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Estimation of corrosion on carbon steel TRU waste drums using the Poisson distribution

B.F. Lyon [a,*], J.A. Holmes [a], S.T. Kosiewicz [b], K.A. Wilbert [a], C.C. Travis [a]

[a] *Health Sciences Research Division, Oak Ridge National Laboratory [1], 1060 Commerce Park, MS-6480, Oak Ridge, TN 37830, USA*
[b] *Waste Management Program Office, Los Alamos National Laboratory, Los Alamos, NM, USA*

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Abstract

The number of container failures due to corrosion is estimated as a function of time for 55-gallon painted carbon steel drums under earthen cover. The calculations are performed using an empirical statistical model that assumes that the corrosion depths are given by a Poisson probability distribution parameterized by an average corrosion rate. Uncertainties in the average corrosion rate for both pitting and general corrosion are addressed, as is uncertainty in the drum wall thickness. Times for specific fractions of the population of drums to breach can be estimated in a manner that incorporates uncertainties in the corrosion process. To improve corrosion predictions, it is recommended that more data on the corrosion of carbon steel drums under earthen cover be collected in the future.

Keywords: Carbon steel drum; Corrosion; Poisson process; Transuranic waste

1. Introduction

Between 1970 and the early 1990s, U.S. Department of Energy (DOE) sites stored containers of transuranic (TRU) waste under earthen cover. TRU waste is defined as waste that is contaminated with alpha-emitting transuranium radionuclides having atomic numbers greater than 92, half-lives greater than 20 years, and concentrations

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[*] Corresponding author. Tel: 1-423-241-2649; Fax: 1-423-576-2962.

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greater than 100 nCi g^{-1} at the time of assay [1]. This interim storage practice was undertaken assuming that the stored waste would be retrieved within 20 years, certified, and shipped to the Waste Isolation Pilot Plant (WIPP) in New Mexico for permanent disposal. The projected 1988 opening of WIPP has been delayed and some containers have remained past their suggested 20 year lifetime limit [1], causing concern about the potential degradation of the containers. States are also mandating that sites bring container storage into compliance with new regulations, and some sites may be ordered to retrieve the waste and activate above-ground on-site storage until WIPP is available.

The purpose of this paper is to describe one approach to estimating the corrosion of TRU waste containers in an environment typical of that used within (DOE) sites. The waste in the containers generally consists of contaminated soil, laboratory or personal equipment, or by-products of processes, and is typically placed in plastic bags or small containers or cast into a cement matrix. Once contained, the waste is placed inside one of several sizes of larger, metallic containers, with the most frequently used containers for this purpose being 55-gallon painted or galvanized carbon steel drums [2].

Although the basic electrochemical theory of the corrosion process is well understood, accurate mechanistic corrosion models capable of predicting corrosion rates for common metals under a variety of environmental conditions do not exist. This situation has been a source of frustration for many years, as shown by the following comments made over a span of five decades:

> ...underground corrosion that has occurred can be explained, but...theory does not permit accurate prediction of the extent of corrosion to be expected to occur [3].
>
> It has been stated that metallic corrosion is an art rather than a science and that, at present, insufficient knowledge is available to predict with any certainty how a particular metal or alloy will behave in a specific environment...the decision to use a particular metal or alloy in preference to others in a given environment...is based usually on previous experience and empirical testing rather than on the application of scientific knowledge [4].
>
> Obviously, more research is needed before practical and scientific questions can be answered successfully and the results applied to the problems in the field [5].
>
> No model at present can quantitatively predict the formation and incubation time of pits [6].

During this time, scientific aspects of the corrosion process have become better understood, but it is still not possible to make accurate predictions of corrosion initiation and growth rates in most commonly encountered environments, chiefly because of a lack of data. Furthermore, in most situations requiring corrosion estimates, the necessary environmental data upon which theoretical calculations depend are either uncertain or unavailable. Nevertheless, decisions must be made that depend on the outcome of the corrosion process.

When the details of a process are too complicated to simulate mechanistically, empirical models are used. The success of such methods depends on the quantity and quality of supporting data and on the ability to correlate the systematic variations of the required quantities with the observed data. In the present case, it is the progression of corrosion on a population of waste drums that is of interest, rather than its detailed evolution on a single drum.

2. The Poisson probabilistic model for corrosion

The approach used for the estimation of external corrosion is an extension of that used in Duncan et al. [7], in which both general and localized corrosion are represented by Poisson distributions [8]. The Poisson distribution, which arises in counting experiments, describes the number of events one can expect within a specified time, given an average event rate. If r denotes the average rate (in events per unit time) and $N(s,s+t)$ denotes the number of events occurring in the time interval $(s,s+t)$, which is taken to be short in the sense that $rt \ll 1$, then the assumptions of a Poisson process are

$$\mathrm{Prob}[N(s,s+t)=1] = rt + o(t) \tag{1}$$

and

$$\mathrm{Prob}[N(s,s+t)=0] = 1 - rt + o(t) \tag{2}$$

where $\mathrm{Prob}[(s,s+t)=n]$ is the probability that there are exactly n arrivals in the interval $(s,s+t)$ and the symbol $o(t)$ denotes a function that, when divided by t, approaches 0 in the limit as t approaches 0. The result is that for small values of t the probability that exactly one arrival occurs is well approximated by rt. The second assumption implies that in the limit of small values of t the only other possibility is that no arrival occurs (i.e., the probability of no arrivals is 1 minus the probability of an arrival). Therefore, the probability of multiple arrivals in time interval t vanishes to first order in t for sufficiently short time intervals. Based on these assumptions, one can show that

$$\mathrm{Prob}[N(s,s+t)=n] = e^{-rt}(rt)^n/n! \tag{3}$$

independent of the initial time s. We note that these assumptions also imply that the occurrence of arrivals in the interval $(s,s+t)$ is unaffected by what happens prior to time s.

Eq. (3) can also be derived as a limiting case of the binomial distribution under the assumption of a large number of possible events, with each event having a very low observation probability. The derivation starts with the binomial distribution, which states that, given a total of N independent events with each described by a probability p of successful outcome, then the probability of obtaining n successful events is

$$P_B(n) = p^n(1-p)^{(N-n)}N!/[n!(N-n)!] \tag{4}$$

The Poisson distribution is obtained from Eq. (4) in the limit of a very large number of observations, $N \to \infty$, and very small success probability, $p \to 0$, taken in such a way that the product $\lambda \equiv Np$, which is the mean number of successes for N events each of success probability p in the binomial distribution, remains finite. In this limit, it is likely that $n \ll N$, so that the replacements $N!/(N-n)! \approx N^n$ and $(1-p)(N-n) \approx (1-p]N \approx \exp(\lambda)$ can be made in Eq. (4). With these replacements, and with the association of the mean number of binomial distribution successes λ with the average number of observed Poisson events rt, Eq. (4) for the binomial distribution can be seen to reduce to Eq. (3).

In using the Poisson distribution to model corrosion, we define an event to be the loss of one mil of drum wall thickness (one mil is 1/1000 in. or, equivalently, 0.0254 mm), either at a certain location (for pitting corrosion) or across the entire drum surface (for general corrosion). Given an average corrosion rate R in mil per year, one can estimate the probability that either pitting or general corrosion has exceeded a given depth L in mil by a time T in years by calculating the probability of at least L events by time T. By representing this as 1 minus the probability of less than L events, the probability that a thickness L will be exceeded by time T is

$$P(T,L) = 1 - \sum_{j=0}^{L-1} e^{-RT}(RT)^j/j! \tag{5}$$

We now note some well-known features of the Poisson probability distribution (Eq. (3). The first point to be made is that the Poisson distribution *is* a probability distribution. The parameter $\lambda \equiv rt$ provides the peak and the mean values of the Poisson probability distribution, but a sampling of the Poisson distribution results in values ranging from zero to infinity. Individual samples can vary significantly, both above and below the mean. When the Poisson parameter becomes large ($\lambda \gg 1$), the Poisson peak can be considered narrow in the sense that the width of the distribution peak is much less than the mean. In this case, the Poisson distribution can be approximated in the vicinity of the peak by a normal (Gaussian) distribution. By comparing, through quadratic terms, the Taylor expansions of the logarithms of the Poisson distribution and the approximate normal distribution about the distribution peak, the width of the Poisson distribution peak is seen to be $w \approx \sqrt{\lambda}$. By comparison with the binomial distribution from which it can be derived, the median value of the Poisson distribution is seen to occur in the vicinity of the peak and mean values, namely $n = \lambda \equiv rt$.

In the present application, the peak of the Poisson distribution falls at the drum thickness L when

$$T_{\text{peak}} = \lambda/R = L/R \tag{6}$$

so the average corrosion rate determines the rate of advance of the Poisson peak. Assuming that $L \gg 1$ mil, the width of the Poisson distribution at this time is $w_{\text{peak}} \approx \sqrt{L}$, so that the time duration for the peak to pass through the width is of the order

$$T_{\text{rise}} \approx w_{\text{peak}}/R = 1/R \times \sqrt{L} \tag{7}$$

To be certain of including the entire peak, we consider an interval of twice the rise time, which is still much less than the arrival time ($2 \times T_{\text{rise}} \ll T_{\text{peak}}$), centered at T_{peak}. To predict the number of failed drums, Eq. (5) is used. At the time T_{peak}, when $\lambda = L$, Eq. (5) shows that half the drums have failed. At the time $T_{\text{peak}} - T_{\text{rise}}$ most of the drums will still be intact, but at the time $T_{\text{peak}} + T_{\text{rise}}$, most of the drums will have failed.

Therefore, in a time interval of duration $2 \times T_{\text{rise}}$ centered about T_{peak}, most of the drums will fail. The important point about this prediction is that the ratio

$$2 \times T_{\text{rise}}/T_{\text{peak}} = 2/\sqrt{\lambda} = 2/\sqrt{L} \tag{8}$$

is small when L is much greater than 1.

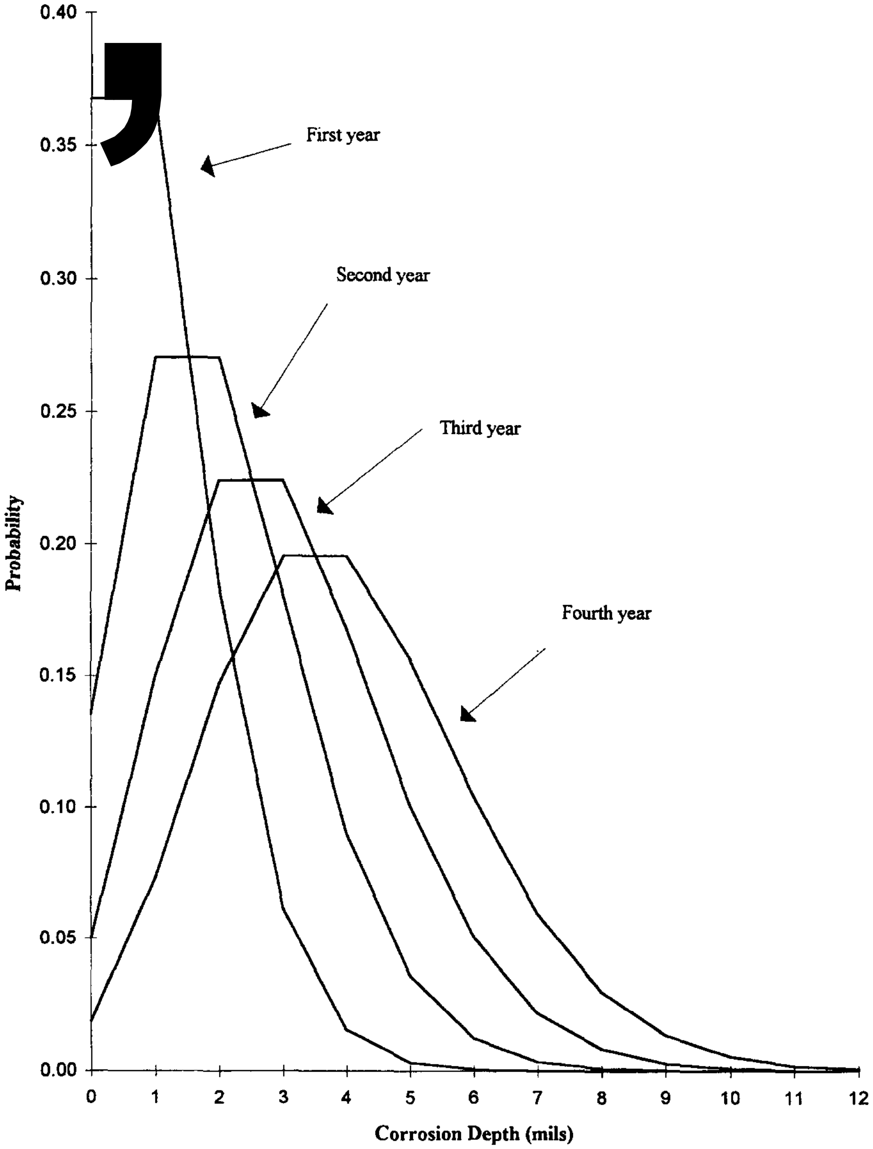

Fig. 1. Poisson probability distributions for parameter values $\lambda = RT = 1, 2, 3,$ and 4.

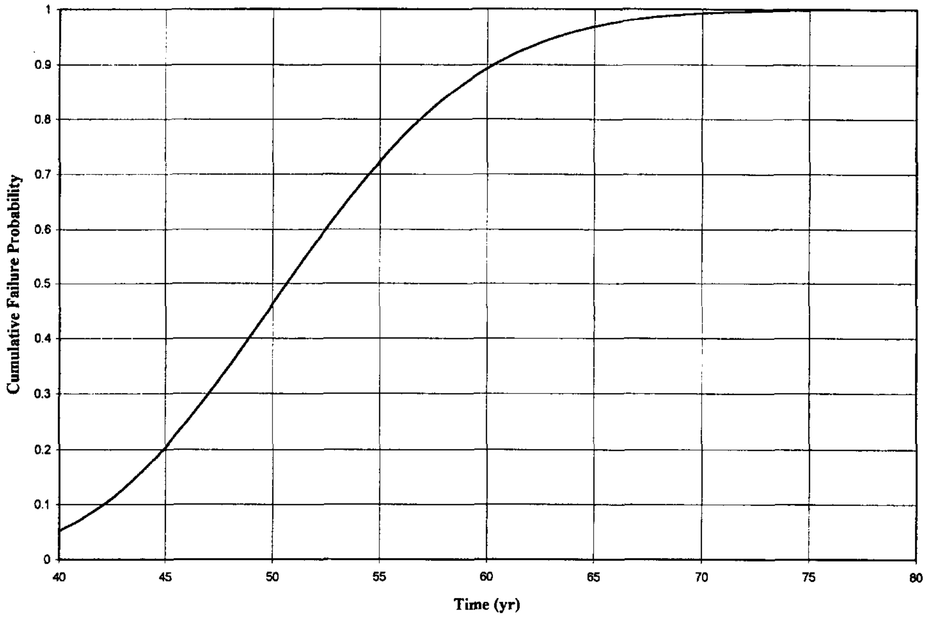

Fig. 2. Drum failure probability versus time from Eq. (5) with $R = 1$ mil per year and drum thickness $L = 50$ mils.

As an example, let us assume an average corrosion rate $R = 1$ mil per year and a drum failure thickness $L = 50$ mils (thickness of 60 mils; drum is assumed to fail when at least 50 mils have corroded). In this case, the average corrosion depth in mils will be $\lambda = RT = T$, the time in years. The resulting Poisson probability distributions of corrosion depths at times of $T = 1$, 2, 3, and 4 years are shown in Fig. 1. Note that corrosion depths greatly exceeding, or less than, the average are possible. For example, at 1 year there is a 5% probability of a corrosion depth of 3 mils. According to Eq. (6), at a time $T_{\text{peak}} = 50$ years, 50% of the drums will have failed, and Eq. (7) predicts that the bulk of all failures will occur during a time interval $2 \times T_{\text{rise}} \approx 14$ yr centered at T_{peak}. At 43 years most of the drums will be intact, but by 57 years most will have failed. This simple analysis predicts that once the drums begin to fail, it will require only a short time until nearly all fail. To test this numerically, Eq. (5) was evaluated for a range of times using $R = 1$ mil per year and $L = 50$ mils. The results shown in Fig. 2 indicate that half the drums have failed by $T_{\text{peak}} = 50$ yr, that at $T_{\text{peak}} - T_{\text{rise}}$ of 43 yr only 12% have failed, and that at $T_{\text{peak}} + T_{\text{rise}}$ of 57 yr 80% have failed. Therefore, 70% of all drum failures occur in the $2 \times T_{\text{rise}} \approx 14$ yr period centered about 50 years. For this reason, the Poisson model indicates that the most important quantities to know are the times T_{peak} and T_{rise}, from which the onset and duration of drum failures can be determined. This analysis is most applicable to cases in which there is a single well-defined average corrosion rate. In the present calculations, the use of a distribution of average corrosion rates increases the rise time in comparison with the arrival of the distribution peak.

3. Corrosion of drums on Pads 1, 2, and 4 at LANL

In January 1943, Project Y, the wartime Los Alamos National Laboratory (LANL), was established at the location of the Los Alamos Ranch School in north–central New Mexico as the nucleus of the War Department's scientific and technical effort to develop a fission bomb. Beginning in 1970, the Atomic Energy Commission (AEC), DOE's predecessor, directed its facilities, including LANL, to begin storing TRU waste in a manner that would allow for eventual retrieval and shipment to the WIPP. Before this, TRU waste at AEC facilities around the country was disposed of with low-level waste (LLW) in shallow landfills. As a consequence of the 1970 AEC directive, however, LANL began segregating TRU waste from LLW and, by the late 1970s, upgraded TRU waste storage facilities to provide a more retrievable configuration. The result was the construction of three above-grade asphalt pads, called Pads 1, 2, and 4, on which TRU waste was placed in densely packed arrays and covered with soil overburden. Corrosion of containers on the pads was not anticipated because of the relatively dry climate of Los Alamos and the short expected life of the pad storage configuration.

The storage environment at LANL on Pads 1, 2, and 4, is defined by cells, typically consisting of clusters of drums stacked three to five high, with vertical layers separated by sheets of plywood, and surrounded on the sides by large crates also containing TRU waste. There are about 4776, 7293, and 4554 drums on Pads 1, 2, and 4, respectively. The cells are located on asphalt pads in rectangular arrays and separated by empty space from adjacent cells. Each cell is covered with a plastic tarpaulin (tarp), the empty space between cells is backfilled, and the whole facility is covered with a mound of the local soil to an approximate depth of 1 m. For most areas, the environment under the tarp is dark, humid (typically over 90% relative humidity), and of moderate and even temperature (about 10–15°C). Factors that can modify this environment and possibly enhance the corrosion rate include: the plywood layering, which frequently contains a corrosive fire-retardant chemical formulation that includes phosphoric acid; the plastic tarp, which can hold condensation in contact with the drums; and direct contact of exterior dirt and/or the interior contents with the drum walls.

Corrosion can occur either on the exterior or in the interior of the waste drums. Exterior corrosion is caused by the environment surrounding the container, whereas interior corrosion results from reactions of the inner wall with the container's contents. Both interior and exterior corrosion rates can be enhanced by localized weaknesses in the container structure. Both interior and exterior corrosion can be classified further as either general or pitting corrosion. General corrosion is defined as corrosion that results in a gradual decrease in drum wall thickness over an extended surface area. Pitting corrosion is defined as corrosion that results in a localized perforation of the drum wall. The corrosion process is often conceptualized in terms of the degree of localization of the corrosion, with rapidly growing, localized pinholes described by pitting models and with slower growing, more extensive areas depicted in terms of general corrosion models. Although interior corrosion may be significant, its quantification is extremely uncertain owing to a lack of information regarding the quantity and effect of each waste form in interaction with the drum walls.

The main cause of internal corrosion on Pads 1, 2, and 4 at LANL is interaction between corrosive agents in the drum and the inside of the drum wall. Although liquids were not intentionally placed in the drums, liquids are known to desorb from the cement waste forms stored on the pads. Out of 16 drums from Pad 2 that were retrieved and examined in 1992, one drum containing cemented residue was found to contain a small amount of liquid [9]. Because the liner was intact, the water was contained, and no internal corrosion had occurred. However, another drum containing a cemented sludge did not have a liner, and pinhole corrosion was present on the drum [10]. Approximately 30% by volume of the waste on the pads is in the form of cemented waste. Quantification of the extent of the internal corrosion is not possible because detailed information regarding the effect of each waste form in interaction with the drum walls is not available; therefore, it is not considered further here. To the extent that internal corrosion is present, the degradation rate of the drums will be enhanced over that predicted here.

External corrosion of the drums on Pads 1, 2, and 4 is caused by a combination of environmental conditions and localized weaknesses of the drum structure. The drum on the pads have been in an environment of darkness, high humidity, and relatively little temperature variation for a span of several years. The oldest drums were stored in 1979, making them 14 years old at the time of this analysis. The final storage on the pads occurred in 1991. It has been observed that the plywood separating the cells has decomposed, leaving by-products to interact with and potentially accelerate the corrosion of the drums [10,11]. The fire-retardant material contained in this plywood may further accelerate the corrosion processes. Additionally, the inspection in 1992 of 16 drums revealed a pattern of accelerated corrosion around unrelieved stress points, such as ribs, sealing rings, and sides. The estimation of exterior pitting and corrosion rates at LANL is now considered.

4. Estimation of corrosion rates

Data are available for corrosion of metals in various types of soil [3] and atmospheric conditions [12]; however, these data are not readily applicable to the specific situation of carbon steel drums on asphalt pads under a plastic tarp and earthen cover. The most appropriate sources of data for the present case are the studies performed at the Hanford site and at Idaho National Engineering Laboratory (INEL) [7,11]. These studies are used as a guide in estimating the probable development of corrosion on the drums.

In addition to the uncertainty in the local corrosion rates, the average values for these rates are also uncertain. Because of this latter uncertainty, the average corrosion rates are themselves represented by a distribution of values. The effect of this will be to broaden the predicted overall distribution of corrosion depths and failure times, which will appear as a less sudden rise in the number of predicted drum failures than would be obtained from a single, fixed, average corrosion rate (see Eqs. (6)–(8). The information used to describe the distribution of average corrosion rates, even though based on available data, represents only a small sample and is probably a rough approximation to the actual situation. Separate distributions are used for general and pitting corrosion.

Several drum studies are used here as a guide to developing estimates of potential corrosion at LANL. An early report by Fowler et al. [13] discusses the corrosion of various candidate materials for TRU waste containment applications in soil and atmosphere but presents no numerical data. Morton [11] found that at Hanford, in an environment similar to that at LANL, drums in direct contact with the tarp corroded at a maximum general corrosion rate of 1 mil per year. These rates apply to the deterioration of the outside surface due to corrosion and not to the reduction of wall thickness due to combined corrosion of both inside and outside surfaces. At INEL, a general corrosion rate of 2 mil per year was assumed, based on drums that were covered for 18–21 years. Duncan et al. [7] assumed a general corrosion rate of 1 mil per year for painted United States Department of Transportation (DOT) 17-H drums stacked under a tarp. These data and assumptions suggest a likely average corrosion rate of about 1 mil per year, with a reasonable upper bound of 2-3 mil per year. Duncan et al. [7] found that, for galvanized drums in a similar environment, the corrosion rate was approximately 0.5 mil per year. Because galvanized steel corrodes at a slower rate than painted steel, this serves as a lower bound in this study. An assumption is made herein that a triangular distribution is used for the average general corrosion rates with a range of 0.5–2 mil per year and a most likely value of 1 mil per year.

It is established that pitting (i.e., localized) corrosion occurs faster than general corrosion. One of the benefits of storing the drums in the environment of the pads at LANL is that the drums are not expected to be subject to high rates of pitting corrosion. However, several factors can potentially result in high corrosion rates. These factors include by-products of the plywood degradation, water condensation on container surfaces in the humid environment, and unintentional soil contact with drums.

In Duncan et al. [7], it is assumed that pitting/crevice corrosion occurs, on average, at twice the rate of general corrosion, and an average pitting rate of 2 mil per year was assumed for painted 17-H drums stacked under a tarp. Similarly, the distribution used here for the pitting corrosion rate is obtained by doubling the general corrosion rate distribution. Therefore, a triangular distribution is used for average pitting corrosion rates over the range 1–4 mil per year with a most likely value of 2 mil per year.

It is worth stressing at this point that the above triangular distributions are for the *average* external general and pitting corrosion rates, which appear as parameters in the statistical model described in the following text and not for the individual rates. Many individual rates are calculated from statistical distributions parameterized by each average rate selected from the triangular distribution. Because of the statistical approach, it is typical to obtain individual corrosion rates falling well outside (both above and below) the ranges of average rates given in the above triangular distributions.

The average thickness of a painted 55-gallon drum is about 55 mils, although it typically varies from 50 to 60 mils, as confirmed by drum retrievals at LANL [14]. For this reason, a uniform distribution is assumed over the range 50–60 mils. In the drum corrosion literature, authors adopt various definitions of drum failure. The arbitrary nature of these definitions obviates the need to perform structural failure analysis of drums in various stages of corrosive degradation, but lacking this information the following is adopted. For general corrosion, drum failure is defined as the loss of structural integrity. As in [7], we assume this to occur when the remaining drum wall thickness is less than or equal to 10 mils. For pitting corrosion, drum failure occurs when a pit breaches the drum wall.

5. Results and discussion

In this analysis, it is important to realize that statistical sampling is occurring in two stages. In the first stage drum thicknesses and average corrosion rates are selected randomly from uniform and triangular probability distributions, respectively. In the second stage, individual corrosion rates are calculated using the average rates as parameters in the Poisson probability distribution. The overall probability distribution is a convolution of Poisson distributions over the uniform distribution of drum wall thicknesses and the triangular distribution of average rates. Before presenting the overall results, let us elaborate on the behavior of fixed-parameter Poisson distribution failure predictions for three general corrosion cases given by average corrosion rates of 1.0, 1.5, and 2.0 mil per year and a fixed drum wall thickness of 55 mils (which implies failure at a corrosion depth of 45 mils according to the adopted general corrosion failure criterion).

The relative failure rates and the total failure probabilities (defined to occur at a corrosion depth of 45 mils) predicted by the Poisson distribution for the three average corrosion rates chosen previously are shown in Figs. 3 and 4. The total failure probability reaches 50% at a time in keeping with the average corrosion rate, and the rise time from small to large failure probability is seen to be small in comparison with the total time until significant failures take place. At very short times (before many

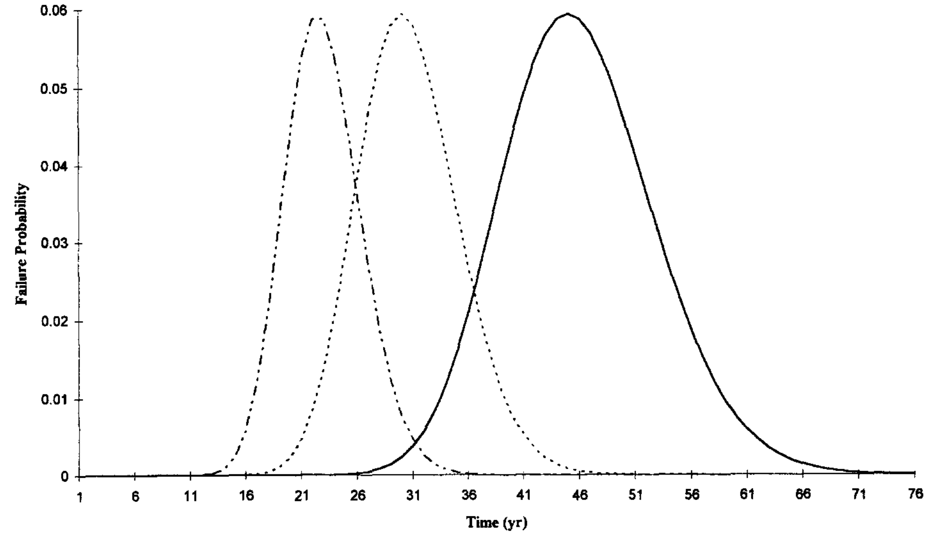

Fig. 3. Drum failure probability versus time for average corrosion rates of 1.0 mil per year (solid curve), 1.5 mil per year (dotted curve), and 2.0 mil per year (dotted–dashed curve).

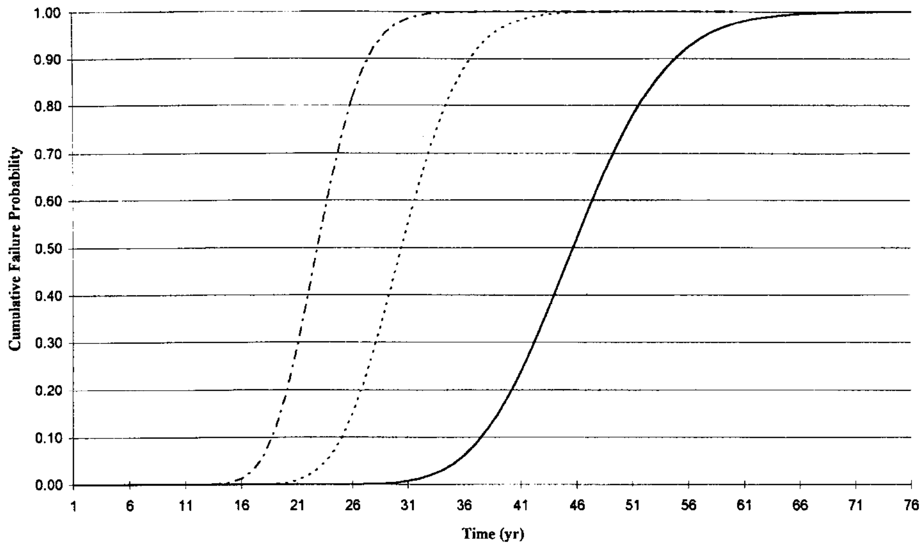

Fig. 4. Cumulative failure probability versus time for average corrosion rates of 1.0 mil per year (solid curve), 1.5 mil per year (dotted curve), and 2.0 mil per year (dotted–dashed curve).

failures have occurred, regardless of average failure rate) and at long times (after most drums have failed regardless of failure rate), the average failure rate is not a critical parameter. However, for a range of intermediate times the total failure probability and the failure rate are very sensitive to the average failure rate. This sensitivity is due to the rapid rise of the total failure probability with time during this period. Therefore, during the rise portion of the overall failure probability curve, small changes in time lead to large changes in failure probability (steepness of curves in Fig. 4), and similarly, small changes in failure rate lead to large changes in failure probability (different rate curves during rise portions in Fig. 4).

The Poisson distribution failure predictions are illustrated more globally in Figs. 5 and 6, which plot relative failure rate and total failure probability as shaded regions versus time and average failure rate. In Fig. 5, the shaded band shows the time period of the failure rate peak as a function of the average failure rate parameter. As described previously, the thickness of the band is narrow in time compared with the time value at the center of the band, and the central time of peak failure rate is inversely proportional to the average corrosion rate.

The overall corrosion failure calculations were performed by randomly selecting the drum wall thicknesses from a uniform distribution and the average Poisson corrosion rates from a triangular distribution, and then using the Poisson distribution with the randomly chosen parameters as discussed previously. For both the general and the pitting corrosion models, Latin Hypercube sampling, as implemented in Crystal Ball® [15], was performed using the distributions specified previously. For the purpose of this analysis, 1000 iterations were performed. Because both types of corrosion were estimated using the Poisson distribution, the results are qualitatively similar. The results in

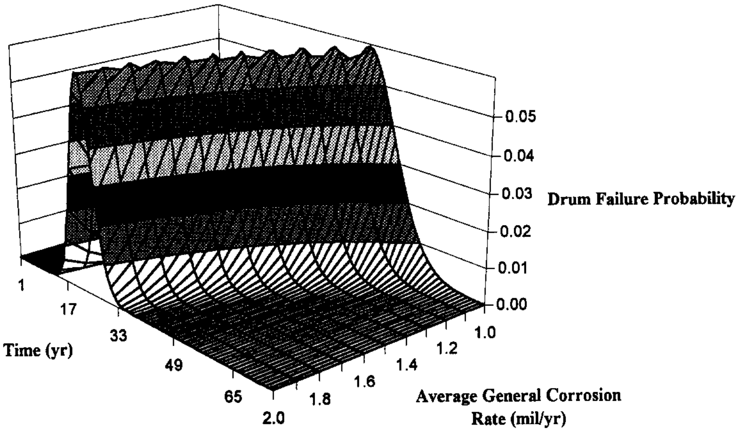

Fig. 5. Drum failure via external corrosion versus time and average corrosion rate as calculated using Poisson distribution.

Table 1 show the median, 5th and 95th percentiles, and median for the distribution percentage of predicted drum failures versus time using Poisson distributions parameterized as discussed above.

As discussed previously in conjunction with Eqs. (6)–(8), the assumption that the corrosion processes are well described by a Poisson distribution implies that the drums begin to fail at significant rates after some critical length of time. This behavior is clearly shown in Table 1 for the upper 95th percentiles for the failure percentage for general and pitting corrosion., and for the median for pitting corrosion. For these cases,

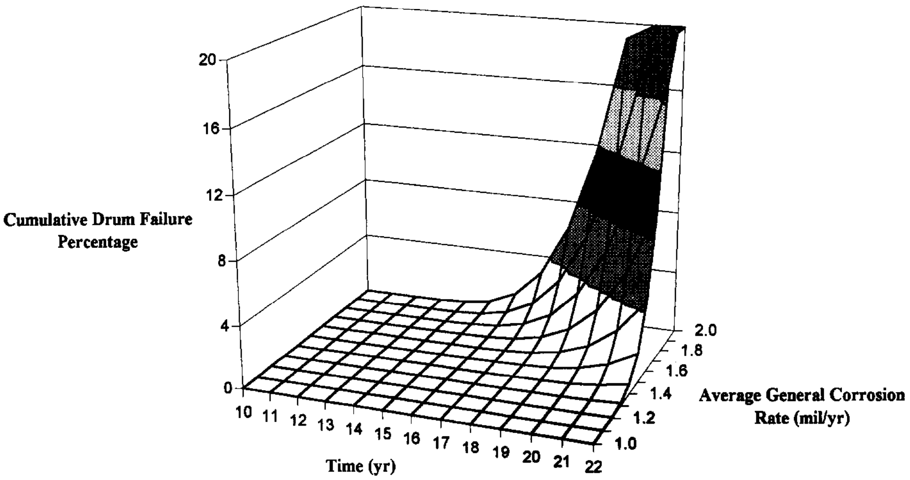

Fig. 6. Cumulative drum failure via external corrosion versus time and average corrosion rate as calculated using Poisson distribution.

if the average corrosion rate for the selected Poisson distribution is associated with the time in Table 1 at which the failure probability exceeds 50%, then the previous analysis indicates that the bulk of the failures should occur in an interval with length on the order of the square root of the time by which it occurs. For example, the upper 95th percentile for failure percentage for general corrosion passes the 50% level at about 25 years, for which the square root is 5. Backing up to 20 years shows that only 5% of the drums are predicted to have failed, whereas advancing to 30 years shows an 85% failure probability.

Although the fastest average corrosion rates in Table 1 provide an overwhelming probability of drum failures by 30 years, the slowest average corrosion rates predict very few failures. This can be seen for the 5th percentile and median for failure by general corrosion and for the 5th percentile for failure by pitting corrosion. These results emphasize the uncertainty associated with the drum failure predictions given our present information.

Table 1
Results of Latin Hypercube calculations

	General corrosion failures/%				Pitting corrosion failures/%			
Time (years) since placement	Mean	5th [a]	Median	95th [b]	Mean	5th [a]	Median	95th [b]
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0.01
10	0	0	0	0	0.03	0	0	0.11
11	0	0	0	0	0.14	0	0	0.71
12	0	0	0	0	0.48	0	0	2.95
13	0	0	0	0	1.31	0	0	8.81
14	0.01	0	0	0.01	2.84	0	0.01	20.16
15	0.02	0	0	0.05	5.24	0	0.04	36.27
16	0.05	0	0	0.18	8.51	0	0.17	54.34
17	0.13	0	0	0.51	12.55	0	0.58	71.48
18	0.28	0	0	1.28	17.18	0	1.60	84.10
19	0.54	0	0	2.80	22.23	0	3.73	92.12
20	0.96	0	0	5.46	27.52	0	7.61	96.53
21	1.60	0	0.01	9.64	32.91	0	13.68	98.63
22	2.50	0	0.02	15.57	38.29	0	22.23	99.51
23	3.70	0	0.04	23.23	43.60	0.01	32.94	99.85
24	5.21	0	0.09	32.34	48.76	0.02	44.97	99.95
25	7.05	0	0.20	42.36	53.73	0.05	56.92	99.99
26	9.18	0	0.40	52.63	58.46	0.11	67.98	100
27	11.58	0	0.74	62.47	62.92	0.25	77.72	100
28	14.21	0	1.35	71.35	67.07	0.51	85.35	100
29	17.02	0	2.26	78.92	70.78	0.99	90.88	100
30	19.97	0	3.63	85.05	74.38	1.78	94.62	100

[a] 5th percentile of the calculated distribution for the failure percentage.

[b] 95th percentile of the calculated distribution for the failure percentage.

Sensitivity analyses were also performed using the results of the Latin Hypercube simulations, with the measure of sensitivity being the rank correlation coefficient between the input variables (average corrosion rate and drum wall thickness) and the output variables (percentage of drums failed by general and pitting corrosion at a given time, calculated using Eq. (5). These results suggest that the uncertainty in the corrosion rates impacts the results more than the uncertainty in the drum wall thickness. Indeed, for all time periods, the absolute value of the rank correlation coefficient between the percentage of drums failed and the corrosion rates is generally above 0.9, but that for the drum wall thickness is only about 0.3.

6. Conclusion

The number of container failures due to corrosion is estimated as a function of time for 55-gallon painted carbon steel drums under earthen cover. The calculations are performed using an empirical statistical model that assumes corrosion depths are given by a Poisson probability distribution parameterized by an average corrosion rate. In addition, uncertainty in the average corrosion rates and drum wall thickness is addressed using probability distributions.

Limitations in corrosion modeling underscore the critical need for applicable data. Such data are rare, yet for the foreseeable future decisions that depend on the results of the corrosion process will have to be made. The return on an investment in data gathering would be the potential to more accurately model corrosion and thereby to formulate effective remediation strategies.

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