicates the inner barrier would be protected cathodically by the outer barrier, and suggests the pitting corrosion of the inner barrier be delayed until the thickness of the carbon steel outer barrier is reduced by 75%.

The cathodic protection measure in terms of the reduction of carbon steel outer barrier thickness has been incorporated into WAPDEG as follows. A waste package (i.e., carbon steel outer barrier) surface is divided into 50,000 patches, and the average general corrosion depth over the 50,000 patches is calculated every 100 years. While these 50,000 patches do not correspond in any way to the 250,000 pits which are sampled, our empirical results have shown that there is little variability in general corrosion depths between different sets of 50,000 patches.

Once the average general corrosion depth exceeds the threshold (in terms of outer barrier thickness reduction) specified in the input file, the time when cathodic protection ceases is determined by interpolating between the current time and the most recently considered time (when the average general corrosion depth did not exceed the threshold.). While linear interpolation may not be correct, it would not be a significant source of error, since the two times being used for interpolation differ only by 100 years.

7. EXAMPLE PROBLEM

In this chapter, an example problem run is illustrated for the case with a thermal loading of 83 metric tons of uranium (MTU)/acre, no backfill and high infiltration (0.3 mm/yr). Model predictions of the temperature and relative humidity histories at the waste package surface for this case are given in the TSPA-1995 report (M&O, 1995).

7.1 Input File

The input file for the example problem run is given in Table 1. The number in the first row refers to the number of time steps.

The next 38 lines provide the 38 time steps. In each of these rows, three numbers are provided. The first number is the year at which we are making predictions. The second number is the relative humidity of the waste package surface at the specified time. The third number is the temperature (in degrees Celsius) of the waste package surface at the specified time. The time steps are chosen such that within a time step, the relative humidity and the temperature are both relatively constant.

The character (either "T" or "F") in the 40th line is a logical variable determining whether the waste package temperature must be below some threshold before corrosion initiates. A "False" value gives the case where corrosion can occur at any temperature, while a "True" value gives the case where corrosion does not initiate until the temperature of the waste package surface is below 100°C. Currently, 100°C is the only threshold used, although that may be changed in the future.

The character (either "T" or "F") in the 41st line is a second logical variable. It determines whether cathodic protection is included in the model. If this option is included (denoted by a value of "True"), then it is followed by a fraction (the 0.75 in this example problem run) which indicates what fraction of the (carbon steel) outer barrier thickness is reduced by general corrosion before the inner barrier pitting corrosion initiates. In the current case, where cathodic protection is not included, the 0.75 value is ignored.

Table 1
Input File for the Example Run

38
560.8 64.89 120.48
568.4 65.07 120.41
603.0 66.33 119.85
655.1 67.42 119.37
697.4 68.72 118.75
759.2 69.78 118.22
824.3 71.12 117.3
911.1 72.45 116.35
1016.0 73.73 115.3
1132.0 74.88 114.24
1227.0 75.71 113.34
1360.0 76.75 112.07
1449.0 78.26 109.85
1571.0 79.44 108.04
1744.0 80.97 106.04
1821.0 82.39 104.74
1876.0 83.72 103.65
1921.0 85.06 103.11
2136.0 86.52 99.44
2231.0 87.07 97.74
2247.0 88.3 97.56
2408.0 89.8 95.13
2460.0 90.75 94.56
2530.0 92.11 93.27
2897.0 93.6 88.0
3496.0 95.11 80.95
4106.0 95.63 74.18
4874.0 95.71 68.43
5792.0 95.79 61.68
7276.0 96.93 55.23
9993.0 97.44 49.93
15000.0 97.5 43.08934
20000.0 97.5 39.01291
30000.0 97.5 33.7014
40000.0 97.5 31.03066
50000.0 97.5 29.51735
100000.0 97.5 26.62484
1000000.0 97.44 25.47
T
F
.75

7.2 Output File

For each waste packages, WAPDEG provides the following: when cathodic protection ceases (this number is 0 if cathodic protection is not included in the model), when the first pit penetrates the waste package, and how many pits have penetrated the waste package at each time steps. An example WAPDEG output file for one waste package for this example case is shown in Table 2. The first number in the first line (528) refers to the number of data points which are provided in the waste package pitting history. The second number (2316.2) refers to the time when the first pit penetrates the waste package. The third number (zero in this example run) refers to when cathodic protection of the inner barrier ceases. The following 528 lines give the waste package pitting history. The first number in each line is the time in years, and the second number is number of pits that have penetrated the waste package at that time.

Table 2
Output File for Example Run

528	.23162E+04	.00000E+00
	.23174E+04	1
	.23443E+04	2
	.23714E+04	2
	.23989E+04	7
	.24266E+04	20
	.24547E+04	31
	.24832E+04	42
	.25119E+04	47
	.25410E+04	50
	.25704E+04	54
	.26002E+04	58
	.26303E+04	61
	.26608E+04	69
	-.26916E+04	-80
	.27227E+04	86
	.27543E+04	104
	.27862E+04	113
	.28184E+04	132
	.28511E+04	150
	.28841E+04	166
	.29175E+04	173
	.29513E+04	180
	.29854E+04	188
	.30200E+04	206
	.30550E+04	221
	.30903E+04	247
	.31261E+04	293
	.31623E+04	320
	.31989E+04	357
	.32360E+04	408
	.32735E+04	465
	.33114E+04	527
	.33497E+04	615
	.33885E+04	704
	.34277E+04	817
	.34674E+04	956
	.35076E+04	1074
	.35482E+04	1126
	.35893E+04	1188
	.36308E+04	1257
	.36729E+04	1338
	.37154E+04	1443
	.37584E+04	1569
	.38020E+04	1701
	.38460E+04	1860
	.38905E+04	2081
	.39356E+04	2345

Table 2 (continued)

.39811E+04	2616
.40272E+04	2978
.40739E+04	3389
.41210E+04	3715
.41688E+04	3896
.42170E+04	4057
.42659E+04	4256
.43153E+04	4481
.43652E+04	4737
.44158E+04	4982
.44669E+04	5303
.45186E+04	5642
.45710E+04	5991
.46239E+04	6414
.46774E+04	6911
.47316E+04	7448
.47864E+04	8059
.48418E+04	8702
.48979E+04	9230
.49546E+04	9503
.50120E+04	9778
.50700E+04	10063
.51287E+04	10369
.51881E+04	10715
.52482E+04	11043
.53089E+04	11395
.53704E+04	11759
.54326E+04	12111
.54955E+04	12529
.55592E+04	12966
.56235E+04	13440
.56886E+04	13948
.57545E+04	14483
.58211E+04	14882
.58886E+04	15059
.59567E+04	15215
.60257E+04	15415
.60955E+04	15614
.61661E+04	15807
.62375E+04	15993
.63097E+04	16211
.63828E+04	16429
.64567E+04	16637
.65314E+04	16882
.66071E+04	17112
.66836E+04	17377
.67610E+04	17610
.68393E+04	17840
.69185E+04	18096
.69986E+04	18367

Table 2 (continued)

.70796E+04	18650
.71616E+04	18934
.72445E+04	19257
.73284E+04	19447
.74133E+04	19543
.74991E+04	19642
.75859E+04	19770
.76738E+04	19891
.77626E+04	20003
.78525E+04	20149
.79434E+04	20266
.80354E+04	20395
.81285E+04	20545
.82226E+04	20678
.83178E+04	20802
.84141E+04	20924
.85116E+04	21053
.86101E+04	21215
.87098E+04	21370
.88107E+04	21490
.89127E+04	21639
.90159E+04	21800
.91203E+04	21969
.92259E+04	22140
.93327E+04	22322
.94408E+04	22492
.95501E+04	22664
.96607E+04	22846
.97726E+04	23004
.98857E+04	23190
.10000E+05	23387
.10116E+05	23473
.10233E+05	23531
.10352E+05	23599
.10472E+05	23664
.10593E+05	23719
.10715E+05	23788
.10840E+05	23836
.10965E+05	23906
.11092E+05	23987
.11220E+05	24058
.11350E+05	24127
.11482E+05	24205
.11615E+05	24273
.11749E+05	24374
.11885E+05	24453
.12023E+05	24531
.12162E+05	24602
.12303E+05	24703
.12445E+05	24786

Table 2 (continued)

.12590E+05	24869
.12735E+05	24964
.12883E+05	25053
.13032E+05	25129
.13183E+05	25213
.13336E+05	25302
.13490E+05	25381
.13646E+05	25460
.13804E+05	25554
.13964E+05	25650
.14126E+05	25745
.14289E+05	25837
.14455E+05	25964
.14622E+05	26061
.14791E+05	26149
.14963E+05	26253
.15136E+05	26311
.15311E+05	26340
.15489E+05	26380
.15668E+05	26426
.15849E+05	26482
.16033E+05	26524
.16218E+05	26570
.16406E+05	26612
.16596E+05	26658
.16788E+05	26695
.16983E+05	26738
.17180E+05	26774
.17378E+05	26823
.17580E+05	26857
.17783E+05	26903
.17989E+05	26948
.18197E+05	26981
.18408E+05	27020
.18621E+05	27069
.18837E+05	27110
.19055E+05	27156
.19276E+05	27196
.19499E+05	27236
.19725E+05	27284
.19953E+05	27345
.20184E+05	27370
.20418E+05	27390
.20654E+05	27402
.20893E+05	27429
.21135E+05	27445
.21380E+05	27468
.21628E+05	27488
.21878E+05	27506
.22132E+05	27522

Table 2 (continued)

.22388E+05	27543
.22647E+05	27560
.22909E+05	27581
.23175E+05	27598
.23443E+05	27621
.23714E+05	27647
.23989E+05	27674
.24267E+05	27708
.24548E+05	27731
.24832E+05	27749
.25120E+05	27772
.25410E+05	27795
.25705E+05	27817
.26002E+05	27841
.26303E+05	27865
.26608E+05	27896
.26916E+05	27921
.27228E+05	27938
.27543E+05	27961
.27862E+05	27987
.28185E+05	28015
.28511E+05	28043
.28841E+05	28072
.29175E+05	28105
.29513E+05	28142
.29855E+05	28172
.30200E+05	28193
.30550E+05	28214
.30904E+05	28226
.31262E+05	28236
.31624E+05	28247
.31990E+05	28259
.32360E+05	28268
.32735E+05	28283
.33114E+05	28298
.33497E+05	28321
.33885E+05	28342
.34278E+05	28355
.34675E+05	28376
.35076E+05	28392
.35482E+05	28411
.35893E+05	28433
.36309E+05	28444
.36729E+05	28463
.37155E+05	28484
.37585E+05	28497
.38020E+05	28516
.38460E+05	28533
.38906E+05	28545
.39356E+05	28564

Table 2 (continued)

.39812E+05	28582
.40273E+05	28591
.40739E+05	28605
.41211E+05	28623
.41688E+05	28636
.42171E+05	28648
.42659E+05	28662
.43153E+05	28679
.43653E+05	28692
.44158E+05	28705
.44670E+05	28720
.45187E+05	28730
.45710E+05	28741
.46239E+05	28755
.46775E+05	28769
.47317E+05	28783
.47864E+05	28796
.48419E+05	28804
.48979E+05	28814
.49547E+05	28827
.50120E+05	28843
.50701E+05	28851
.51288E+05	28860
.51882E+05	28867
.52482E+05	28875
.53090E+05	28887
.53705E+05	28896
.54327E+05	28910
.54956E+05	28924
.55592E+05	28927
.56236E+05	28940
.56887E+05	28950
.57546E+05	28961
.58212E+05	28973
.58886E+05	28984
.59568E+05	28992
.60258E+05	29005
.60956E+05	29018
.61661E+05	29033
.62375E+05	29045
.63098E+05	29055
.63828E+05	29063
.64567E+05	29078
.65315E+05	29089
.66071E+05	29096
.66836E+05	29103
.67610E+05	29120
.68393E+05	29137
.69185E+05	29152
.69986E+05	29164

Table 2 (continued)

.70797E+05	29178
.71617E+05	29187
.72446E+05	29195
.73285E+05	29208
.74133E+05	29222
.74992E+05	29241
.75860E+05	29256
.76739E+05	29270
.77627E+05	29282
.78526E+05	29294
.79435E+05	29305
.80355E+05	29318
.81286E+05	29332
.82227E+05	29350
.83179E+05	29372
.84142E+05	29390
.85117E+05	29407
.86102E+05	29422
.87099E+05	29445
.88108E+05	29453
.89128E+05	29469
.90160E+05	29483
.91204E+05	29502
.92260E+05	29520
.93328E+05	29537
.94409E+05	29556
.95502E+05	29577
.96608E+05	29597
.97727E+05	29619
.98859E+05	29649
.10000E+06	29667
.10116E+06	29678
.10233E+06	29691
.10352E+06	29708
.10472E+06	29721
.10593E+06	29738
.10716E+06	29749
.10840E+06	29763
.10965E+06	29772
.11092E+06	29787
.11221E+06	29804
.11350E+06	29812
.11482E+06	29825
.11615E+06	29832
.11749E+06	29846
.11885E+06	29862
.12023E+06	29869
.12162E+06	29890
.12303E+06	29906

Table 2 (continued)

.12446E+06	29919
.12590E+06	29929
.12735E+06	29938
.12883E+06	29961
.13032E+06	29978
.13183E+06	29991
.13336E+06	30009
.13490E+06	30023
.13646E+06	30049
.13804E+06	30063
.13964E+06	30079
.14126E+06	30092
.14289E+06	30110
.14455E+06	30123
.14622E+06	30141
.14792E+06	30174
.14963E+06	30191
.15136E+06	30209
.15311E+06	30232
.15489E+06	30253
.15668E+06	30272
.15849E+06	30291
.16033E+06	30308
.16219E+06	30333
.16406E+06	30349
.16596E+06	30375
.16789E+06	30401
.16983E+06	30419
.17180E+06	30446
.17379E+06	30468
.17580E+06	30486
.17783E+06	30504
.17989E+06	30523
.18198E+06	30552
.18408E+06	30575
.18622E+06	30588
.18837E+06	30605
.19055E+06	30633
.19276E+06	30654
.19499E+06	30690
.19725E+06	30715
.19953E+06	30738
.20184E+06	30777
.20418E+06	30792
.20655E+06	30826
.20894E+06	30850
.21136E+06	30871
.21380E+06	30900
.21628E+06	30932

Table 2 (continued)

.21878E+06	30954
.22132E+06	30973
.22388E+06	31000
.22647E+06	31022
.22910E+06	31053
.23175E+06	31084
.23443E+06	31117
.23715E+06	31142
.23989E+06	31179
.24267E+06	31211
.24548E+06	31242
.24832E+06	31274
.25120E+06	31311
.25411E+06	31347
.25705E+06	31387
.26003E+06	31421
.26304E+06	31450
.26608E+06	31480
.26916E+06	31512
.27228E+06	31541
.27543E+06	31574
.27862E+06	31604
.28185E+06	31635
.28511E+06	31667
.28841E+06	31704
.29175E+06	31740
.29513E+06	31778
.29855E+06	31828
.30201E+06	31865
.30550E+06	31897
.30904E+06	31940
.31262E+06	31975
.31624E+06	32018
.31990E+06	32065
.32361E+06	32106
.32735E+06	32146
.33114E+06	32193
.33498E+06	32241
.33886E+06	32286
.34278E+06	32335
.34675E+06	32379
.35077E+06	32411
.35483E+06	32451
.35894E+06	32493
.36309E+06	32545
.36730E+06	32585
.37155E+06	32630
.37585E+06	32663
.38020E+06	32710

Table 2 (continued)

.38461E+06	32767
.38906E+06	32818
.39357E+06	32860
.39812E+06	32904
.40273E+06	32968
.40740E+06	33019
.41211E+06	33078
.41689E+06	33123
.42171E+06	33172
.42660E+06	33224
.43154E+06	33271
.43653E+06	33319
.44159E+06	33377
.44670E+06	33439
.45187E+06	33486
.45711E+06	33532
.46240E+06	33588
.46775E+06	33645
.47317E+06	33717
.47865E+06	33766
.48419E+06	33834
.48980E+06	33888
.49547E+06	33952
.50121E+06	34019
.50701E+06	34091
.51288E+06	34159
.51882E+06	34238
.52483E+06	34301
.53091E+06	34371
.53705E+06	34444
.54327E+06	34526
.54956E+06	34600
.55593E+06	34683
.56236E+06	34756
.56888E+06	34844
.57546E+06	34928
.58213E+06	35020
.58887E+06	35105
.59569E+06	35185
.60258E+06	35263
.60956E+06	35348
.61662E+06	35432
.62376E+06	35518
.63098E+06	35601
.63829E+06	35683
.64568E+06	35771
.65316E+06	35867
.66072E+06	35968
.66837E+06	36059

Table 2 (continued)

.67611E+06	36153
.68394E+06	36251
.69186E+06	36369
.69987E+06	36471
.70798E+06	36589
.71617E+06	36685
.72447E+06	36778
.73286E+06	36881
.74134E+06	36990
.74993E+06	37083
.75861E+06	37196
.76739E+06	37324
.77628E+06	37435
.78527E+06	37535
.79436E+06	37644
.80356E+06	37740
.81287E+06	37827
.82228E+06	37936
.83180E+06	38060
.84143E+06	38172
.85118E+06	38290
.86103E+06	38420
.87100E+06	38535
.88109E+06	38656
.89129E+06	38789
.90161E+06	38899
.91205E+06	39022
.92261E+06	39165
.93330E+06	39307
.94410E+06	39419
.95503E+06	39558
.96609E+06	39694
.97728E+06	39833
.98860E+06	39980
.10000E+07	40135

8. POST-PROCESSING OF WAPDEG RESULTS

The WAPDEG simulation results are processed with a number of Fortran programs. Two of these programs are described briefly here.

- 1) Program **sort1.f** rearrange the simulation result output according to the times that the first pit penetrate each of the waste packages. This arrangement is to prepare the simulation results for a graphical representation of an empirical cumulative density function (CDF) for the first pit penetration time. This empirical CDF for the example problem is shown in Figure 3. This figure was made by plotting the two columns in the output file produced by **sort1.f**.
- 2) Program **trim.f** arranges the simulation result output to make it easier to prepare a plot for pitting history of waste packages (i.e., the number of pits which have penetrated against time). It skips the leading row (the one containing three numbers as shown in Table 2) for each waste package from the file. This program then trims the pitting history by dropping points which are within a threshold (.01 log units) of the estimate which would be obtained by (log-log) interpolation between neighboring points. The program then reverses the order of the "trimmed" pitting histories for alternating waste packages. This is done so that when the two columns are plotted all of the line segments connecting neighboring waste packages will fall on the vertical line where time is 1,000,000 years or the horizontal line where one pit has penetrated the waste package. Pitting histories for 25 representative waste packages are shown in Figure 4. This figure was made by plotting the two columns in the output file produced by **trim.f**.

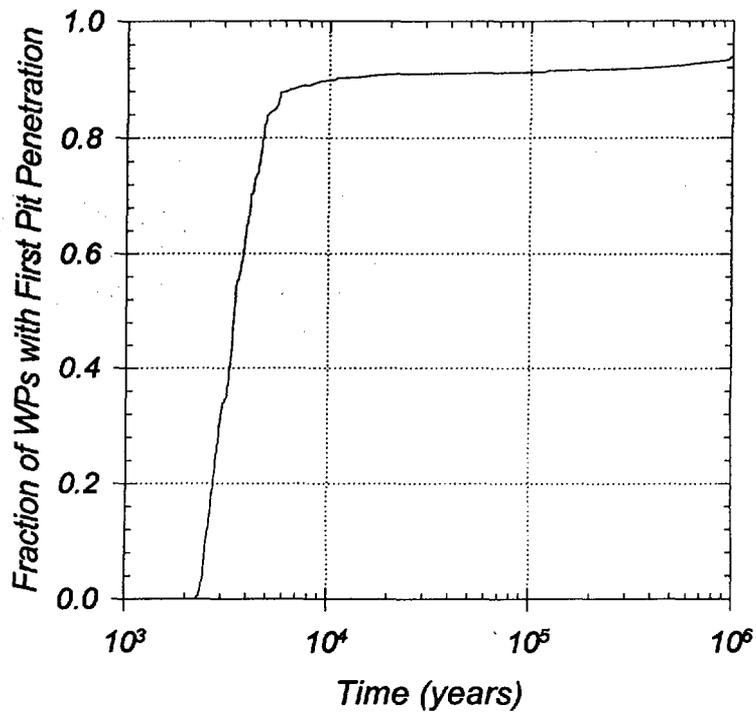


Figure 3 Waste Package Failure History for the Example Problem. Waste package failure is defined as having at least one pit penetration through the waste package container wall.

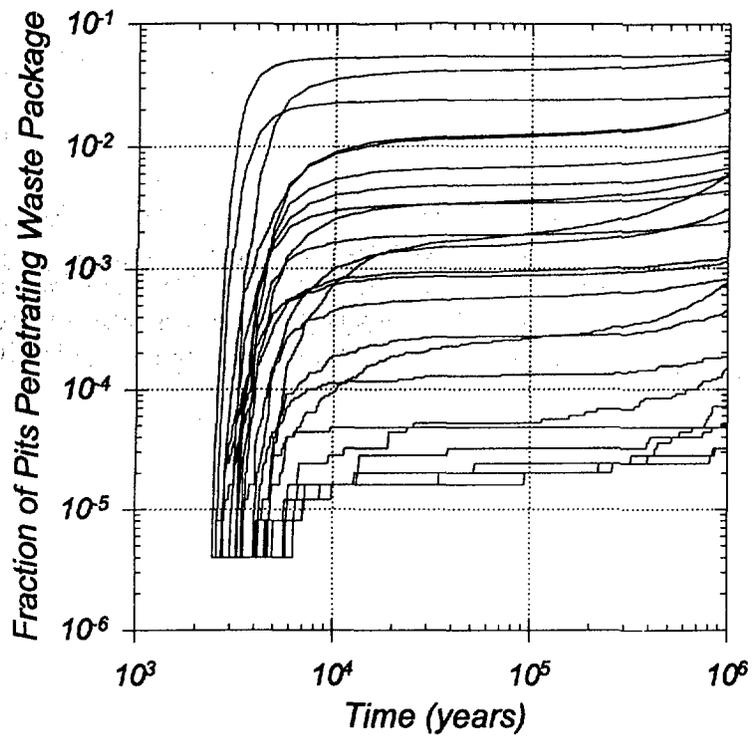


Figure 4 Pitting Histories of 25 Representative Waste Packages for the Example Problem.

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