Conceptual Model and Risk Assessment of Waste Package Evolution - 15643

Joseph Rustick *, David Kosson **, Steven Krahn **, Michael T. Ryan *, James Clarke **
* Vanderbilt University
** Vanderbilt University/CRESP

ABSTRACT

A generic disposal facility model was created to mirror disposal of low-level radioactive waste in a humid environment. The standard waste package used is a painted and primed carbon steel box stacked four high and placed next to one another within the disposal facility, preventing outward deformations of individual boxes. Waste is placed in the facility in sections, and as each section is filled it is covered with a layer of natural soil. It was assumed that boxes are exposed to natural precipitation rates for approximately 12 months, reduced to natural background infiltration to simulate the soil cover, and dropping to 1% of background infiltration when the facility is filled and a water-shedding interim cover is installed. It was also assumed that each box retains its structural integrity at the time of disposal, with the exception of the top box, which has its lid collapse inward from the overlying soil cover. Waste packages experience different rates of corrosion, differential amounts of infiltration, and fill with liquid at different rates based on when and where they are placed in the facility. Using historical literature and DOE site reports, calculations were made to estimate a range of waste package failure outcomes.

INTRODUCTION

Disposal of low-level radioactive waste (LLW) is regulated by a set of performance objectives established to ensure protection to human health and the environment from radiological hazards. These limits are typically represented as an activity per unit volume over a period of time at a set distance from the disposal facility. For waste generated by the Department of Energy (DOE) this is 1000 yrs. following site closure and 100 m. down gradient or down wind from the facility [1]. A near surface disposal facility (NSDF) is designed to handle waste streams for a specific site, and a performance assessment (PA) is conducted to establish an overall and radionuclide-specific maximum allowable inventory and demonstrate facility compliance with the performance objectives using a site conceptual model. We suggest that a NSDF can be considered a three-component system. Waste form, composition, and waste package represent the *disposal component*; facility bottom and cover layer(s) represent the *engineered component*; and site-specific features including precipitation and soil composition represent the *environmental component*. All components are linked, and allows for the overall performance of the NSDF to be assessed in an integrated manner.

Large uncertainties are present in predicting processes and events over a 1000 yr. timespan, with a PA relying on simplifying and conservative assumptions to reduce under and over estimations of facility performance. One common assumption is that waste packages are fully degraded or are made fully degraded through mechanical processes at the end of the institutional control period, thus providing no barrier to waste movement within the NSDF. This assumption is considered conservative because it lowers the maximum allowable inventory. However, facility performance could be significantly different compared to modeled performance if a situation were present where the waste package remained intact and provided a level of isolation for the contained waste.

This paper describes development of an analytical basis for a generic NSDF in a humid environment that incorporates the presence of an intact waste package up to and beyond the end of institutional controls. The focus is on waste available for transport to the surrounding environment, known as the source term. The objective is to analyze scenarios that involve different degradation rates for buried waste packages to evaluate effects on facility performance.

Waste Package Degradation

Modern waste packages are primarily made of carbon steel boxes that have been primed and painted to reduce corrosion [1, 2]. These containers are designed to transport waste from generator to disposal facility and provide structural stability when stacked. Waste packages are required to hold several thousand kg. of waste, withstand a uniform load of four full boxes, and be watertight at time of disposal. Once in the ground, each box begins to corrode and degrade. For sites in humid environments with significant annual precipitation, it has been modeled that over the institutional control period most waste packages will corrode to the point of collapse, causing subsidence in the interim facility cover [3-5]. Cover subsidence can cause large amounts of infiltration into the waste zone, and during institutional controls, any damage to the cover system can be identified and repaired. At the end of this period, an accelerating agent such as dynamic compaction or a static surcharge is used to compact the remaining waste packages that have not collapsed in order to prevent future subsidence.

However, under certain conditions the above approach is unlikely to be an accurate representation of waste package corrosion over time, and therefore facility performance. Corrosion of iron structures buried in soil have been shown to undergo time-variable rates of corrosion depending on the metal and soil type [6, 7]. In moist soils, buried iron and steel containers will commonly undergo pitting corrosion, with pits forming on the metal surface and working their way through the metal structure. The rate of this corrosion can be constant or slowing over time, depending on the soil conditions. In one study, published in 1957 by the National Bureau of Standards (NBS) to measure corrosion of different metals in a variety of soil types, found that corrosion of iron is dependent on soil characteristics (e.g. pH levels, Cl^- concentration, soil resistivity) and soil aeration [6, 8]. Soil corrosivity determines the initial rate of corrosion, and soil aeration determines the rate of corrosion change over time. In 1986, another study by Mughabghab and Sullivan was conducted mirroring the NBS study but specifically looking at carbon steels [8]. The objective was to show that carbon steel behaved similarly to the types of steels and irons from the NBS study. It was demonstrated that carbon steels did in fact follow similar corrosion relationships to wrought iron. Both studies showed that in well-aerated soils, which have a high sand content with good drainage and are close to the soil surface, corrosion slows rapidly over time. In poorly aerated soils, containing mostly clays with poor drainage and found deeper beneath the soil surface, corrosion slows much less rapidly.

Within LLW disposal, an eight year study of buried metal boxes containing simulated waste at the Savannah River Site was conducted from 1993 to 2001 to extrapolate corrosion over the institutional control period [9]. Four carbon steel boxes were filled with wood, sealed and buried in native soil, with two stacked boxes under 1.22 m. of soil and the other two separate under an additional meter of soil. In 2001 the top stacked box was exhumed for testing, leaving the other three for future tests. Three important observations were noted: the lid of the top box was collapsed inward, the same box was filled to the top with liquid, and the underlying box also was found to have collected moisture despite remaining sealed. This last observation was discovered when the lid of the underlying box was accidently removed. This demonstrated that it was possible for liquid to accumulate within a sealed waste package over time and also that this liquid could remain in the waste package for an extended period of time.

The combination of historical literature values for corrosion and the Dunn study at Savannah River are the basis for the development of an analysis incorporating waste packages that remain intact beyond the operational phase of disposal. While the Dunn study was focused on volume of metal loss from each side of the waste package to determine how structural integrity would change over time as corrosion progressed, our analysis was adapted to calculate the time taken for a box to initially corrode through, which is important for retention of box leachate. The waste packages are assumed to provide a level of structural integrity for the interior of the disposal cell and a degree of containment for the waste. Waste packages and engineered barrier designs are borrowed from the E-Area engineered trenches at Savannah River to provide real-world supplemental data for the analysis. The Savannah River Site was chosen for its decades of successful near-surface LLW disposal operations, availability of numerous published reports and studies on site-specific disposal, and its location in a humid environment.

METHODS

A waste package analysis was created based on the current disposal practices of the Engineered Trenches at Savannah River, a DOE site in a humid environment [1, 10]. The standard waste package used in the analysis is made of carbon steel with interior dimensions of 1.17 m. by 1.83 m. by 1.19 m., for a total volume of 2.55 m^3 [9, 11, 12]. This type of box (named B-25 at Savannah River) is not the only type of steel box waste package used at Savannah River or at other DOE sites, but it is the most common type used in the Engineered Trenches, accounting for approximately 77% of waste packages. Each box is constructed of 12-guage carbon (0.15%) hot-rolled, sheet and strip, commercial steel, with a thickness of 2.78 mm (ASTM designation A-569-93) [9]. Three steel 100 mm. tall risers are affixed to the bottom of each box to allow for movement and stacking by forklift. The inside of the box lid is sealed with a rubber gasket to prevent liquid infiltration [11]. Each box can hold up to 2722 kg. of solid radioactive waste, and is designed to support a uniform load of four full additional boxes, with a total weight of 1.18×10^4 kg. A variety of solid waste forms are disposed of using the B-25 box, with each box filled to the lid, though void space within the waste can vary between 10%-90% [12]. Exterior surfaces are coated with a 0.051 mm thick primer then painted with an alkyd enamel coat 0.032 mm. thick, while the interior receives a coat of primer but no enamel.

Common disposal practices involve stacks of four waste packages for a total height of 5.28 m. including risers [13]. In the analysis it was assumed that no significant infiltration or corrosion occurs before placement of the interim cover, since the layers of primer and paint are designed to resist corrosion from precipitation and there is no soil cover during the operational phase to depress the lid of the top box. At Savannah River the amount of annual precipitation is 1220 mm/yr. [14]. A layer of soil 1.22 m. thick is placed over each full section as a base layer of the interim cover and reduces the infiltration rate into the disposal facility from natural precipitation down to 286 mm/yr. [15, 16]. Disposal facility fill rates are variable, so a time period of one year was chosen as an average time between emplacement and covering of a waste package. It was estimated that the disposal facility is full after twelve years, and upon completion a high-density polyethylene (HDPE) geomembrane is installed over the operational soil cover of soil as a final layer of the interim cover. Infiltration through the interim cover into the disposal cell drops to 10 mm per year, as estimated using the HELP computer code for the E-Area trench closure plan at Savannah River [15].

Two corrosion cases were considered for this analysis, a constant corrosion rate and a slowing corrosion rate. Release of leachate from each box is assumed to occur when the bottom of the box corrodes through fully, developing a hole for liquid to leave the box. The bottom of the waste package was chosen because it undergoes the highest rate of corrosion, as measured in Dunn. This is a result of transportation from waste generator to disposal, when the metal tines of the forklift used for transport scrape off a section of paint and primer.

For the base case (constant corrosion), extrapolating from the eight year Dunn study, in which the waste package was buried in unsaturated soil at 75% relative humidity, it can be estimated that corrosion through the box bottom occurs around 42 years [12]. This is assuming that annual infiltration remains close to 285 mm/yr. of infiltration and that soil conditions do not change. For the second case, corrosion rates were taken from the 1957 NBS report, and are mentioned within several Savannah River reports [6, 9, 12]. The NBS study derived an equation for corrosion rates that followed a power law (equation 1) [4, 6, 8, 9, 12]:

$$h_m = kt^n \quad (1)$$

h_m = maximum pit depth;
k = site dependent soil corrosivity fitting parameter;
t = time;
n = soil aeration dependent fitting parameter

Well-aerated soils have lower values of n, and poorly aerated soils have higher n values. The NBS and subsequent study by Mughabghab and Sullivan showed that k values are based on both the corrosivity and aeration of the soil, with increasing corrosivity leading to high k; as well better aerated soils have higher k values compared to poorly aerated soils. At Savannah River, soil conditions were estimated to be similar to very poorly aerated clay soil with low soil corrosivity based on their use of 0.8 for a value of n [12]. Site-specific Savannah River k values and not Mughabghab were used for this analysis, as the corrosivity of the soil in Mughabghab was high compared to Savannah River due to large concentrations of Cl^- and SO_4^{-2} [8]. Table 1 shows the values for k and n that were used in the analysis.

Three scenarios were looked at for each corrosion case to compare constant corrosion to a slowing corrosion rate. For this analysis only waste packages disposed of in year 1 and year 12 were considered, to demonstrate corrosion effects from opposite time periods of disposal. The assumption was made that while the facility remains open at one end, waste packages experience corrosion under “good” aeration conditions, since oxygen and moisture can permeate through the open end of the facility. Upon closure at 12 years, the waste packages switch to “very poor” aerated corrosion conditions as oxygen becomes depleted within the waste facility.

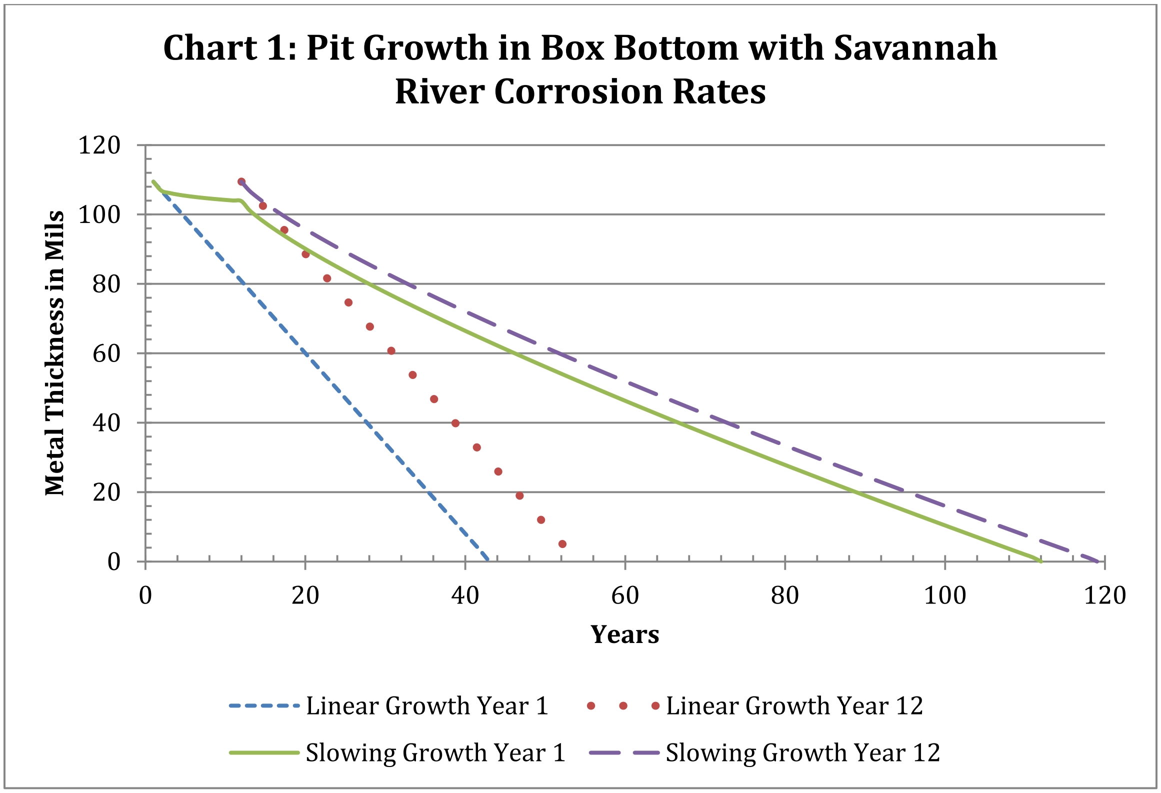
In the first scenario, the corrosion fitting parameter k was kept at the measured SRS value, and the aeration values n were selected from the NBS study for “good” and SRS value for “very poor” aerated soil. For the second scenario, the corrosion fitting parameter k was doubled for “good” aerated soil and kept normal for “very poor” aerated soil. This was done to mirror the findings in the NBS and Mughabghab and Sullivan studies, where values for k were double or more in “good” compared to “very poor” soil aeration. In the third scenario, the corrosion fitting parameter k was quadrupled for “good” aerated soil and doubled for “very poor” aerated soil, to see what would happen in a more corrosive environment, since SRS has relatively non-corrosive soil.

Table 1: k and n values used

Scenario	**1**	**2**	**3**
k good	2.6	5.2	10.4
k poor	2.6	5.2	5.2
n good	0.32	0.32	0.32
n poor	0.8	0.8	0.8

RESULTS

The results from constant and slowing corrosion cases for each scenario can be found in charts 1 through 3. In scenario one (chart 1), the year one constant corrosion box developed an estimated through-hole in 42 yrs. and the year twelve box in 54 yrs. The slowing corrosion boxes developed holes for year one at 112 yrs. and year twelve at 119 yrs. For the second scenario (chart 2), holes were estimated in the year one constant corrosion waste packages at 32 yrs. and 54 yrs. for the year twelve waste packages. The slowing corrosion method returned 106 yrs. for year one waste packages and 119 years for year twelve waste packages. In the third scenario (chart 3), it was estimated that holes formed in the waste packages at 11.5 yrs. for year one waste and 33 years for year twelve waste packages. The slowing corrosion method developed estimated holes at 46 yrs. for year one waste packages and 57 yrs. for year twelve waste packages.



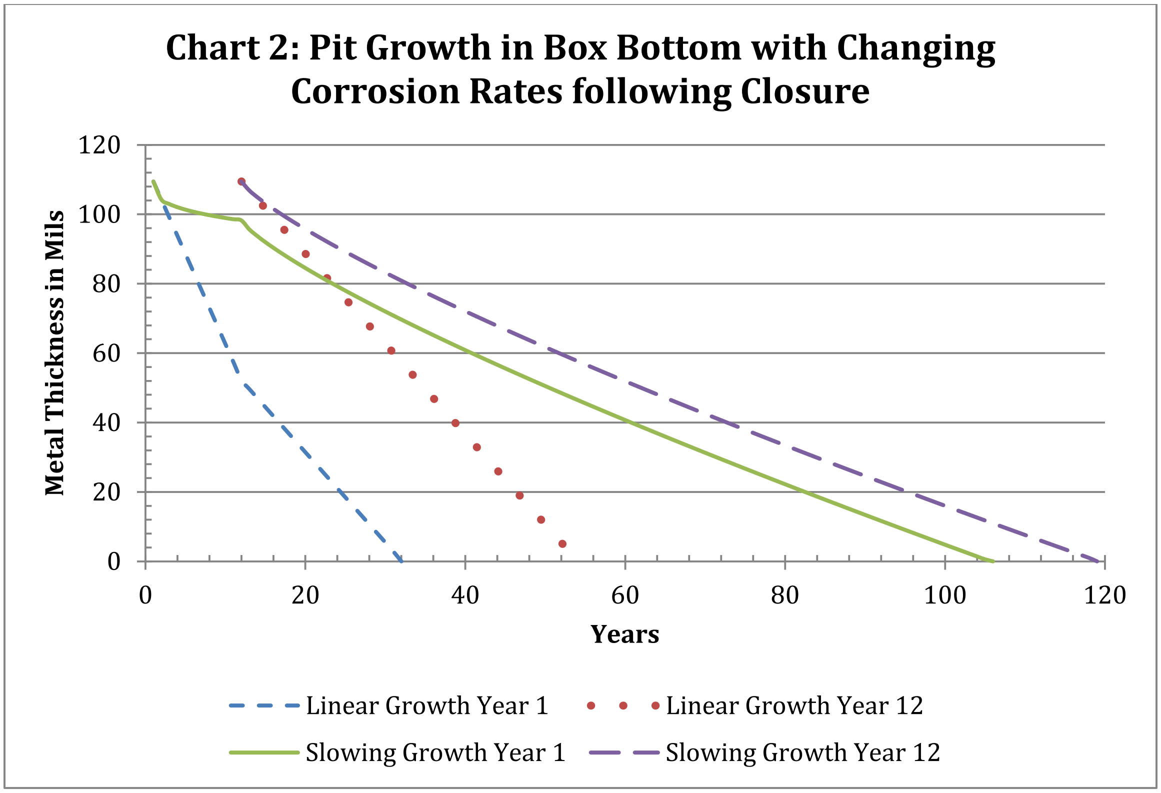


Chart 2: Pit Growth in Box Bottom with Changing Corrosion Rates following Closure

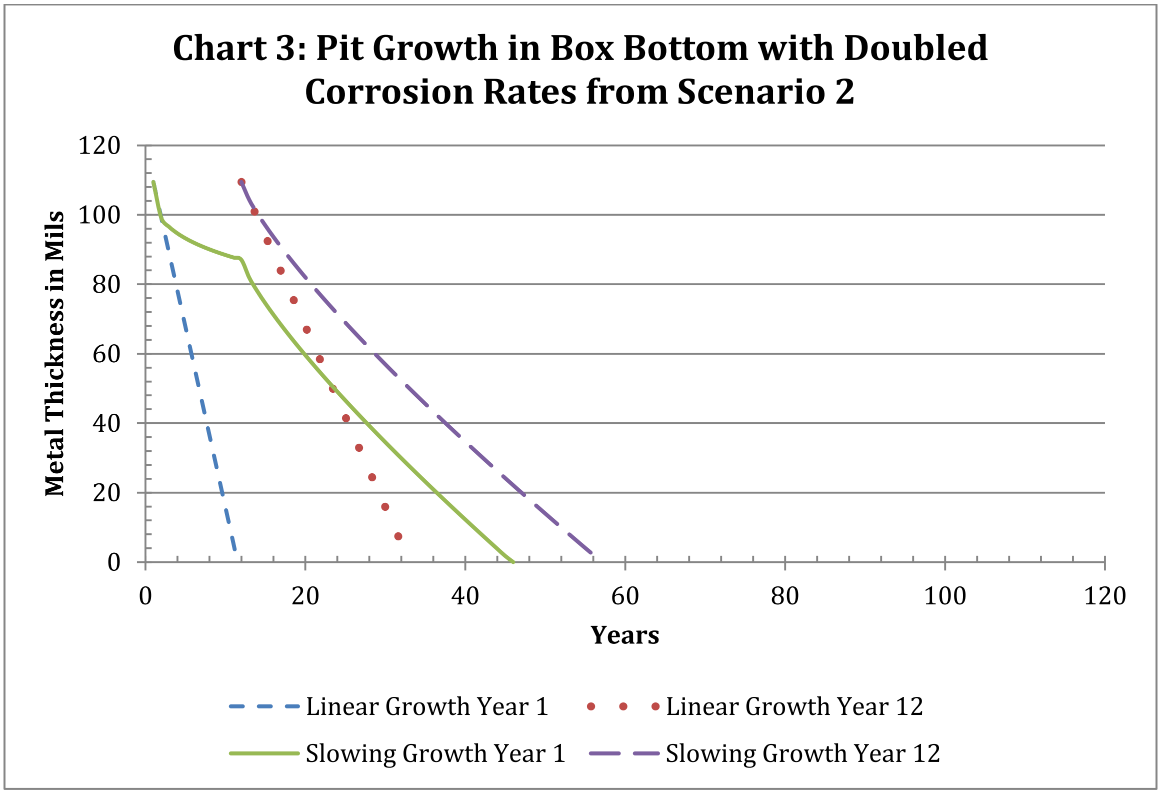


Chart 3: Pit Growth in Box Bottom with Doubled Corrosion Rates from Scenario 2

DISCUSSION

Looking at the results, there are a few initial insights that can be drawn. The spread between the first and last waste package sections are the highest in scenario 2 at 13 yrs. for the slowing corrosion case, but are equally high at 22 yrs. in both scenario 2 and 3 for the constant corrosion case. In scenario 1 and 2, which represent lower corrosivity environments, there is potential for waste packages to remain leachate-tight beyond 100 yrs. under the slowing corrosion case. Conversely, in a higher corrosivity environment represented by scenario 3, some of the early waste packages could develop holes before interim closure of the facility

As a result of a number of simplified assumption built into this analysis, there are several areas of further study that could have a significant effect on the results stated above. Leachate buildup within waste packages could provide a mechanism for earlier development of holes, as accumulated liquid pressure is exerted on weakened waste package sections from corrosion pits. In the Dunn study, the uppermost B-25 box was completely filled with liquid after eight years, and there was approximately 610 mm. of liquid in the underlying box (based on rough visual estimates of the box being half full of liquid) [9, 11]. While there are many factors that would go into whether a waste package could retain leachate for many decades, the possibility does exist. In addition to through-hole development in the early disposed waste packages that are initially exposed to 285 mm/yr. of infiltration, early vs. late waste package disposal, the difference in waste package leachate fill rate by level, and the installation of a HDPE geomembrane as the top layer of the interim cover could all affect through-hole development. Another issue is the presence of microbial activity within the waste package. Depending on a number of factors including waste compositions, waste package leachate, microbial colonies, and oxygen levels, corrosion could become accelerated within the interior of the waste package.

Finally, there is also the potential to use estimates of liquid leaving each waste package as a performance confirmation metric. Through monitoring of the vadose zone directly beneath the disposal facility (or other forms of leachate collection such as a sump), a spike in radionuclide concentration should be observed that corresponds to the formation of holes in waste packages. This would help provide more data on rates of waste package corrosion. The use of tracer material specific to waste sections or vertical levels of waste packages could further increase the resolution of the observations.

CONCLUSION

Analysis of a general LLW disposal facility in a humid environment has shown a wide variation in corrosion rates depending on the type of corrosion and soil conditions. While all of the scenarios involving an assumed constant rate of corrosion developed holes in waste packages during the institutional control period, with a low enough corrosion rate some waste packages undergoing a diminishing corrosion rate could develop holes beyond final site closure. On the opposite end, under a high enough corrosion rate some waste packages could develop holes before the installation of a final interim cover. Additional study is needed to assess the effects of leachate buildup within waste packages and the presence of microbial activity.

One next step will be to create estimates of the mass flux of radionuclides out of the waste packages and into the environment following hole creation. This flux could be in units of either grams or curies of radionuclides per square meter per year. To account for the complexity and large uncertainty involved in calculating solubility limits and partitioning coefficients for the waste within each waste package, it could be assumed that the waste is evenly distributed within each waste package, and that each radionuclide present is dissolved in the waste package pore water and available for transport when the package corrodes through. This data could then be coupled to a subsurface transport model to provide rough estimate of performance for the entire disposal facility system at the compliance point.

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