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Updated Estimate of Tritium Permeation from TPBAR Disposal Containers in ILV (U)

Maximilian B. Gorensek

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EXECUTIVE SUMMARY

A tritium source term analysis was performed for TPBAR disposal in the E-Area Intermediate Level Vaults for the E-Area Low-Level Waste Facility Performance Assessment (PA). This analysis is based on an earlier source term analysis which treated the bulk of the tritium residual as tightly bound by the TPBAR getter material, with only a small fraction existing as tritiated moisture in the lithium aluminate ceramic pellets. Together with atmospheric moisture trapped in the free volume, the tritiated water vapor is assumed to corrode steel surfaces inside the disposal container, covering them with a magnetite film while generating hydrogen. The carbon steel walls of the disposal container are permeable to hydrogen, providing a pathway for tritium to escape containment. The rate of hydrogen generation is assumed to be limited by the rate of corrosion, which is assumed to be governed by parabolic reaction kinetics obtained from the literature. This relies on the further assumption that the water vapor consumed by the corrosion reaction is continually replaced by moisture from the lithium aluminate pellets until all of that moisture is gone. In addition to tritium permeation, the analysis also includes a slow leak through the disposal container walls at the maximum allowable leak rate, 1×10^{-4} standard cm^3/s. Results were obtained for four different combinations of internal and container wall temperatures, established in an earlier thermal analysis that considered two different vault loadings and two different TPBAR activity levels (Table ES-1). Instantaneous release rates for these four cases are plotted in Figure ES-1 below.

Table ES-1. Temperatures Used in Source Term Calculations.

Case	Description	Internal Temperature, °C	Wall Temperature, °C
Case 1	1-y old TPBARS, 8 containers per ILV	140	130
Case 2	5-y old TPBARS, 8 containers per ILV	109	95
Case 3	1-y old TPBARS, 4 containers per ILV	96	89
Case 4	5-y old TPBARS, 4 containers per ILV	79	71

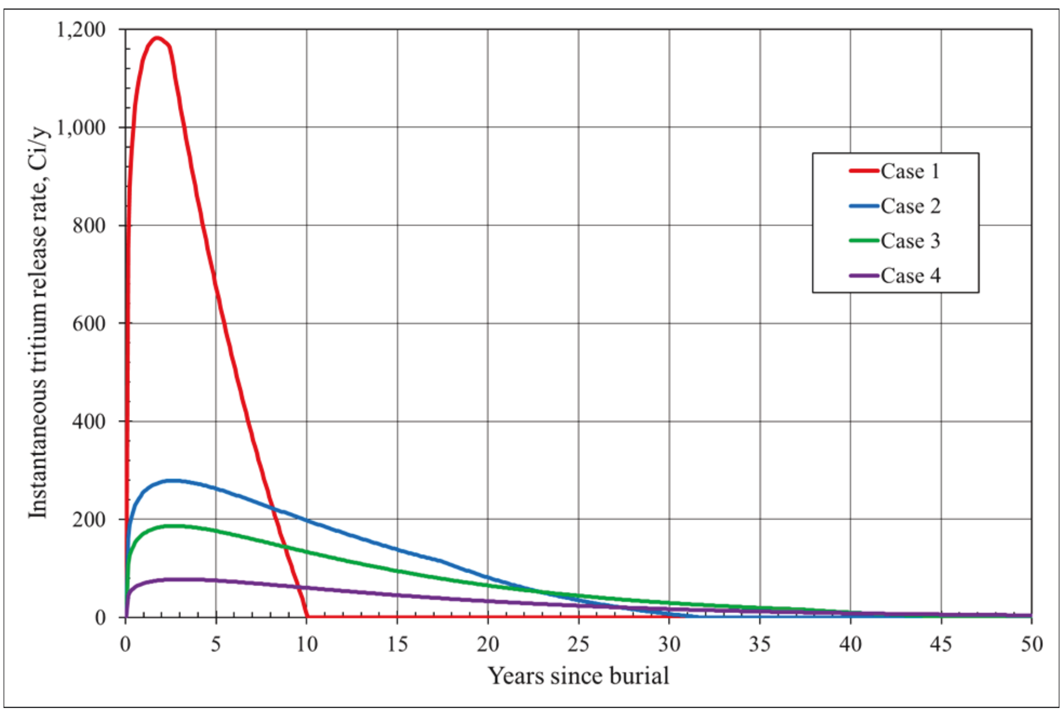

Figure ES-1. Instantaneous Tritium Release Rates over Time for the 4 ILV Disposal Cases.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

IAEA	International Atomic Energy Agency
IBRAE	Institut problem Bezopasnogo Razvitiya Atomnoi Energetiki, transl. Nuclear Safety Institute (of the Russian Academy of Sciences)
ILV	Intermediate Level Vaults
RH	Relative humidity
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
TEF	Tritium Extraction Facility
TPBAR	Tritium-producing burnable absorber rod
TVA	Tennessee Valley Authority
UDQE	Unreviewed Disposal Question Evaluation

1.0 Introduction

Tritium for the US Defense Program is produced in the Tennessee Valley Authority's (TVA's) Watts Bar Nuclear Plant, a commercial nuclear power generating station that had its operating license amended for this purpose [1]. Westinghouse pressurized water reactors like those at Watts Bar use boron in so-called burnable absorber rods that are placed in the core to absorb neutrons and control reactivity. When boron-10 nuclei absorb a neutron, they split to form lithium-7 and helium-4. To make tritium at Watts Bar, the boron is replaced with lithium-6 in the form of lithium aluminate in a limited number of so-called tritium-producing burnable absorber rods (TPBARs). Lithium-6 nuclei split into tritium and helium-4 upon absorbing a neutron. Since all hydrogen isotopes can permeate metals, TPBARs also incorporate Zircaloy-4 getter material that chemically binds hydrogen to trap tritium atoms. Nevertheless, it is difficult to keep tritium from diffusing out of the TPBARs and into the pressurized water coolant, which can carry it throughout the plant and ultimately into the environment. Consequently, TPBARs can only be used in restricted numbers at Watts Bar to avoid exceeding the strict regulatory limits on tritium release.

Irradiated TPBARs containing tritium are shipped to the Tritium Extraction Facility (TEF) at the Savannah River Site (SRS). Here they are processed in an extraction furnace at high temperature and under a vacuum to remove and collect their tritium content. Spent TPBARs emit gamma radiation because their stainless-steel cladding has been activated by neutron irradiation in the Watts Bar reactor. Consequently, they must be disposed of inside shielded containers that are then buried in the Intermediate Level Vaults (ILV) in E-Area at SRS.

Spent TPBARs inevitably contain some residual tritium due to their use of Zircaloy-4 getters that have such a high affinity for hydrogen that complete removal is unattainable. However, the tritium trapped in the spent TPBARs can slowly escape over time and permeate the thick walls of the disposal container, eventually reaching ground water. Tritium could then be carried out of E-Area by ground water transport, potentially violating ILV permits.

This report provides an analysis of tritium release over time from spent TPBARs in the E-Area ILV. The release profile generated is intended to serve as the tritium source term in a separate analysis of tritium migration in E-Area ground water. Conservatism is ensured by picking the scenario with the greatest or fastest release potential whenever presented with a choice. This helps guarantee that the result is a truly bounding, or worst-case analysis.

2.0 Analysis

The approach used for this analysis is based on the one developed by Lanning and Gilbert in 2005 [2]. Lanning and Gilbert posited that the rate of tritium release from the TPBARs to the ILV environment is controlled by the rate at which hydrogen is generated due to corrosion of steel surfaces by moisture trapped inside the disposal containers and by the rate at which the hydrogen thus generated permeates the container walls. This analysis adds one additional release path: a hypothetical leak at a rate equivalent to the maximum allowable leak between the interior and exterior of the disposal containers as set by the containers' procurement specification (M-SPP-H-00418, Rev. 2) [3].

2.1 Tritium Distribution in the TPBARs

TPBARs are clad in Type 316 stainless steel. To prevent inward diffusion of hydrogen from the coolant as well as outward diffusion of tritium from the TPBAR, an aluminide coating is placed on the cladding inner surface. Tritium is generated in annular sintered, high-density, lithium aluminate ($LiAlO_2$) ceramic pellets. A metal getter tube composed of nickel-plated Zircaloy-4 is placed between the cladding and the lithium aluminate pellets. The getter absorbs molecular tritium (T_2) generated during irradiation. Nickel plating on both sides of the getter prevents oxidation of the Zircaloy-4 surfaces, which would reduce the tritium absorption rate. An unplated Zircaloy-4 tube, or liner is placed inside the annular pellets. This reactive metal liner is needed to reduce any T_2O species made in the pellets to molecular tritium and to provide mechanical support during TPBAR handling [4].

Irradiated TPBARs are chopped open at one end and subjected to high temperatures and vacuum during the extraction process so that as much tritium as possible can be recovered. This means that any residual tritium is very tightly bound in the getter, where it originally accumulated as it was being made in the reactor. The maximum temperature reached by the TPBARs in ILV disposal due to the combined heating effects of radioactive decay and grout curing is so low in comparison, that the amount that could desorb and permeate the disposal container walls is nearly negligible, as will be shown further below.

Lanning and Gilbert's analysis assumes that the TPBARs, which are chopped open for tritium extraction, could be exposed to moist air at some point following extraction so that these pellets could pick up moisture. It further assumes that the absorbed moisture would undergo isotopic exchange with the tritium residual, making a small amount of THO. This tritiated moisture would become available to corrode any steel surface inside the disposal container once it is sealed. Corrosion of iron into magnetite yields hydrogen as a by-product, providing a means by which tritium could escape the disposal container, thanks to the mobility of molecular hydrogen [2].

2.2 Tritium Release from Getter Material

Residual tritium is so tightly bound in the getter material, that the amount that can escape by desorption is negligible. This was one of the outcomes of Lanning and Gilbert's analysis [2], which relied on a 1976 IAEA-published binary zirconium-hydrogen phase diagram with equilibrium hydrogen pressures [5] as reproduced in a 1999 Russian Academy of Sciences Nuclear Safety Institute (Institut problem Besopasnogo Razvitiya Atomnoi Energetiki, IBRAE) paper [6]. Lanning and Gilbert extrapolated the equilibrium partial pressure of tritium (as hydrogen) that can exist in equilibrium with the residual in the Zircaloy-4 getter from the IBRAE graph to 150°F (339K) and found it to be 4.78 x 10^{-20} atm [2]. If this partial pressure were to be maintained inside the disposal container, their analysis showed that the steady-state permeation rate would be only 20 μCi/y [2], essentially rendering it negligible.

An independent check of this conclusion was undertaken for this analysis. The solubility of hydrogen isotopes in metals is known to obey Sieverts' Law [7-9]:

$$\boldsymbol{c = K_S(T)\sqrt{p}} \qquad 2\text{-}1$$

Here, c is the absorbed hydrogen content expressed as the hydrogen to metal atom ratio (atom H/atom Zr), K_S the temperature-dependent Sieverts constant (atom H/atom Zr-Pa$^{-½}$), T the absolute temperature (K), and p the partial pressure of hydrogen (Pa). The Sieverts constant has an Arrhenius temperature dependence:

$$\boldsymbol{K_S(T) = k_S^o e^{-\Delta H_S/RT}} \qquad 2\text{-}2$$

Here, k_S^o is the preexponential factor (atom H/atom Zr-Pa$^{-½}$), ΔH_S the enthalpy of solution of hydrogen in zirconium (J/gmol), and R the universal gas constant (8.314463 J/gmol-K).

Values of k_S^o and ΔH_S measured for hydrogen absorption in α-zirconium are shown in Table 2-1 below. (The Sieverts constant reported by Kearns is actually in units of atom fraction H-Pa$^{-½}$ [7], but is included with the other sources [8, 9] for comparison. This difference could be the reason why the magnitude of the apparent enthalpy of solution measured by Kearns is the smallest of the five.) In general, the solubility of hydrogen in zirconium alloys (Zircaloy-2 and Zircaloy-4) was found to be similar to that in pure zirconium [7]. An isotopic effect was observed such that the Sieverts constant for deuterium absorption in α-zirconium over the 770-1020K temperature range is about 11-12% higher than for protium [8]. This means that the equilibrium partial pressure for deuterium absorbed at the same H/Zr atom ratio would be about 23-25%

higher than for protium. A similar effect could be expected for tritium, implying that the equilibrium partial pressure for tritium absorbed at the same H/Zr atom ratio would be no more than about 50% higher. Finally, the publication in which Tada and Huang's Sieverts constant parameters were originally published could not be identified from the citation provided by Yamanaka et al., so the values shown are actually those reported by Yamanaka et al. [9].

Table 2-1. Experimentally Determined Sieverts Constant Temperature Dependence Parameters for Hydrogen Solubility in α-Zirconium.

Source	k_S^o (atom H/ atom Zr-Pa½)	ΔH_S (J/gmol)	Temperature range, K
Kearns (1967) [7]	1.21×10^{-5}*	-49,540	683-1003
Tada and Huang (1971) as reported in [9]†	1.67×10^{-5}	-51,900	673-1173
Watanabe (1985) – protium [8]	5.735×10^{-6}	-54,590	756-1025
Watanabe (1985) – deuterium [8]	5.294×10^{-6}	-54,380	772-1022
Yamanaka, Higuchi, and Miyake (1995) [9]	6.79×10^{-6}	-54,700	773-1123

The solubility of hydrogen in α-zirconium at 1 Pa (9.9×10^{-6} atm) partial pressure is plotted as a function of temperature based on these Sieverts constant correlations in Figure 2-1 below. Solid curves depict correlated solubilities over the experimental temperature ranges for the five sources in Table 2-1, while dashed curves extrapolate the correlations to lower temperatures. Kearns' correlation is meaningless below about 250°C at this partial pressure because extrapolation results in H atom fractions greater than 1. The other correlations asymptotically approach an H atom fraction of 1 as the temperature decreases.

* Actual units for this k_S^o entry are atom fraction-Pa½, consistent with source.

† Original source could not be located, values are those cited by Yamanaka et al.

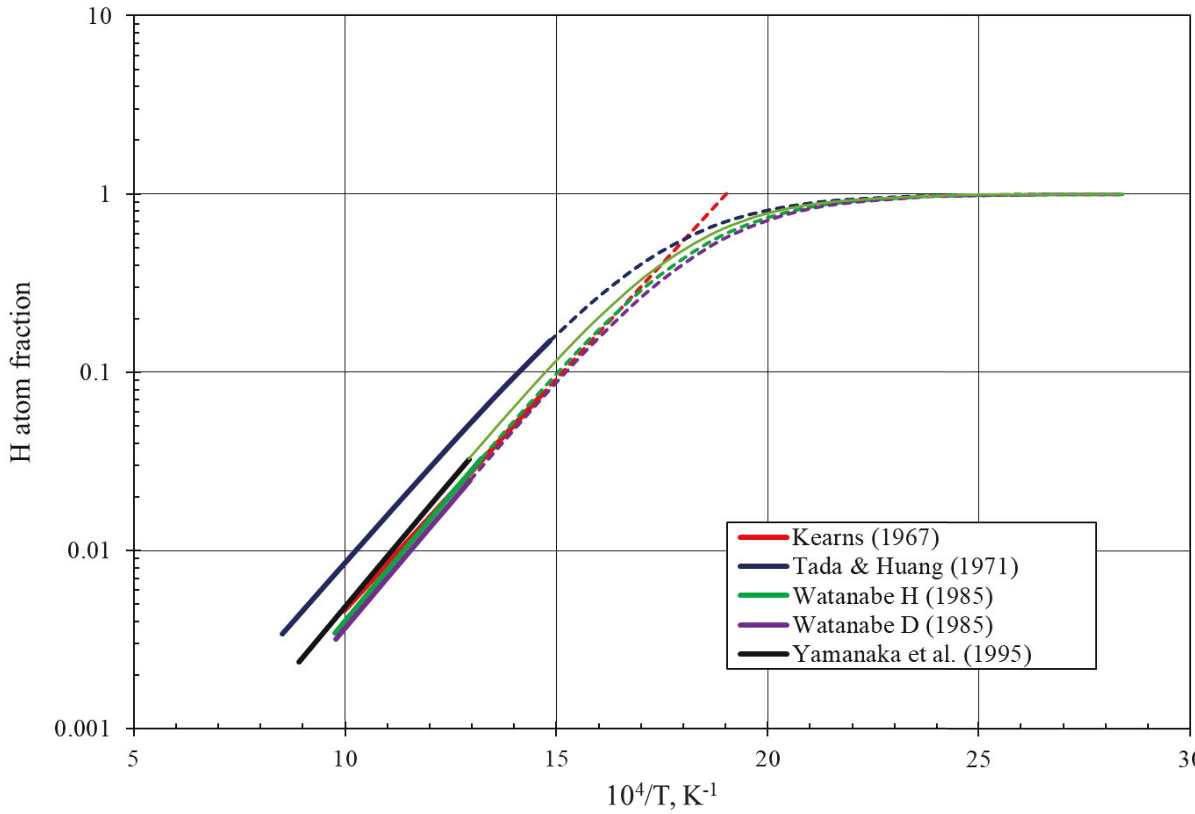

Figure 2-1. Hydrogen Solubility at 1 Pa Partial Pressure in α-Zirconium as a Function of Temperature.

The highest temperature that the TPBARs will reach in ILV disposal due to decay heat and grout curing is 140°C (413K) [10]. That corresponds to a 1/T value of 24.2 x $10^{-4}K^{-1}$, for which the lowest solubility is predicted by Watanabe's correlation for deuterium, which gives an atom fraction of 0.975 – clearly an unrealistic value, reflecting how tightly zirconium binds hydrogen.

The tritium residual in spent TPBARs is 133 Ci/TPBAR and the mass of Zircaloy-4 getter is 154.18 g/TPBAR [11]. Given that the getter is α-zirconium, with an atomic weight of 91.224 g Zr/gmol Zr, and that the atomic weight and molar activity of tritium are 3.016049 g T/gmol T and 9,621.03 Ci/g T, respectively [12], the equivalent H/Zr atom ratio of the residual in the getter is 0.002576 atom H/atom Zr. Kearns's correlation predicts a Sieverts constant of 528.8 atom fraction H-$Pa^{-½}$ at 150°F, or 339K (it is the least soluble of the correlations in Table 2-1 at this temperature), which results in a partial pressure of 2.36 x 10^{-11} Pa (2.33 x 10^{-16} atm) at equilibrium. While this is 3½ orders of magnitude higher than the value extrapolated by Lanning and Gilbert, it is still so small as to result in a nearly negligible permeation rate. Consequently, the tritium bound in the getter is nearly immobile and is considered separately from the small fraction isotopically exchanged with moisture in the pellets, further detailed below.

2.3 Tritium Release Due to Corrosion

If spent TPBARs are exposed to moist air, the lithium aluminate pellets inside can absorb atmospheric moisture. The protium atoms in the absorbed water molecules could then undergo isotopic exchange with the tritium residual, providing an alternative mechanism by which tritium could escape confinement.

This mechanism was proposed by Lanning and Gilbert in their analysis of tritium release from TPBAR disposal [2]. It relies on the corrosion of steel surfaces inside the disposal containers by moisture inadvertently picked up prior to disposal. The corrosion reaction converts iron metal to magnetite, Fe_3O_4, as shown below:

$$3\ Fe + 4\ H_2O \rightarrow Fe_3O_4 + 4\ H_2$$

Hydrogen is a co-product of this reaction. Since the water is partially tritiated by isotopic exchange within the pellets, the hydrogen will be as well, allowing tritium to permeate the steel walls of the disposal container. Tritium release from the disposal containers occurs primarily by this mechanism, which is treated separately from getter desorption as noted in Section 2.2 above.

Lanning and Gilbert's analysis assumes that corrosion is the rate-limiting step for hydrogen production. They allow for the disposal container to be sealed with ambient air at 70% relative humidity (RH), providing an initial amount of water that can immediately corrode the steel surfaces inside. The lithium aluminate pellets are considered to be an active moisture source, maintaining water vapor at a constant level by offsetting depletion due to the corrosion reaction. Justification for this is provided by Lanning and Gilbert's observation that the consequent release rate from the pellets is on the order of 0.001 µCi/g/s, which is said to be comparable to literature vales for lithium aluminate pellets at similar temperatures as reported by Nishikawa et al [13]. Corrosion continues unabated until all of the moisture is consumed [2].

Two different types of steel are present inside the disposal containers. One is carbon steel, which is what the containers themselves are made of. The other is stainless steel, which is used for the TPBAR cladding and to make the consolidation containers and extraction baskets. At least four different types of stainless steel are used: Type 316 for the TPBAR cladding [4], Type RA-330 and Type 304L for the bulk of the consolidation containers and extraction baskets [14-16], and 17-4 for miscellaneous parts [14-16]. Lanning and Gilbert's analysis took into account corrosion of the disposal container walls and TPBAR cladding only, apparently ignoring the considerable surface area contributed by the consolidation containers and extraction baskets [2]. Theye used corrosion rate information from Robertson [17] to estimate the rate at which magnetite was being made, which in turn established the hydrogen generation rate.

Robertson observed that carbon steel corrodes in water to form duplex films of magnetite in which diffusion control gives an oxide film whose thickness, x (cm) varies parabolically with time, t (s):

$$\boldsymbol{x^2 = k_p t} \qquad 2\text{-}3$$

Here k_p (cm^2/s) is a parabolic corrosion rate constant that is proportional to the underlying diffusion constant. As a result, k_p can be expected to exhibit an Arrhenius temperature dependence. Robertson collected data from several different sources to develop linear plots of the logarithm of k_p as functions of inverse absolute temperature. Different linear correlations were found for steam and water as the sources of corrosion, and surface finish was seen to affect corrosion rates as well, with a rougher finish resulting in faster rates. A straight-line logk_p versus $1000/T$ curve obtained by digitizing the line in Figure 2 in Robertson [17] for corrosion of milled surface carbon steel by water fitted to the data of Warzee et al. [18] is shown in Figure 2-2 below (blue line). Corrosion of the disposal container walls was assumed to be governed by this parabolic rate constant extrapolated to the temperatures encountered in ILV disposal.

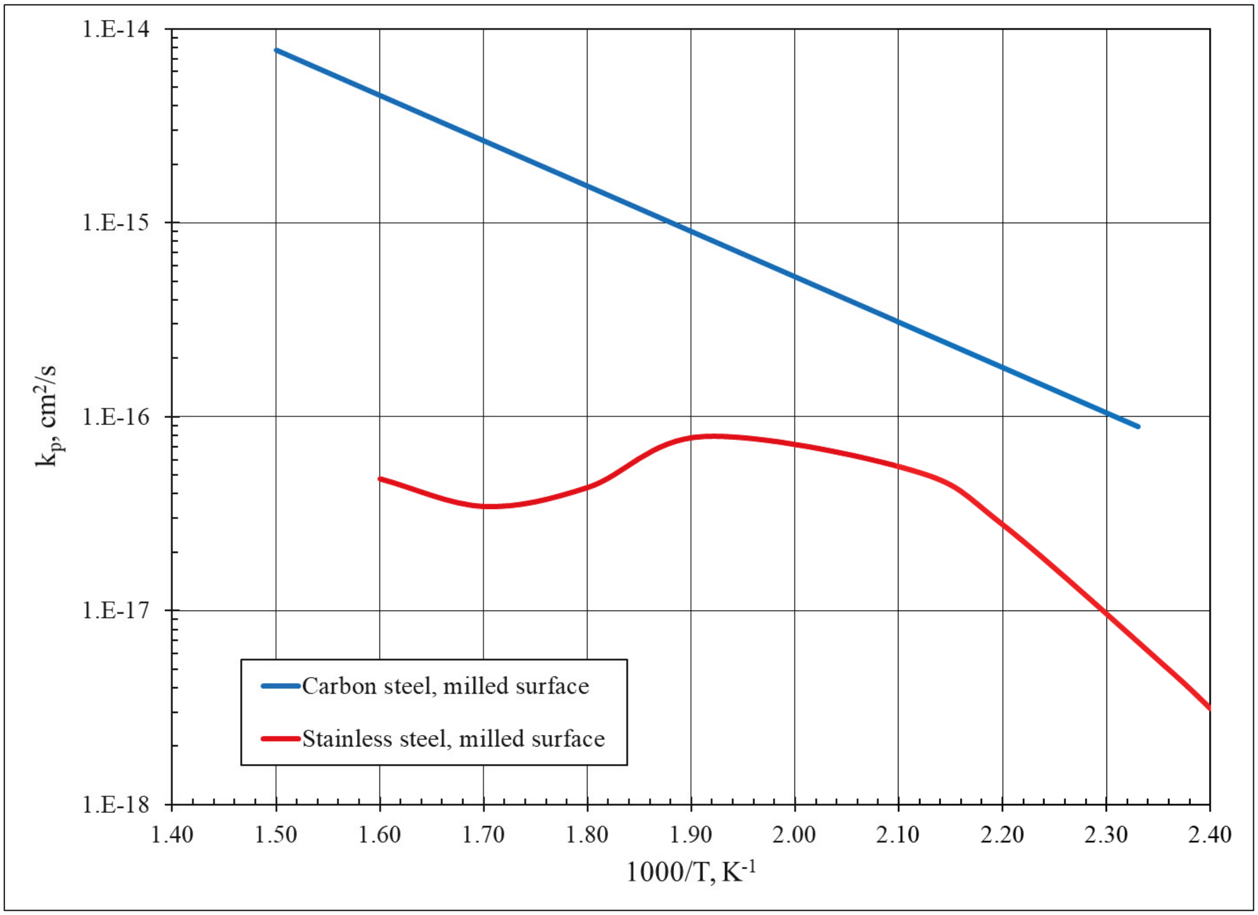

Figure 2-2. Temperature dependence of parabolic corrosion rate constants for carbon and stainless steels from Robertson [17].

Figure 2-2 also shows a red curve for the for corrosion of milled surface stainless steel by water. This curve plots the effective value of k_p at 1,000 h calculated from a two-phase model fitted by Robertson [17] to the data of Warzee et al. [18] for milled surface Type 304 stainless steel. Corrosion of all the stainless-steel surfaces inside the disposal container was assumed to be governed by Robertson's two-phase corrosion model at the temperatures encountered in ILV disposal.

It should be noted that the oxygen present in the free volume when the disposal containers are sealed could also cause corrosion of the interior surfaces in competition with the moisture content. In fact, when internal temperatures are above the moisture dew point, dry oxidation is the more likely corrosion mechanism [19]. However, ignoring the possibility of corrosion by oxygen is conservative and valid for bounding purposes.

2.4 Disposal Container Dimensions and Specifications

The dimensions and specifications of the TPBAR disposal containers are similar to those detailed in Clark's 2004 analysis [20], reflected in Lanning and Gilbert's analysis [2], and most recently used in a calculation of the rate of tritium release due to permeation during onsite transfer [21] and an Unreviewed Disposal Question Evaluation (UDQE) that assessed the impact of a leak rate that exceeds the procurement specification limit [22]. Figure 2-3 below illustrates a TPBAR container lying on its side [23]. An exploded view of the top of a container is shown in Figure 2-4 [20].

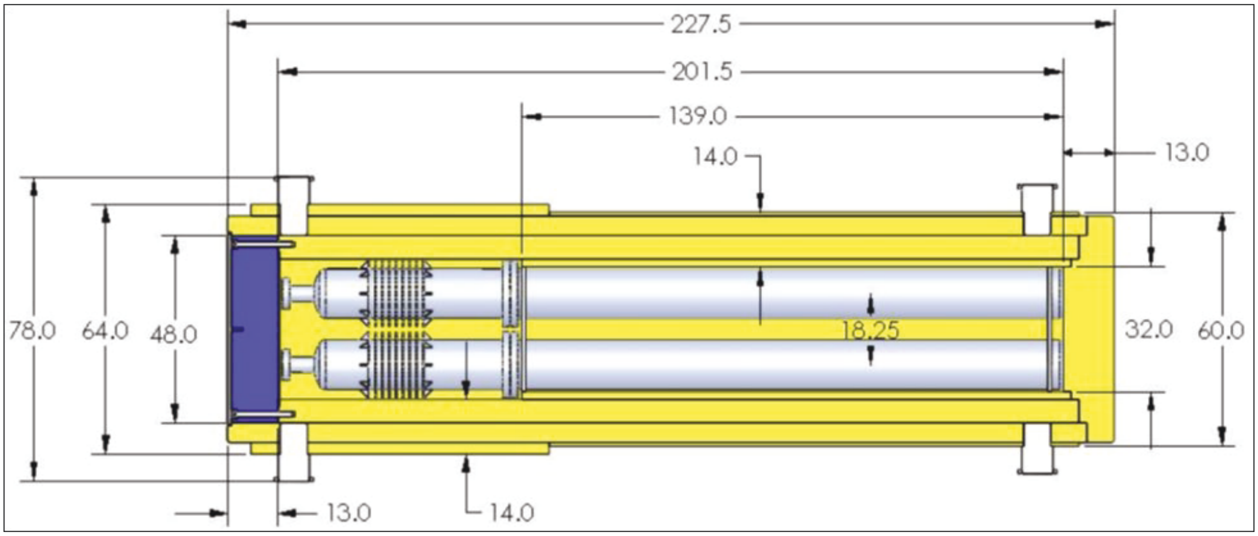

Figure 2-3. TPBAR Disposal Container Side View [6].

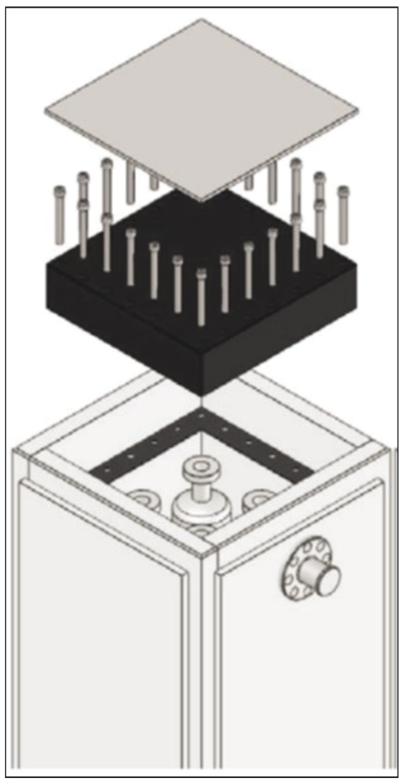

Figure 2-4. TPBAR Disposal Container Top Exploded View [2].

Each container holds four 16-ft tall, 12-in diameter extraction baskets. Two such baskets can be seen in Figure 2-3 (the two gray cylinders – the other two lie directly behind). Each basket encloses a consolidation container filled with 300 TPBARs. The four sides and bottom of the container are made from 13-in thick normalized carbon steel (SA516 Grade 70, Fine Grain Practice) slabs, held together with full penetration welds on all containment boundary joints [23]. The top of the container has a 12-in thick steel shielding plate that is secured with threaded fasteners. An elastomeric seal provides interim sealing of the contents after loading operations until the final closure plate (1-in thick carbon steel) is seal welded in place to meet the leak rate requirements [23]. The container dimensions (in) used in Clark's [20] and subsequent tritium permeation analyses [2, 21, 22] are summarized in Table 2-2 together with their values converted to cm. Clark assumed a void fraction of 0.2, based on the internal dimensions, for the fractional volume inside the container occupied by air [20]. The disposal container procurement specification stipulates that the assembled container must have a leak rate less than 1 x 10^{-4} standard cm^3 air/s [3].

Table 2-2. Disposal Container Dimensions Used in Permeation Analysis.

Description	Dimension	
	in	cm
Container Wall Thickness:	13	33.02
Container Internal Dimensions:		
Bottom Section:		
Height	139	353.06
Length	32	81.28
Width	32	81.28
Top Section:		
Height	62.5	158.75
Length	36	91.44
Width	36	91.44
Container Outer Lid Dimensions:		
Length	49.5	125.73
Width	49.5	125.73
Thickness	1	2.54
Seal Weld Dimensions:		
Length	198	502.92
Width	0.5	1.27
Thickness	0.5	1.27

The side walls of the container have an additional 1-in thick carbon steel plate welded on all four sides of the bottom section, and 2-in thick carbon steel plate on all four sides of the top section, so the actual side wall thickness is closer to 14 in. However, the thickness of the container bottom is only 13 in; consequently, credit is taken only for that thickness for conservatism.

2.5 Tritium Permeation Analysis

Clark, Lanning and Gilbert, and others considered three permeation paths: 1) through the side walls and bottom of the container; 2) through the outer seal lid (taking no credit for the bolted upper lid with elastomeric seal); and 3) through the weld used to attach the outer seal lid. With regard to the welded lid, they all conservatively assumed that all internal seals fail and that the inside surfaces of the welded lid and the weld are exposed to the same tritium partial pressure as the interior walls.

The permeability of tritium, Φ is defined by

$$\boldsymbol{\Phi} \equiv \boldsymbol{D} \times \boldsymbol{S} \qquad 2\text{-}4$$

where D is the diffusivity of tritium in the material (cm^2/s) and S is the solubility of tritium in that material (gmol H_2/cm^3 material). Thus, the units of Φ are gmol H_2/cm-s material. The maximum permeation rate through a material of thickness L (cm) for a given partial pressure of tritium on one side occurs when tritium is removed as soon as it reaches the other side and a steady-state concentration profile is established along L. This is the so-called steady-state flux, J_∞:

$$\boldsymbol{J_\infty = \frac{\Phi}{L}} \quad \text{2-5}$$

The flux is the amount of tritium (gmol H_2/cm^2-s) that permeates the material per unit area and time. Because hydrogen diffusivity in carbon steel is so rapid, Clark found that steady-state permeation of tritium through the 13-in thick walls could be achieved in about one week, and even faster along the much shorter seal lid (1-in) and weld paths (½-in) [20]. Consequently, the steady-state equation can accurately describe tritium permeation through carbon steel occurring over a period of years.

Clark and subsequent analysts used equation 2-4 to calculate the permeability of tritium in carbon steel from its diffusivity and solubility. They used correlations for protium in iron published by Quick and Johnson [24], reasoning that tritium diffusivity would actually be lower due to its threefold higher atomic mass, providing additional conservatism. In fact, Quick and Johnson measured solubilities, diffusivities, and permeabilities in iron for both protium and deuterium over a wide temperature range, finding that protium permeability was consistently higher than that of deuterium by a factor of 1.3-1.9 [24]. This confirms the implicit conservatism of using protium permeability to estimate that of tritium. It also underscores the fact that Quick and Johnson published a correlation for permeability, allowing it to be calculated directly instead of from correlated values of diffusivity and solubility via equation 2-4. This is more straightforward and is the method that was used in this work.

Quick and Johnson's correlation for protium permeability in iron is

$$\boldsymbol{\Phi = \varphi(T)\sqrt{p}} \quad \text{2-6}$$

where

$$\boldsymbol{\varphi(T) = \varphi_0 e^{-E_\varphi/RT}} \quad \text{2-7}$$

Here $\varphi_0 = 2.53 \times 10^{17}$ atom H/cm-s-atm^{½}, p is the partial pressure of protium (atm), $E_\varphi = 8520$ cal/gmol, R is the universal gas constant (1.987 cal/gmol-K), and T is the absolute temperature (K) [24]. The square root dependence of protium permeability on partial pressure is consistent with its Sieverts' Law solubility: protium exists in diatomic form as a gas, but dissolves in iron in monatomic form.

The units for φ_0 used by Quick and Johnson are not convenient. They can be converted to gmol H_2/cm-s-atm^{½} by dividing by Avogadro's number (6.022×10^{23} atom H/gmol H) and by the stoichiometric ratio 2 gmol H/gmol H_2. This yields $\varphi_0 = 2.10 \times 10^{-7}$ gmol H_2/cm-s-atm^{½}.

The partial pressure of hydrogen equivalent to the amount of tritium in the free space inside the container at any time can be calculated by material balance and the ideal gas relationship. Once that value is established, the tritium flow rate $\dot{n}$ (gmol/s) through each of the three permeation paths can be calculated from the permeability – equations 2-6 and 2-7 – and the cross sectional area A (cm^2) and length of the permeation path:

$$\boldsymbol{\dot{n} = J_\infty A = \frac{A\Phi}{L} = \frac{A\sqrt{p}\varphi_0 e^{-E_\varphi/RT}}{L}} \quad \text{2-8}$$

Based on the dimensions detailed in Table 2-2, the cross sectional areas for tritium permeation through the 1) bottom, ledge, and sides, 2) outer lid, and 3) seal weld are 1) 4 × [(353.06 × 81.28) + (158.75 × 91.44)] + 91.44 × 91.44 = 181,212.5 cm^2, 2) 125.73 × 125.73 = 15,808.0 cm^2, and 3) 502.92 × 1.27 = 638.71 cm^2, respectively. The corresponding permeation path lengths are 1) 33.02 cm, 2) 2.54 cm, and 3) 1.27 cm.

A shortcoming of this approach is that it does not take corner effects into account. The surface area of the container exterior is almost twice that of the interior. However, the expected increase in calculated permeation rate, if corner effects were to be included, is much smaller, on the order of 10% or less. Since no analytic solution for permeation through the walls of a vessel with square cross section could be found, and since extensive conservatism is already built into the calculation, no additional analysis is warranted.

One final check confirms the validity of using the steady-state equation to describe the permeation of hydrogen through the container walls over the time scale of this analysis. By analogy with the identical heat transfer problem solved in Carslaw and Yeager [25], Lanning and Gilbert developed an equation for the flux at the outer surface of a wall of thickness L, J_t (gmol H_2/cm^2-s), as a fraction of the steady-state flux over time:

$$\frac{J_t}{J_\infty} = 1 - \frac{4}{\pi}\sum_n \frac{(-1)^n}{2n+1} e^{-D(2n+1)^2 \frac{\pi^2 t}{4L^2}} \qquad 2\text{-}9$$

Using Lanning and Gilbert's value of the diffusivity of tritium in SA516 carbon steel alloy, 3.1×10^{-10} m^2/s [2], attributed to Ichitani and Kanno [26], the flux of tritium through a 13-in thick carbon steel wall takes years to approach the steady-state value, as shown by the red curve in Figure 2-5 below.

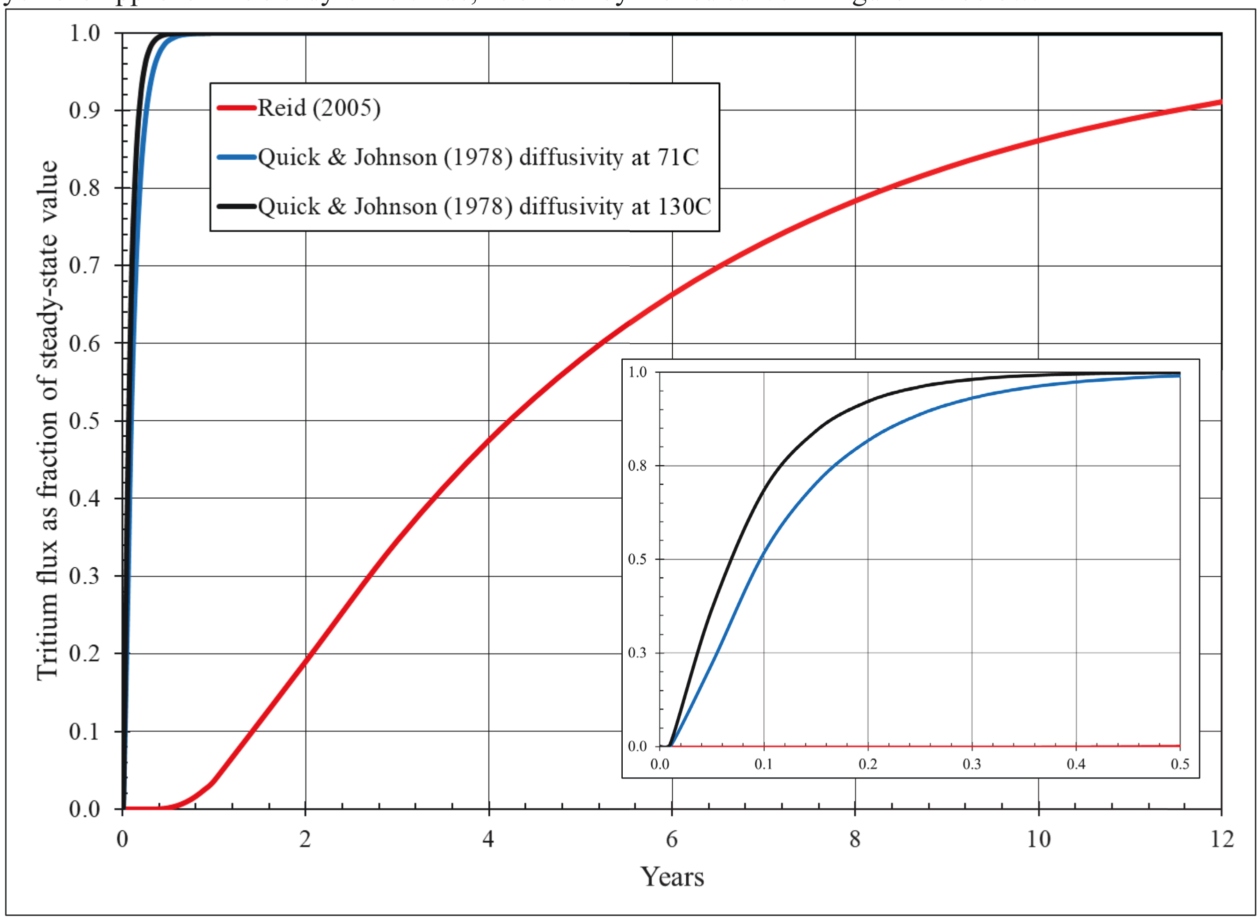

Figure 2-5. Tritium Flux through a 13-in Thick SA316 Carbon Steel Wall as a Fraction of the Steady-state Value over Time (Inset Shows 0.5-y Close-up).

However, using the higher, and, therefore, more conservative values of the diffusivity of hydrogen in iron calculated from the correlation reported by Quick and Johnson (1.36×10^{-8} m^2/s at 71°C, blue line, and 1.95×10^{-8} m^2/s at 130°C, black line) [24], the steady-state flux is approached much more quickly, achieving 98% in 0.3 y at the higher temperature. Of course, the steady-state flux through the 1-in thick lid and ½-in thick weld is achieved in an even much shorter time period. In reality, the hydrogen partial pressure inside the disposal container continually increases as the metal surfaces inside corrode. Once all the moisture has been consumed, the hydrogen partial pressure decreases due to permeation of the container walls, eventually approaching zero. Using the steady-state flux for the permeation calculation will over-estimate the permeation rate during the period of increasing hydrogen partial pressure, speeding up the early release of tritium and adding conservatism to the prediction.

2.6 Tritium Leak Analysis

The very slow (1×10^{-4} standard cm^3/s) maximum allowable air leak through the 13-in thick steel wall of the cask can be assumed to be isothermal, given the overwhelmingly larger thermal mass of the solid. In the absence of any conflicting information, it can also be assumed that the leak path (≥ 13-in) is orders of magnitude longer than its hydraulic diameter (necessarily microscopic in size). Although velocities and Mach numbers are small, compressibility effects are important when the total pressure drop is a large fraction of the inlet pressure, as it is here. (Both the helium leak test and the vacuum decay test used in acceptance testing of TPBAR disposal containers impose a 1-atm absolute pressure on the cask exterior and a near vacuum on the interior to force a measurable leak [3].) Perry's Handbook, 7th ed., gives an equation describing isothermal compressible flow in long transport lines (equation 6-114, page 6-22) that can be applied to this analysis [27].

According to Perry's Handbook, for an ideal gas with $\rho = pM_w/RT$, and assuming a constant friction factor f over a length L of a flow channel of constant cross section and hydraulic diameter D_H, integration of the momentum balance equations yields

$$p_1^2 - p_2^2 = G^2 \frac{RT}{M_w}\left[\frac{4fL}{D_H} + 2\ln\left(\frac{p_1}{p_2}\right)\right] \qquad \text{2-10}$$

where the mass flux $G = w/A = \rho V$ is the mass flow rate per unit cross-sectional area of the channel. (Here w is the mass flow rate, A the cross-sectional area of the flow channel, ρ the mass density of the gas, and V its velocity.) Applying this equation to the leak test, p_1 and p_2 are the absolute pressures at the inlet and outlet of the leak path, respectively, R is the universal gas constant, T the test temperature, and M_w the average molecular weight of air. The assumption that the leak path has a constant cross section and friction factor is no less realistic than the assumption that the leak path functions as a throttling valve with an effective flow coefficient.

The leak test measures the leak as a volumetric flow rate Q and treats air as an ideal gas. The maximum allowable leak rate is 1×10^{-4} standard cm^3/s, with standard conditions defined as 1 atm pressure and 298K temperature. Applying the ideal gas law, this is equivalent to a molar leak rate of

$$\dot{n} = \frac{p_s Q}{RT_s} = \frac{(1\,\text{atm})(1 \times 10^{-4}\,\text{cm}^3/\text{s})}{(82.0574\,\text{cm}^3 \cdot \text{atm/gmol·K})(298\text{K})} = 4.09 \times 10^{-9}\,\text{gmol/s} \qquad \text{2-11}$$

To convert equation 2-10 to a molar flow basis, the following relationship can be applied:

$$G = \frac{w}{A} = \frac{\dot{n}M_w}{A} \qquad \text{2-12}$$

This gives:

$$p_1^2 - p_2^2 = \left(\frac{\dot{n}M_w}{A}\right)^2 \frac{RT}{M_w}\left[\frac{4fL}{D_H} + 2\ln\left(\frac{p_1}{p_2}\right)\right] \qquad \text{2-13}$$

Solving for $\dot{n}$,

$$\dot{n} = p_1 A \sqrt{\frac{D_H}{M_w RT}} \sqrt{\frac{1 - \left(\frac{p_2}{p_1}\right)^2}{4fL - 2\,D_H \ln\left(\frac{p_2}{p_1}\right)}} \tag{2-14}$$

Assuming a cylindrical leak path,

$$A = \frac{\pi D_H^2}{4} \tag{2-15}$$

Substituting into equation 2-14 and simplifying,

$$\dot{n} = \frac{\pi p_1 D_H^{5/2}}{8\sqrt{M_w RT}} \sqrt{\frac{1 - \left(\frac{p_2}{p_1}\right)^2}{fL - \frac{1}{2}\,D_H \ln\left(\frac{p_2}{p_1}\right)}} \tag{2-16}$$

The apparent hydraulic diameter can be calculated from the conditions of the vacuum decay test ($\dot{n}$ = 4.09 × 10^{-9} gmol/s = 4.09 × 10^{-12} kmol/s, p_1 = 1 atm = 101325 Pa, p_2 = 800 millitorr = 106.7 Pa, T = 298K), solving iteratively for D_H using equation 2-16. Here M_w = 28.964 kg/kmol (dry air [28]), R = 8.314463 Pa-m^3/kmol-K. The leak flow path length, L can be assumed to be equal to the wall thickness, 13 in = 0.3302 m, while the friction factor, f can be arbitrarily set at 0.01. This approach results in a value of 1.907 × 10^{-5} m.

Applying this analysis to the leak, the volumetric flow rate of in-leakage as a function of internal pressure is depicted in Figure 2-6 below. The same relationship will be assumed to apply in the reverse direction, i.e., for the case where the cask internal pressure exceeds the external pressure due to internal heat generation resulting from radioactive decay. Equation 2-16 will be assumed to govern the leak rate to the exterior, with L = 0.3302 m, f = 0.01, and D_H = 1.907 × 10^{-5} m.

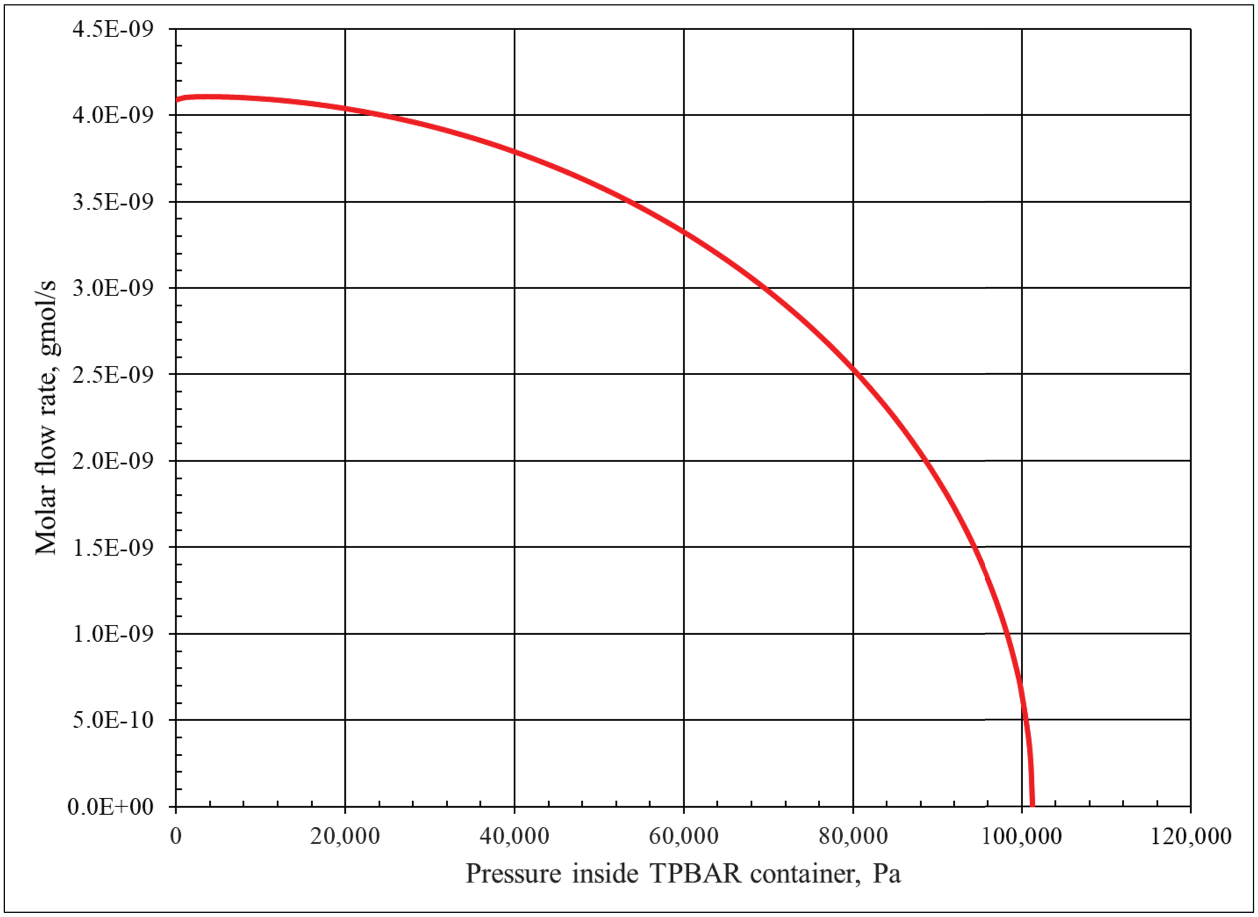

Figure 2-6. In-leakage of air as a function of disposal container internal pressure.

3.0 Implementation

The analysis detailed in Section 2.0 was implemented in a spreadsheet workbook (New Tritium Source Term Calculation r2.xlsx) that allows easy recalculation of the tritium release rate as a function of time for different input assumptions. It functions as a forward integration in 0.1-y time steps. The set-up of the spreadsheet is explained below. Inputs are identified by their "Tab!Cell" locations in the workbook.

The calculation assumes that each disposal container is instantaneously loaded with fresh TPBAR extraction baskets and welded shut at time zero with an internal atmosphere of moist air (70% relative humidity, RelCalcSetUp!D9) at the ambient temperature and pressure. It then immediately heats up to the maximum temperature as determined by a separate thermal analysis of TPBAR disposal in the ILV [10], with instantaneously established steady-state hydrogen concentration profiles along all three carbon steel permeation paths. Corrosion of the internal surfaces begins immediately, with the water thus consumed being continually replenished by desorption of the moisture tied up in the lithium aluminate pellets. This is a conservative approach because the maximum temperatures may not be achieved for several months and pseudo-steady-state hydrogen concentration profiles may take several hours to several months to be established along all three permeation paths. Consequently, the actual tritium release curve should have a much lower peak release rate.

The thermal analysis established maximum TPBAR extraction basket and maximum disposal container wall temperatures for four different scenarios [10]. Each is characterized by a different combination of peak basket and wall temperatures. This analysis assumes that the air inside the disposal container is maintained at the maximum extraction basket temperature and the walls, lid, and weld at the maximum wall temperature, beginning at time zero. The highest maximum temperatures were calculated for the case in which the TPBARs had been discharged from the Watts Bar reactor only one year prior, and the ILV had been loaded with eight disposal containers. In this case, the maximum basket and wall temperatures were found to be 140°C (RelCalcSetUp!D29) and 130°C (RelCalcSetUp!D31), respectively [10]. These are the values that will be used in the calculations that follow.

The free volume of the disposal container determines how much air is trapped when the container is welded shut. This analysis uses Clark's and Lanning and Gilbert's estimate of the fraction of the volume contained by the permeation boundary that is free as 0.2 (DispCont!D25) [2, 20], which is calculated as 731,964 cm^3. Assuming an ambient temperature of 76°F (RelCalcSetUp!D3) and pressure of 1 atm (RelCalcSetUp!D6), the quantity of moist air trapped in the free volume is 29.9742 gmol.

The residual tritium in each individual rod is assumed to be 133 Ci/rod (DispContSetUp!E6), each extraction basket is assumed to hold 300 rod/basket (DispContSetUp!E5), and each disposal container is assumed to hold 4 basket/container (DispContSetUp!E4). Thus, the total tritium inventory is 159,600 Ci. Using the activity density, 9621.03 Ci/g T (Constants!B4) and atomic mass of tritium, 3.01605 g/gmol T (Constants!B12) [12], this can be converted to the more convenient quantity of 5.50013 gmol T. Of this amount, a fraction of 0.05 (DispContSetUp!E10), or 0.275006 gmol T is assumed to have entered the moisture in the lithium aluminate via isotope exchange.

Each TPBAR contains 180.02 g of lithium aluminate pellets (DispContSetUp!E8) [11], resulting in a total pellet inventory of 216.024 kg $LiAlO_2$ per disposal container. Assuming an absorbed moisture content of 300 ppm (DispContSetUp!E9), this means the pellets hold 64.8072 g, or 3.597402 gmol H_2O. An additional 0.634980 gmol is present as water vapor, calculated from 70% RH at initial conditions. Thus, the total H content of the water available for corrosion is 7.194804 gmol H. Assuming that the tritiated moisture in the pellets instantaneously redistributes itself throughout the total water inventory, the initial tritium atom fraction (T/H_{total}) is 0.032488

Thus, the total molar quantity of dry air in the free volume at time zero is 29.33921 gmol air, the quantity of water vapor is 0.634980 gmol H_2O, and the quantities of hydrogen, helium-3, and "produced" oxygen are zero (helium-3 and "produced" oxygen are tracked explicitly as TH and THO decay products to maintain material balance). Given a free volume temperature of 140°C and assuming the ideal gas law, the internal pressure immediately increases to 1.388299 atm. The average molecular weight of the gas in the free volume is 28.7321 g/gmol, calculated from the sum of the products of the individual component molecular weights, $M_{w,i}$ (28.964 g/gmol air, Constants!B27; 18.0154 g/gmol H_2O, Constants!C20; 2.0160 g/gmol H_2, Constants!C22; 3.01603 g/gmol ^3He, Constants!B15; and 31.9988 g/gmol O_2 Constants!C24) and their mole fractions, y_i.

$$\boldsymbol{M_w = \sum_i y_i M_{w,i}} \tag{3-1}$$

Isotopic differences between protium and tritium are ignored in calculating the average molecular weight for simplicity. The effect on the results should be negligible.

Ninety-five percent of the residual tritium is assumed to be tied up in the getter. Based on the previously cited mass of Zircaloy-4 material (154.18 g/TPBAR, DispContSetUp!E97, Section 2.2 [11]) that translates to a 2.58×10^{-3} T/Zr atom ratio, for which the equilibrium T_2 partial pressure at 140°C is 1.33×10^{-13} atm. The permeability coefficient for tritium can be calculated from equation 2-7 and the cask wall temperature, 130°C, to get $\varphi = 5.05467 \times 10^{-12}$ gmol T_2/cm-s-atm^{½}. Using the calculated tritium partial pressure and equation 2-6, this gives a tritium permeability of 1.84×10^{-18} gmol T_2/cm-s. The rate of tritium permeation through the walls, lid, and sealing weld can now be calculated using the permeation area (DispContSetUp!D45:D47) and length (DispContSetUp!D50,D52,D54) values derived in Section 2.5 and the relationship $\dot{n} = A\Phi/L$ to get

- $\dot{n}_{walls} = 3.19 \times 10^{-7}$ gmol T_2/y,
- $\dot{n}_{lid} = 3.62 \times 10^{-7}$ gmol T_2/y, and
- $\dot{n}_{weld} = 2.92 \times 10^{-8}$ gmol T_2/y,
- $\dot{n}_{perm,\, total} = 7.10 \times 10^{-7}$ gmol T_2/y = 0.0412 Ci/y,

assuming 1 y = 365.25 d (Constants!B51). While this is more than three orders of magnitude higher than the permeation rate predicted by Lanning and Gilbert, it is still much smaller than the rate resulting from the tritiated hydrogen generated via corrosion, as will be shown below. The reasons for the higher rate are: 1) use of the steady-state instead of the transient permeation rate equation; 2) higher permeability correlation used for tritium transport through container walls; and 3) lower tritium solubility correlation used for Zircaloy-4 getter material. Since the tritium bound in the getter is released at a rate and magnitude that is orders of magnitude smaller than the tritium released by corrosion, it is tracked separately. Once the moisture is depleted and the tritium released by corrosion has escaped the container or decayed away, the low level of tritium release from the getter becomes the dominant, albeit minuscule release mechanism.

Having established the initial conditions inside the container and the initial permeation rate, the effects of all the ongoing phenomena over a time step can now be calculated. The leak rate is computed at the conditions at the beginning of the time step, using equation 2-16, with p_1 = 1.388299 atm = 140669 Pa (calculated above), p_2 = 1 atm = 101325 Pa (default external pressure), T = 130°C = 403.15K (the wall temperature), and M_W = 28.7321 g/gmol (calculated above). As noted at the end of Section 2.6, L = 0.3302 m (RelCalcSetUp!D51), f = 0.01 (RelCalcSetUp!D52), and $D_H = 1.907 \times 10^{-5}$ m (RelCalcSetUp!D53). The resulting leak rate is 3.4108×10^{-9} gmol/s, which causes 0.0107636 gmol (RelSchedZ7) to exit the container over the 3,155,760-s (Constants!B55) duration of the time step.

At the same time, the metal surfaces inside the disposal container are being corroded by moisture in the gas phase. As explained in Section 2.3, all carbon steel and stainless-steel surfaces are involved. The actual areas under corrosive attack are calculated on four different tabs: DispCont, TPBARs, Basket, and Consol. The exposed surface area of the carbon steel disposal container is found to be 189,573.8 cm^2 (DispCont!C40). Three different components contribute to the stainless-steel surface area undergoing corrosion. First, the TPBARs are clad in Type 316 stainless steel [4], contributing 139.1765 m^2 (TPBARs!F11) of surface area. Second, the extraction baskets are fabricated primarily out of Types RA-300 and 304L stainless steel, with some 17-4 alloy parts [14, 15]. They contribute a combined total of 121.1461 m^2 (Basket!E165) of surface area. Finally, the consolidation containers are made out of Type 304 stainless steel with some 17-4 alloy parts [16], contributing an additional 25.5928 m^2 (Consol!F129) of surface area. (Details of the surface area calculations are omitted here for brevity but can be found on the four tabs of the spreadsheet workbook noted above.) The combined total of all of the stainless-steel surfaces inside the disposal container is 2,859,155 cm^2 (DispContSetUp!D59).

The quantity of magnetite generated over the time step due to corrosion is calculated with the help of two corrosion tables, one for carbon steel (tab CSCorrosionTable) and the other for stainless steel (tab SSCorrosionTable). The two worksheets contain tables of oxide film thickness in elapsed time increments of 0.1 y calculated based on the temperature of the corroding material. Equation 2-3, with

$$\boldsymbol{k_p = 2.5069 \times 10^{-11} e^{-5387.8/T,\mathrm{K}}}\ \mathrm{cm^2/s}, \qquad \text{3-2}$$

obtained by digitizing the line in Figure 2 in Robertson [17] for corrosion of milled surface carbon steel was used to calculate oxide film thickness over time for carbon steel, while the two-phase model developed by Robertson [17] for milled surface Type 304 stainless steel was used to calculate oxide film thickness over time for stainless steel. Carbon steel grows a 0.1115-μ (CSCorrosionTable!C11) thick film over the first 0.1-y time increment, while stainless steel grows a 0.0277-μ (SSCorrosionTable!C9) thick film. Converting the thicknesses to cm, multiplying by the corresponding surface areas in cm^2, adding together the resulting volumes, multiplying by the density of magnetite (5.17 g/cm^3, Constants!E73), and dividing by its molecular weight (231.533g/gmol, Constants!E74), the quantity of Fe_3O_4 produced over the first 0.1-y time increment is 0.2241536 gmol (RelSched!AA7). Four times as many moles of hydrogen are produced (RelSched!AB7) and moles of water vapor consumed (RelSched!AC7).

Ignoring the extremely low partial pressure of tritium that exists at equilibrium with the getter, no hydrogen is present in the free volume at the very beginning (RelSched!Q6). Consequently, the permeability is zero (RelSched!R6) and zero hydrogen permeates over the initial time step (RelSched!AG7).

The total amount of hydrogen released from the disposal container over the time step can be calculated from the product of the hydrogen mole fraction and total molar amount of the leak plus the quantity permeated through the container itself. The water vapor is also tritiated, so the molar quantity passed by the leak needs to be added (RelSched!AR7). Multiplying by the moisture tritium atom fraction, this results in a tritium release of 0.000015 gmol (RelSched!AS7) or 0.429919 Ci (RelSched!AT7).

The tritium inside the container is continually undergoing β-decay to helium-3, which is monatomic. Thus, 1 gmol of diatomic tritium decays to make 2 gmol of monatomic helium,

$$T_2 \rightarrow 2\ He,$$

while 1 gmol of di-tritium oxide decays to make 2 gmol of monatomic helium and ½ gmol of oxygen,

$$T_2O \rightarrow 2\ He + \tfrac{1}{2}\ O_2.$$

(For the sake of simplicity, it is assumed that tritium exists in the disposal container as T_2 and T_2O rather than TH and THO. The net effect is the same, regardless which form it actually occurs in.) These reactions result in changes in the molar quantity of gaseous species (both helium and the oxygen liberated by decay are tracked separately in the spreadsheet), which affects the pressure inside the disposal container and needs to be accounted for. The amount that actually decays is determined by the half-life, $t_{½}$, which is 12.32 y [12] (Constants!B8) and the elapsed time interval, t, 0.1 y. Specifically, the fraction decayed in one 0.1-y time interval is

$$\text{fraction decayed} = \left(\mathbf{1} - \mathbf{0.5}^{\mathbf{0.1/12.32}}\right) = \mathbf{0.00561040} \qquad 3\text{-}3$$

(Constants!D56). Applying this to the tritiated moisture, the tritium atom fraction at the end of the time step (RelSched!T7) is reduced by this fractional amount. The tritium content of the getter at the end of the time step (RelSched!U7) is reduced by the same fraction. The effects of the container leak, permeation losses, corrosion reaction, and tritium decay can now be applied to calculate the contents of the free volume following the time step.

The molar quantity of air remaining in the free volume (RelSched!B7) is calculated by subtracting the product of the total moles of gas leaked and the mole fraction of air at the beginning of the time step (RelSched!H6) from the molar quantity at the beginning of the time step (RelSched!B6).

Determining the molar quantity of water vapor at the end of the time step (RelSched!C7) is a little more complicated. As indicated earlier, it is assumed that water vapor consumed by the corrosion reaction is immediately replaced with moisture desorbed from the $LiAlO_2$ pellets. Consequently, the availability of that moisture needs to be checked. Furthermore, a small fraction of the water vapor is tritiated and will undergo decay. Thus, the molar quantity of water vapor remaining is calculated by first subtracting the product of the total moles of gas leaked and the mole fraction of water vapor at the beginning of the time step (RelSched!I6) from the molar quantity of water vapor at the beginning of the time step (RelSched!C6). The molar quantity of water consumed due to corrosion over the time step (RelSched!AC7) is compared to the quantity of moisture available in the pellets (RelSched!O6). If there is enough moisture, no correction is made, otherwise the difference between RelSched!AC7 and RelSched!O6 is subtracted from the quantity of water vapor remaining. Finally, a correction is applied to account for the fraction of tritiated moisture that decays to helium and oxygen. The total molar quantity of water vapor is multiplied by 1 minus the difference between the moisture tritium atom fraction at the beginning, f_0 (RelSched!T6) and at the end, f_1 (RelSched!T7) of the time step, $(1 - (f_0 - f_1))$.

Calculating the molar quantity of hydrogen in the free volume at the end of the time step (RelSched!D7) is also somewhat complicated. The effects of the leak, corrosion reaction, permeation, and tritium decay all need to be accounted for. As with the other gaseous species, the molar quantity of hydrogen remaining is calculated by first subtracting the product of the total moles of gas leaked and the mole fraction of hydrogen at the beginning of the time step (RelSched!J6) from the molar quantity of hydrogen at the beginning of the time step (RelSched!D6). The total molar quantity of hydrogen generated by corrosion (RelSched!AB7) is then added, and the quantity removed by permeation (RelSched!AG7) subtracted. The resulting molar quantity of hydrogen is multiplied by $(1 - (f_0 - f_1))$ to give the final value.

Calculating how much helium and "produced" oxygen has accumulated in the free volume due to tritium decay requires knowing how much of the tritiated moisture, water vapor, and hydrogen, as well as the how much of the tritium bound in the getter has decayed. Multiplying the molar quantity of water vapor at the end of the time step by the ratio $(f_0 - f_1)/(1 - (f_0 - f_1))$ provides the molar quantity of tritiated water vapor that has decayed (RelSched!AI7). Similarly, multiplying the molar quantity of hydrogen at the end of the time step by $(f_0 - f_1)/(1 - (f_0 - f_1))$ provides the molar quantity of tritiated hydrogen that has decayed (RelSched!AJ7). The molar quantity of moisture remaining in the $LiAlO_2$ pellets (RelSched!O7) is calculated by subtracting the amount of water consumed by corrosion over the time step (RelSched!AC7) from the amount present at the beginning of the step (RelSched!O6) and multiplying the result by $(1 - (f_0 - f_1))$. If the quantity of water consumed by reaction is greater than the quantity available at the beginning of the step, the moisture in the pellets has been depleted and the molar quantity is set to zero. The molar quantity of absorbed moisture remaining is multiplied by $(f_0 - f_1)/(1 - (f_0 - f_1))$ to obtain the molar quantity of tritiated moisture that has decayed (RelSched!AH7). Finally, the molar quantity of bound tritium that has decayed (RelSched!AQ7) is calculated from the difference between the tritium content of the getter at the beginning and at the end of the time step.

The molar quantity of helium in the free volume (RelSched!E7) is calculated by subtracting the product of the total moles of gas leaked and the mole fraction of helium at the beginning of the time step (RelSched!K6) from the molar quantity of helium at the beginning of the time step (RelSched!E6) and adding the molar quantity generated by tritium decay, which is twice (T_2 and T_2O decay both yield 2 He) the molar quantity of tritiated absorbed moisture, water vapor, and hydrogen lost to decay (RelSched!AH7:AJ7) plus the molar quantity of bound tritium (each T decays to He) lost to decay (RelSched!AQ7).

The molar quantity of "produced" oxygen in the free volume (RelSched!F7) is calculated by subtracting the product of the total moles of gas leaked and the mole fraction of "produced" oxygen at the beginning of the time step (RelSched!L6) from the molar quantity of "produced" oxygen at the beginning of the time step (RelSched!F6) and adding the molar quantity generated by tritium decay, which is one half (T_2O decays to yield ½O_2) of the molar quantity of tritiated absorbed moisture and water vapor lost to decay (RelSched!AH7:AI7).

Having determined the molar quantities of all gaseous species in the free volume at the end of the time step, the total molar quantity (RelSched!G7), species mole fractions (RelSched!H7:L7), internal pressure (RelSched!M7), average molecular weight (RelSched!N7), and hydrogen partial pressure (RelSched!Q7) can be recalculated at the end of the time step in the same way as they were at the beginning. The total molar water inventory (RelSched!P7) can now be updated by adding the amount of water vapor remaining (RelSched!C7) to the amount of moisture remaining in the pellets (RelSched!O7). The total molar quantity of tritium contained in this water (RelSched!S7) can also be updated by multiplying the total water inventory by twice the fraction tritiated (RelSched!T7). Multiplying the permeability coefficient of the container walls (RelCalcSetUp!D41) by the square root of the hydrogen partial pressure updates the hydrogen permeability (RelSched!R7).

With regard to the tritium bound in the getter, the T/Zr atom ratio at the end of the time step (RelSched!V7) can be calculated from the remaining residual (RelSched!U7), allowing the corresponding equilibrium T_2 partial pressure (RelSched!W7) to be computed from its Sieverts' Law solubility. When divided by the total pressure (RelSched!M7), this gives the mole fraction of tritium that could exist in the free volume at equilibrium with that bound in the getter at the end of the time step (RelSched!X7). Multiplying the permeability coefficient of the container walls by the square root of the bound tritium partial pressure updates the bound tritium permeability (RelSched!Y7).

The molar quantities of bound tritium permeated through the three permeation paths (RelSched!AK7:AM7) is calculated in the same way as it is for hydrogen, using the above-determined bound tritium permeability. The total amount permeated (RelSched!AN7) is added to the quantity passed by the leak (RelSched!AN7) and multiplied by the activity (Constants!B6) to establish the bound tritium released in units of Ci (RelSched!AP7).

Adding together the amounts of bound (RelSched!AP7) and mobile (RelSched!AT7) tritium released over the time step gives the total released (RelSched!AU7). Dividing by the length of the time interval yields the average instantaneous release rate over the interval (RelSched!AV7) and adding together successive releases provides the cumulative release (RelSched!AW7).

With the free volume, $LiALO_2$ pellet, and Zircaloy-4 getter contents following the preceding time step thus established, the spreadsheet begins the next time step by repeating the leak, permeation, corrosion, Sieverts' Law, and decay calculations. The process is repeated for as much elapsed time as needed. Depending on the internal temperature, the moisture will eventually be all consumed and hydrogen generation cease. However, the bound tritium content in the getter, which accounts for the bulk, will be released very slowly over time and at a very low rate..

4.0 Results

Bounding cumulative tritium release curve were calculated for the four different cases developed in the thermal analysis [10]. The cases are summarized in Table 4-1 below.

Table 4-1. Temperatures Used in Source Term Calculations.

Case	Description	Internal Temperature, °C	Wall Temperature, °C
Case 1	1-y old TPBARS, 8 containers per ILV	140	130
Case 2	5-y old TPBARS, 8 containers per ILV	109	95
Case 3	1-y old TPBARS, 4 containers per ILV	96	89
Case 4	5-y old TPBARS, 4 containers per ILV	79	71

Cumulative release curves for all four are shown in Figure 4-1. The red curve plots the values for Case 1, the green for Case 2, the blue for Case 3, and the purple for Case 4. Tabular data are provided in Table A-1 in Appendix A.

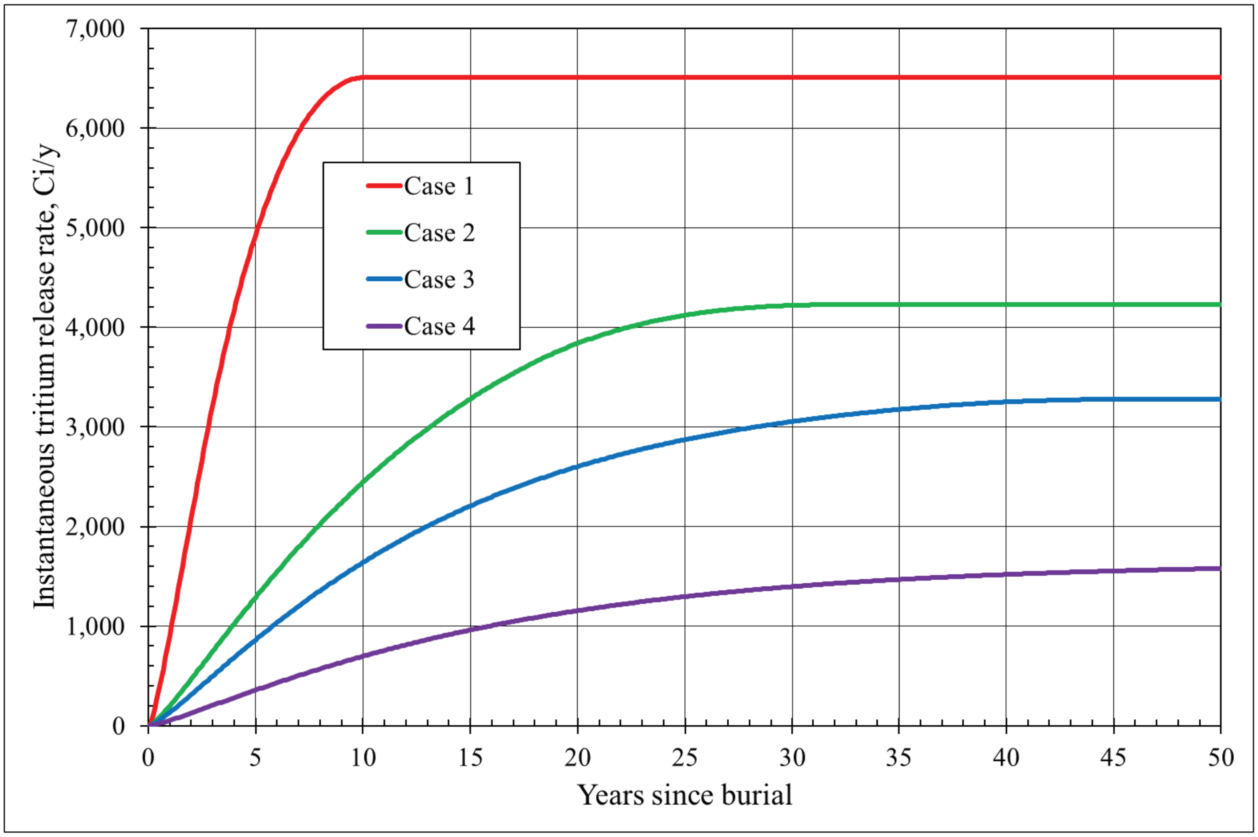

Figure 4-1. Cumulative Tritium Release over Time for the 4 ILV Disposal Cases.

Instantaneous release curves for the four cases are plotted in Figure 4-2, using the same color scheme.

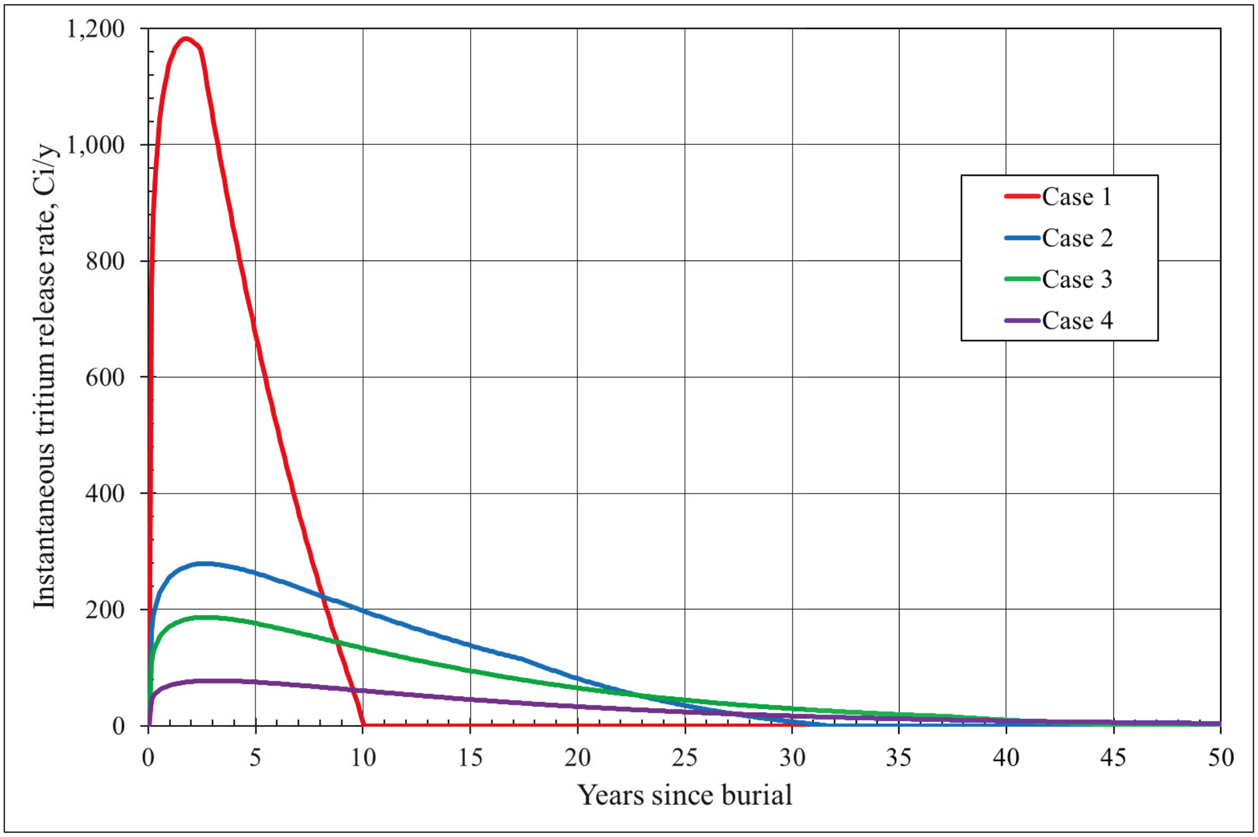

Figure 4-2. Instantaneous Tritium Release Rates over Time for the 4 ILV Disposal Cases.

Case 1 has the highest cumulative release of tritium. Only 5% of the tritium residual, 7,980 Ci, is mobile. The rest is tightly held by the getter. Roughly 81.5% of that amount, 6,507 Ci, is released before the moisture trapped in the disposal container is completely consumed and the resulting tritiated hydrogen either permeates and/or leaks out or decays away. This occurs at the 10-y mark. The difference, roughly 1,473 Ci is lost to radioactive decay. Once the mobile tritium is gone, the bound tritium continues to permeate and/or leak at a very low rate, initially around 0.02 Ci/y at 10 y, and decreasing by an order of magnitude to 0.0025 Ci/y at the 50-y mark.

Case 1 also has the highest instantaneous release rate, 1,182 Ci/y, which occurs at the 1.8-y mark. This is below the peak value predicted by Lanning and Gilbert's analysis, 2.210 Ci/y, which occurred at the 3.5-y mark [2]. Lanning and Gilbert assumed lower temperatures for the interior (200°F, 93.3°C) and the container wall (165°F, 73.9°C), yet found that all of the mobile tritium would be gone by 5.1 y.

The other three cases have lower interior and wall temperatures. That means lower corrosion, permeation, and leak rates, so the tritium release rate is significantly slower, providing more time for radioactive decay. The mobile tritium is completely gone after 31.7 y for Case 2 and 46.7 y for Case 3, and mostly gone after 50 y for Case 4. The corresponding cumulative releases are 4,225 Ci, 3,279 Ci, and 1,578 Ci, respectively.

5.0 Conclusions

A bounding calculation was performed for the rate at which tritium will be released from spent TPBARs placed in ILV for disposal. The analysis estimated how much tritium would escape an individual shielded disposal container holding 4 fully loaded extraction baskets containing 300 spent TPBARs each. An earlier thermal analysis [10] established maximum internal and container wall temperatures for four different disposal scenarios, depending on the number of containers placed per vault (4 or 8) and the elapsed time since the TPBARs were pulled from the Watts Bar reactor (1 or 5 years). The approach used was based on an earlier analysis performed by Lanning and Gilbert [2], which assumed that the bulk of the tritium residual was tightly bound in the TPBAR getter material and only a small fraction was mobile, initially existing as tritiated moisture in the TPBAR lithium aluminate pellets. Corrosion of the internal steel surfaces by this moisture, resulting in tritiated hydrogen generation with subsequent container wall permeation was the primary means by which tritium could escape the disposal container. The analysis also included a leak in the container walls at the maximum allowable leak rate, 1×10^{-4} standard cm^3/s. The rate of tritium leaving the container via this leak was found to be roughly two orders of magnitude smaller than the permeation rate.

As expected, the highest tritium release rates and largest cumulative tritium release were found for the disposal scenario with the highest temperatures. This was for the higher vault loading (8 containers) and higher TPBAR activity (1 year since irradiation) case. The maximum internal and container wall temperatures were 140 and 130°C, respectively [10]. Under these conditions, the peak tritium release rate was found to be 1,182.3 Ci/y, occurring 1.8 y following placement in ILV. The water content was completely consumed by corrosion 2.5 y after disposal, and the mobile tritium completely escaped or decayed after 10 y. The total quantity of tritium released at this point was 6,507.1 Ci. An additional 0.4 Ci was found to escape over the next 40 y due to residual tritium desorption from the getter with subsequent permeation.

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Appendix A. Instantaneous Tritium Source Term Release Rates and Cumulative Releases

Table A-1. Instantaneous Tritium Release Rates and Cumulative Releases over the 50-y Period of the Source Term Analysis.

		Instantaneous tritium release rate, Ci/y				Cumulative tritium release, Ci			
Elapsed time, y	Interval midpoint, y	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
0.0						0	0	0	0
0.1	0.05	4.340383	3.7686434	3.4599839	3.0581795	0.4340383	0.3768643	0.3459984	0.3058179
0.2	0.15	755.17303	161.34709	108.07169	43.864614	75.951341	16.511573	11.153168	4.6922794
0.3	0.25	877.33619	188.73123	126.26577	51.117393	163.68496	35.384696	23.779745	9.8040187
0.4	0.35	951.95926	206.05214	137.78117	55.755795	258.88089	55.98991	37.557861	15.379598
0.5	0.45	1004.5518	218.69063	146.18913	59.176379	359.33606	77.858973	52.176774	21.297236
0.6	0.55	1044.0606	228.53656	152.74388	61.869792	463.74212	100.71263	67.451162	27.484215
0.7	0.65	1074.7852	236.49915	158.04881	64.072135	571.22064	124.36254	83.256043	33.891429
0.8	0.75	1099.1581	243.09326	162.44557	65.917134	681.13645	148.67187	99.500601	40.483142
0.9	0.85	1118.7032	248.64183	166.14846	67.488673	793.00677	173.53605	116.11545	47.23201
1.0	0.95	1134.4452	253.36216	169.30166	68.843214	906.45129	198.87227	133.04561	54.116331
1.1	1.05	1147.1098	257.4083	172.00737	70.020785	1021.1623	224.6131	150.24635	61.11841
1.2	1.15	1157.2316	260.89383	174.34097	71.050911	1136.8854	250.70248	167.68045	68.223501
1.3	1.25	1165.2172	263.90524	176.35982	71.956072	1253.4072	277.09301	185.31643	75.419108
1.4	1.35	1171.3838	266.51004	178.10873	72.753826	1370.5455	303.74401	203.1273	82.69449
1.5	1.45	1175.9839	268.76208	179.62341	73.458179	1488.1439	330.62022	221.08964	90.040308
1.6	1.55	1179.2226	270.7051	180.93288	74.080509	1606.0662	357.69073	239.18293	97.448359
1.7	1.65	1181.2685	272.37515	182.06105	74.630199	1724.193	384.92824	257.38904	104.91138
1.8	1.75	1182.2625	273.80234	183.0279	75.115089	1842.4193	412.30848	275.69182	112.42289
1.9	1.85	1181.7707	275.01213	183.8503	75.541806	1960.5963	439.80969	294.07685	119.97707
2.0	1.95	1180.2837	276.02624	184.54268	75.916012	2078.6247	467.41231	312.53112	127.56867
2.1	2.05	1178.0821	276.86338	185.11743	76.242582	2196.4329	495.09865	331.04287	135.19293
2.2	2.15	1175.2395	277.53979	185.58534	76.525751	2313.9569	522.85263	349.6014	142.8455
2.3	2.25	1171.8204	278.06967	185.95582	76.769226	2431.1389	550.6596	368.19698	150.52243
2.4	2.35	1167.881	278.46553	186.23716	76.976269	2547.927	578.50615	386.8207	158.22005

2.5	2.45	1163.4712	278.73842	186.4367	77.14977	2664.2741	606.37999	405.46437	165.93503
2.6	2.55	1145.6889	278.89819	186.56097	77.292302	2778.843	634.26981	424.12047	173.66426
2.7	2.65	1124.032	278.95366	186.61581	77.406168	2891.2462	662.16518	442.78205	181.40488
2.8	2.75	1102.5942	278.91272	186.60647	77.493438	3001.5056	690.05645	461.44269	189.15422
2.9	2.85	1081.3736	278.7825	186.53767	77.555979	3109.643	717.9347	480.09646	196.90982
3.0	2.95	1060.3683	278.56948	186.4137	77.595486	3215.6798	745.79165	498.73783	204.66937
3.1	3.05	1039.5763	278.27951	186.23845	77.613495	3319.6375	773.6196	517.36168	212.43072
3.2	3.15	1018.9956	277.91795	186.01547	77.611412	3421.537	801.41139	535.96322	220.19186
3.3	3.25	998.62429	277.48967	185.748	77.590522	3521.3994	829.16036	554.53802	227.95091
3.4	3.35	978.46055	276.99917	185.43902	77.552002	3619.2455	856.86028	573.08193	235.70611
3.5	3.45	958.50246	276.45056	185.09125	77.496937	3715.0957	884.50533	591.59105	243.4558
3.6	3.55	938.74815	275.84764	184.70722	77.426329	3808.9706	912.0901	610.06177	251.19844
3.7	3.65	919.19576	275.19391	184.28924	77.341101	3900.8901	939.60949	628.4907	258.93255
3.8	3.75	899.84345	274.49262	183.83948	77.24211	3990.8745	967.05875	646.87464	266.65676
3.9	3.85	880.68941	273.74677	183.35992	77.130152	4078.9434	994.43343	665.21064	274.36977
4.0	3.95	861.7318	272.95917	182.85242	77.005967	4165.1166	1021.7293	683.49588	282.07037
4.1	4.05	842.96885	272.1324	182.31871	76.870243	4249.4135	1048.9426	701.72775	289.75739
4.2	4.15	824.39877	271.2689	181.7604	76.723626	4331.8534	1076.0695	719.90379	297.42976
4.3	4.25	806.01979	270.37093	181.17899	76.566717	4412.4553	1103.1066	738.02169	305.08643
4.4	4.35	787.83016	269.44061	180.57588	76.400079	4491.2384	1130.0506	756.07928	312.72644
4.5	4.45	769.82813	268.47992	179.9524	76.22424	4568.2212	1156.8986	774.07452	320.34886
4.6	4.55	752.01199	267.49073	179.30977	76.039698	4643.4224	1183.6477	792.00549	327.95283
4.7	4.65	734.38	266.47477	178.64915	75.846919	4716.8604	1210.2952	809.87041	335.53752
4.8	4.75	716.93047	265.43368	177.97164	75.646343	4788.5534	1236.8385	827.66757	343.10216
4.9	4.85	699.66172	264.36903	177.27826	75.438383	4858.5196	1263.2754	845.3954	350.64599
5.0	4.95	682.57205	263.28225	176.56998	75.223431	4926.7768	1289.6037	863.0524	358.16834
5.1	5.05	665.65981	262.17472	175.8477	75.001856	4993.3428	1315.8211	880.63717	365.66852
5.2	5.15	648.92333	261.04773	175.1123	74.774007	5058.2351	1341.9259	898.1484	373.14592
5.3	5.25	632.36098	259.90252	174.36457	74.540215	5121.4712	1367.9162	915.58486	380.59995
5.4	5.35	615.97112	258.74024	173.6053	74.300793	5183.0683	1393.7902	932.94539	388.03002

5.5	5.45	599.75211	257.56198	172.83521	74.056039	5243.0435	1419.5464	950.22891	395.43563
5.6	5.55	583.70236	256.36878	172.05498	73.806233	5301.4138	1445.1833	967.43441	402.81625
5.7	5.65	567.82024	255.16163	171.26528	73.551644	5358.1958	1470.6994	984.56093	410.17142
5.8	5.75	552.10416	253.94146	170.46673	73.292526	5413.4062	1496.0936	1001.6076	417.50067
5.9	5.85	536.55252	252.70915	169.6599	73.029122	5467.0615	1521.3645	1018.5736	424.80358
6.0	5.95	521.16375	251.46555	168.84537	72.761661	5519.1778	1546.511	1035.4581	432.07975
6.1	6.05	505.93627	250.21145	168.02366	72.490365	5569.7715	1571.5322	1052.2605	439.32878
6.2	6.15	490.86849	248.94762	167.19528	72.215441	5618.8583	1596.4269	1068.98	446.55033
6.3	6.25	475.95885	247.67479	166.36071	71.93709	5666.4542	1621.1944	1085.6161	453.74404
6.4	6.35	461.20579	246.39363	165.52042	71.655501	5712.5748	1645.8338	1102.1681	460.90959
6.5	6.45	446.60774	245.10481	164.67483	71.370858	5757.2355	1670.3443	1118.6356	468.04667
6.6	6.55	432.16313	243.80895	163.82436	71.083334	5800.4519	1694.7252	1135.0181	475.15501
6.7	6.65	417.8704	242.50664	162.96942	70.793094	5842.2389	1718.9758	1151.315	482.23432
6.8	6.75	403.72798	241.19847	162.11037	70.500299	5882.6117	1743.0957	1167.526	489.28435
6.9	6.85	389.7343	239.88496	161.24759	70.205099	5921.5851	1767.0842	1183.6508	496.30486
7.0	6.95	375.88777	238.56664	160.38141	69.907641	5959.1739	1790.9408	1199.6889	503.29562
7.1	7.05	362.18682	237.244	159.51217	69.608064	5995.3926	1814.6652	1215.6402	510.25643
7.2	7.15	348.62983	235.91752	158.64018	69.306501	6030.2556	1838.257	1231.5042	517.18708
7.3	7.25	335.21518	234.58764	157.76575	69.003081	6063.7771	1861.7158	1247.2807	524.08738
7.4	7.35	321.94123	233.2548	156.88915	68.697926	6095.9712	1885.0412	1262.9697	530.95718
7.5	7.45	308.80633	231.91941	156.01067	68.391153	6126.8518	1908.2332	1278.5707	537.79629
7.6	7.55	295.80876	230.58187	155.13057	68.082876	6156.4327	1931.2914	1294.0838	544.60458
7.7	7.65	282.94679	229.24255	154.24909	67.773204	6184.7274	1954.2156	1309.5087	551.3819
7.8	7.75	270.21864	227.90181	153.36649	67.46224	6211.7493	1977.0058	1324.8453	558.12812
7.9	7.85	257.62246	226.56	152.483	67.150083	6237.5115	1999.6618	1340.0936	564.84313
8.0	7.95	245.15634	225.21745	151.59883	66.836831	6262.0271	2022.1835	1355.2535	571.52682
8.1	8.05	232.81827	223.87447	150.71419	66.522576	6285.309	2044.571	1370.3249	578.17907
8.2	8.15	220.60615	222.53137	149.82929	66.207405	6307.3696	2066.8241	1385.3079	584.79981
8.3	8.25	208.51772	221.18845	148.94433	65.891405	6328.2214	2088.943	1400.2023	591.38895
8.4	8.35	196.55058	219.84597	148.05948	65.574657	6347.8764	2110.9276	1415.0083	597.94642

8.5	8.45	184.70212	218.50421	147.17493	65.257241	6366.3466	2132.778	1429.7258	604.47214
8.6	8.55	172.96944	217.16341	146.29085	64.939231	6383.6436	2154.4943	1444.3548	610.96607
8.7	8.65	161.34932	215.82383	145.4074	64.620701	6399.7785	2176.0767	1458.8956	617.42814
8.8	8.75	149.8381	214.48569	144.52474	64.301721	6414.7623	2197.5253	1473.348	623.85831
8.9	8.85	138.43152	213.14923	143.64301	63.98236	6428.6055	2218.8402	1487.7123	630.25655
9.0	8.95	127.12454	211.81466	142.76237	63.662681	6441.3179	2240.0217	1501.9886	636.62281
9.1	9.05	115.91101	210.48217	141.88296	63.342747	6452.909	2261.0699	1516.1769	642.95709
9.2	9.15	104.78324	209.15198	141.00489	63.022619	6463.3873	2281.9851	1530.2774	649.25935
9.3	9.25	93.73124	207.82427	140.12831	62.702355	6472.7605	2302.7675	1544.2902	655.52959
9.4	9.35	82.741515	206.49921	139.25333	62.382012	6481.0346	2323.4174	1558.2155	661.76779
9.5	9.45	71.794898	205.17699	138.38007	62.061641	6488.2141	2343.9351	1572.0535	667.97395
9.6	9.55	60.862386	203.85777	137.50864	61.741297	6494.3003	2364.3209	1585.8044	674.14808
9.7	9.65	49.896233	202.54171	136.63915	61.421028	6499.29	2384.5751	1599.4683	680.29018
9.8	9.75	38.807645	201.22895	135.7717	61.100883	6503.1707	2404.698	1613.0455	686.40027
9.9	9.85	27.395076	199.91966	134.90639	60.780909	6505.9102	2424.6899	1626.5361	692.47836
10.0	9.95	11.766151	198.61396	134.04331	60.461149	6507.0869	2444.5513	1639.9405	698.52448
10.1	10.05	0.0234657	197.31199	133.18256	60.141648	6507.0892	2464.2825	1653.2587	704.53864
10.2	10.15	0.0233341	196.01389	132.32421	59.822447	6507.0915	2483.8839	1666.4911	710.52089
10.3	10.25	0.0232032	194.71976	131.46836	59.503586	6507.0939	2503.3559	1679.638	716.47125
10.4	10.35	0.023073	193.42973	130.61509	59.185103	6507.0962	2522.6989	1692.6995	722.38976
10.5	10.45	0.0229435	192.14391	129.76446	58.867035	6507.0985	2541.9133	1705.6759	728.27646
10.6	10.55	0.0228148	190.8624	128.91655	58.549419	6507.1007	2560.9995	1718.5676	734.1314
10.7	10.65	0.0226868	189.58532	128.07144	58.232289	6507.103	2579.958	1731.3747	739.95463
10.8	10.75	0.0225595	188.31275	127.22918	57.915679	6507.1053	2598.7893	1744.0976	745.7462
10.9	10.85	0.022433	187.0448	126.38984	57.599619	6507.1075	2617.4938	1756.7366	751.50616
11.0	10.95	0.0223071	185.78154	125.55348	57.284142	6507.1097	2636.0719	1769.292	757.23457
11.1	11.05	0.022182	184.52307	124.72016	56.969277	6507.112	2654.5243	1781.764	762.9315
11.2	11.15	0.0220575	183.26947	123.88994	56.655053	6507.1142	2672.8512	1794.153	768.59701
11.3	11.25	0.0219338	182.02081	123.06286	56.341496	6507.1164	2691.0533	1806.4593	774.23116
11.4	11.35	0.0218107	180.77717	122.23898	56.028635	6507.1185	2709.131	1818.6832	779.83402

11.5	11.45	0.0216883	179.53861	121.41834	55.716494	6507.1207	2727.0849	1830.825	785.40567
11.6	11.55	0.0215667	178.30521	120.601	55.405099	6507.1229	2744.9154	1842.8851	790.94618
11.7	11.65	0.0214457	177.07703	119.78699	55.094472	6507.125	2762.6231	1854.8638	796.45563
11.8	11.75	0.0213253	175.85412	118.97636	54.784637	6507.1271	2780.2085	1866.7614	801.93409
11.9	11.85	0.0212057	174.63655	118.16915	54.475616	6507.1293	2797.6722	1878.5784	807.38165
12.0	11.95	0.0210867	173.42437	117.36538	54.16743	6507.1314	2815.0146	1890.3149	812.79839
12.1	12.05	0.0209684	172.21764	116.56511	53.860099	6507.1335	2832.2364	1901.9714	818.1844
12.2	12.15	0.0208508	171.01639	115.76836	53.553643	6507.1356	2849.338	1913.5482	823.53977
12.3	12.25	0.0207338	169.82068	114.97517	53.24808	6507.1376	2866.3201	1925.0458	828.86458
12.4	12.35	0.0206175	168.63055	114.18556	52.94343	6507.1397	2883.1831	1936.4643	834.15892
12.5	12.45	0.0205018	167.44603	113.39956	52.639708	6507.1417	2899.9277	1947.8043	839.42289
12.6	12.55	0.0203868	166.26718	112.61721	52.336933	6507.1438	2916.5544	1959.066	844.65658
12.7	12.65	0.0202724	165.09403	111.83852	52.035119	6507.1458	2933.0638	1970.2498	849.8601
12.8	12.75	0.0201587	163.9266	111.06352	51.734283	6507.1478	2949.4565	1981.3562	855.03352
12.9	12.85	0.0200456	162.76494	110.29223	51.434439	6507.1498	2965.733	1992.3854	860.17697
13.0	12.95	0.0199331	161.59256	109.52468	51.135602	6507.1518	2981.8922	2003.3379	865.29053
13.1	13.05	0.0198213	160.39341	108.76088	50.837784	6507.1538	2997.9316	2014.214	870.37431
13.2	13.15	0.0197101	159.20093	108.00085	50.540999	6507.1558	3013.8517	2025.0141	875.42841
13.3	13.25	0.0195995	158.01514	107.24462	50.24526	6507.1577	3029.6532	2035.7385	880.45293
13.4	13.35	0.0194895	156.83605	106.49219	49.950578	6507.1597	3045.3368	2046.3877	885.44799
13.5	13.45	0.0193802	155.66367	105.74358	49.656966	6507.1616	3060.9032	2056.9621	890.41369
13.6	13.55	0.0192714	154.498	104.9988	49.364433	6507.1635	3076.353	2067.462	895.35013
13.7	13.65	0.0191633	153.33905	104.25787	49.07299	6507.1655	3091.6869	2077.8878	900.25743
13.8	13.75	0.0190558	152.18682	103.5208	48.782648	6507.1674	3106.9056	2088.2398	905.13569
13.9	13.85	0.0189489	151.04133	102.7876	48.493415	6507.1693	3122.0097	2098.5186	909.98504
14.0	13.95	0.0188426	149.90257	102.05828	48.205302	6507.1711	3136.9999	2108.7244	914.80557
14.1	14.05	0.0187369	148.77053	101.33284	47.918316	6507.173	3151.877	2118.8577	919.5974
14.2	14.15	0.0186318	147.64524	100.61131	47.632466	6507.1749	3166.6415	2128.9188	924.36064
14.3	14.25	0.0185272	146.52667	99.893667	47.34776	6507.1767	3181.2942	2138.9082	929.09542
14.4	14.35	0.0184233	145.41483	99.179937	47.064205	6507.1786	3195.8357	2148.8262	933.80184

14.5	14.45	0.0183199	144.30971	98.47012	46.781808	6507.1804	3210.2666	2158.6732	938.48002
14.6	14.55	0.0182171	143.21131	97.76422	46.500576	6507.1822	3224.5878	2168.4496	943.13008
14.7	14.65	0.0181149	142.11963	97.062241	46.220516	6507.184	3238.7997	2178.1559	947.75213
14.8	14.75	0.0180133	141.03465	96.364185	45.941633	6507.1858	3252.9032	2187.7923	952.34629
14.9	14.85	0.0179122	139.95637	95.670054	45.663934	6507.1876	3266.8988	2197.3593	956.91269
15.0	14.95	0.0178117	138.88478	94.97985	45.387422	6507.1894	3280.7873	2206.8573	961.45143
15.1	15.05	0.0177118	137.81987	94.293573	45.112105	6507.1912	3294.5693	2216.2866	965.96264
15.2	15.15	0.0176124	136.76162	93.611224	44.837985	6507.1929	3308.2455	2225.6478	970.44644
15.3	15.25	0.0175136	135.71004	92.9328	44.565068	6507.1947	3321.8165	2234.941	974.90295
15.4	15.35	0.0174154	134.6651	92.258302	44.293358	6507.1964	3335.283	2244.1669	979.33228
15.5	15.45	0.0173177	133.62679	91.587726	44.022859	6507.1982	3348.6457	2253.3256	983.73457
15.6	15.55	0.0172205	132.5951	90.921071	43.753574	6507.1999	3361.9052	2262.4177	988.10992
15.7	15.65	0.0171239	131.57002	90.258334	43.485506	6507.2016	3375.0622	2271.4436	992.45848
15.8	15.75	0.0170278	130.55152	89.59951	43.218659	6507.2033	3388.1173	2280.4035	996.78034
15.9	15.85	0.0169323	129.5396	88.944596	42.953035	6507.205	3401.0713	2289.298	1001.0756
16.0	15.95	0.0168373	128.53424	88.293587	42.688638	6507.2067	3413.9247	2298.1273	1005.3445
16.1	16.05	0.0167428	127.53541	87.646478	42.425469	6507.2084	3426.6783	2306.892	1009.5871
16.2	16.15	0.0166489	126.54311	87.003263	42.16353	6507.21	3439.3326	2315.5923	1013.8034
16.3	16.25	0.0165555	125.55731	86.363936	41.902823	6507.2117	3451.8883	2324.2287	1017.9937
16.4	16.35	0.0164626	124.57799	85.72849	41.643351	6507.2133	3464.3461	2332.8016	1022.158
16.5	16.45	0.0163702	123.60514	85.096919	41.385114	6507.215	3476.7066	2341.3113	1026.2965
16.6	16.55	0.0162784	122.63873	84.469215	41.128114	6507.2166	3488.9705	2349.7582	1030.4093
16.7	16.65	0.0161871	121.67875	83.84537	40.872351	6507.2182	3501.1384	2358.1427	1034.4966
16.8	16.75	0.0160962	120.72518	83.225377	40.617828	6507.2198	3513.2109	2366.4653	1038.5584
16.9	16.85	0.0160059	119.77799	82.609226	40.364543	6507.2214	3525.1887	2374.7262	1042.5948
17.0	16.95	0.0159161	118.83716	81.996909	40.112498	6507.223	3537.0724	2382.9259	1046.6061
17.1	17.05	0.0158268	117.90267	81.388416	39.861694	6507.2246	3548.8627	2391.0647	1050.5922
17.2	17.15	0.0157381	116.97449	80.783738	39.61213	6507.2262	3560.5601	2399.1431	1054.5535
17.3	17.25	0.0156498	116.05261	80.182865	39.363806	6507.2277	3572.1654	2407.1614	1058.4898
17.4	17.35	0.015562	115.137	79.585786	39.116722	6507.2293	3583.6791	2415.1199	1062.4015

17.5	17.45	0.0154746	114.22763	78.992492	38.870878	6507.2308	3595.1018	2423.0192	1066.2886
17.6	17.55	0.0153878	113.32449	78.402971	38.626273	6507.2324	3606.4343	2430.8595	1070.1512
17.7	17.65	0.0153015	112.21742	77.817213	38.382907	6507.2339	3617.656	2438.6412	1073.9895
17.8	17.75	0.0152156	110.76917	77.235205	38.140779	6507.2354	3628.7329	2446.3647	1077.8036
17.9	17.85	0.0151303	109.33418	76.656936	37.899888	6507.2369	3639.6664	2454.0304	1081.5936
18.0	17.95	0.0150454	107.91233	76.082395	37.660232	6507.2384	3650.4576	2461.6387	1085.3596
18.1	18.05	0.014961	106.50353	75.511569	37.421812	6507.2399	3661.1079	2469.1898	1089.1018
18.2	18.15	0.014877	105.10766	74.944446	37.184625	6507.2414	3671.6187	2476.6843	1092.8202
18.3	18.25	0.0147936	103.72463	74.381013	36.94867	6507.2429	3681.9912	2484.1224	1096.5151
18.4	18.35	0.0147106	102.35431	73.821258	36.713945	6507.2444	3692.2266	2491.5045	1100.1865
18.5	18.45	0.0146281	100.99663	73.265167	36.48045	6507.2458	3702.3263	2498.831	1103.8346
18.6	18.55	0.014546	99.651454	72.712727	36.248181	6507.2473	3712.2914	2506.1023	1107.4594
18.7	18.65	0.0144644	98.318699	72.163926	36.017137	6507.2487	3722.1233	2513.3187	1111.0611
18.8	18.75	0.0143832	96.998257	71.618748	35.787317	6507.2502	3731.8231	2520.4806	1114.6398
18.9	18.85	0.0143025	95.690029	71.077182	35.558718	6507.2516	3741.3921	2527.5883	1118.1957
19.0	18.95	0.0142223	94.393915	70.539212	35.331338	6507.253	3750.8315	2534.6422	1121.7288
19.1	19.05	0.0141425	93.109814	70.004824	35.105174	6507.2545	3760.1425	2541.6427	1125.2393
19.2	19.15	0.0140631	91.837629	69.474005	34.880225	6507.2559	3769.3262	2548.5901	1128.7274
19.3	19.25	0.0139842	90.577261	68.94674	34.656487	6507.2573	3778.384	2555.4847	1132.193
19.4	19.35	0.0139058	89.328615	68.423014	34.433959	6507.2586	3787.3168	2562.327	1135.6364
19.5	19.45	0.0138278	88.091592	67.902814	34.212637	6507.26	3796.126	2569.1173	1139.0577
19.6	19.55	0.0137502	86.866099	67.386123	33.992519	6507.2614	3804.8126	2575.8559	1142.4569
19.7	19.65	0.013673	85.652039	66.872927	33.773602	6507.2628	3813.3778	2582.5432	1145.8343
19.8	19.75	0.0135963	84.44932	66.363212	33.555884	6507.2641	3821.8227	2589.1796	1149.1899
19.9	19.85	0.0135201	83.257847	65.856961	33.33936	6507.2655	3830.1485	2595.7653	1152.5238
20.0	19.95	0.0134442	82.077529	65.35416	33.124029	6507.2668	3838.3563	2602.3007	1155.8362
20.1	20.05	0.0133688	80.908273	64.854794	32.909887	6507.2682	3846.4471	2608.7861	1159.1272
20.2	20.15	0.0132938	79.749988	64.358846	32.696931	6507.2695	3854.4221	2615.222	1162.3969
20.3	20.25	0.0132192	78.602583	63.866302	32.485157	6507.2708	3862.2824	2621.6087	1165.6454
20.4	20.35	0.013145	77.46597	63.377146	32.274563	6507.2721	3870.029	2627.9464	1168.8729

20.5	20.45	0.0130713	76.340058	62.891361	32.065146	6507.2734	3877.663	2634.2355	1172.0794
20.6	20.55	0.0129979	75.224759	62.408933	31.8569	6507.2747	3885.1854	2640.4764	1175.2651
20.7	20.65	0.012925	74.119986	61.929846	31.649824	6507.276	3892.5974	2646.6694	1178.43
20.8	20.75	0.0128525	73.025652	61.454082	31.443914	6507.2773	3899.9	2652.8148	1181.5744
20.9	20.85	0.0127804	71.94167	60.981628	31.239166	6507.2786	3907.0942	2658.913	1184.6984
21.0	20.95	0.0127087	70.867954	60.512466	31.035576	6507.2799	3914.181	2664.9642	1187.8019
21.1	21.05	0.0126374	69.80442	60.04658	30.833141	6507.2811	3921.1614	2670.9689	1190.8852
21.2	21.15	0.0125665	68.750983	59.583955	30.631857	6507.2824	3928.0365	2676.9273	1193.9484
21.3	21.25	0.012496	67.707559	59.124574	30.431721	6507.2836	3934.8073	2682.8397	1196.9916
21.4	21.35	0.0124259	66.674066	58.66842	30.232728	6507.2849	3941.4747	2688.7066	1200.0149
21.5	21.45	0.0123562	65.65042	58.215478	30.034874	6507.2861	3948.0397	2694.5281	1203.0183
21.6	21.55	0.0122868	64.63654	57.765731	29.838157	6507.2873	3954.5034	2700.3047	1206.0022
21.7	21.65	0.0122179	63.632345	57.319163	29.642571	6507.2886	3960.8666	2706.0366	1208.9664
21.8	21.75	0.0121494	62.637754	56.875758	29.448113	6507.2898	3967.1304	2711.7242	1211.9112
21.9	21.85	0.0120812	61.652688	56.435498	29.254778	6507.291	3973.2956	2717.3677	1214.8367
22.0	21.95	0.0120134	60.677066	55.998368	29.062564	6507.2922	3979.3633	2722.9676	1217.743
22.1	22.05	0.011946	59.710811	55.564352	28.871465	6507.2934	3985.3344	2728.524	1220.6301
22.2	22.15	0.011879	58.753844	55.133432	28.681478	6507.2946	3991.2098	2734.0373	1223.4983
22.3	22.25	0.0118123	57.806087	54.705592	28.492598	6507.2958	3996.9904	2739.5079	1226.3475
22.4	22.35	0.0117461	56.867464	54.280815	28.304821	6507.2969	4002.6772	2744.936	1229.178
22.5	22.45	0.0116802	55.937898	53.859086	28.118144	6507.2981	4008.271	2750.3219	1231.9898
22.6	22.55	0.0116146	55.017314	53.440387	27.932561	6507.2993	4013.7727	2755.6659	1234.7831
22.7	22.65	0.0115495	54.105636	53.024702	27.748069	6507.3004	4019.1832	2760.9684	1237.5579
22.8	22.75	0.0114847	53.20279	52.612015	27.564663	6507.3016	4024.5035	2766.2296	1240.3143
22.9	22.85	0.0114203	52.308702	52.202309	27.382339	6507.3027	4029.7344	2771.4498	1243.0526
23.0	22.95	0.0113562	51.423298	51.795567	27.201093	6507.3038	4034.8767	2776.6294	1245.7727
23.1	23.05	0.0112925	50.546505	51.391773	27.02092	6507.305	4039.9314	2781.7686	1248.4748
23.2	23.15	0.0112291	49.678252	50.99091	26.841816	6507.3061	4044.8992	2786.8677	1251.159
23.3	23.25	0.0111661	48.818465	50.592962	26.663776	6507.3072	4049.7811	2791.927	1253.8253
23.4	23.35	0.0111035	47.967075	50.197913	26.486797	6507.3083	4054.5778	2796.9467	1256.474

23.5	23.45	0.0110412	47.12401	49.805745	26.310873	6507.3094	4059.2902	2801.9273	1259.1051
23.6	23.55	0.0109792	46.2892	49.416442	26.136001	6507.3105	4063.9191	2806.869	1261.7187
23.7	23.65	0.0109176	45.462575	49.029989	25.962175	6507.3116	4068.4653	2811.772	1264.3149
23.8	23.75	0.0108564	44.644066	48.646367	25.789392	6507.3127	4072.9297	2816.6366	1266.8939
23.9	23.85	0.0107955	43.833605	48.265562	25.617646	6507.3138	4077.3131	2821.4632	1269.4556
24.0	23.95	0.0107349	43.031124	47.887556	25.446934	6507.3148	4081.6162	2826.2519	1272.0003
24.1	24.05	0.0106747	42.236554	47.512333	25.277251	6507.3159	4085.8399	2831.0031	1274.528
24.2	24.15	0.0106148	41.449829	47.139877	25.108592	6507.317	4089.9849	2835.7171	1277.0389
24.3	24.25	0.0105552	40.670883	46.770172	24.940953	6507.318	4094.0519	2840.3941	1279.533
24.4	24.35	0.010496	39.899648	46.4032	24.774329	6507.3191	4098.0419	2845.0345	1282.0104
24.5	24.45	0.0104371	39.13606	46.038947	24.608716	6507.3201	4101.9555	2849.6384	1284.4713
24.6	24.55	0.0103786	38.380054	45.677395	24.444109	6507.3212	4105.7935	2854.2061	1286.9157
24.7	24.65	0.0103203	37.631564	45.318528	24.280503	6507.3222	4109.5567	2858.738	1289.3438
24.8	24.75	0.0102624	36.890527	44.96233	24.117895	6507.3232	4113.2457	2863.2342	1291.7556
24.9	24.85	0.0102049	36.156878	44.608786	23.956279	6507.3242	4116.8614	2867.6951	1294.1512
25.0	24.95	0.0101476	35.430556	44.257878	23.79565	6507.3253	4120.4045	2872.1209	1296.5307
25.1	25.05	0.0100907	34.711495	43.909591	23.636006	6507.3263	4123.8756	2876.5118	1298.8943
25.2	25.15	0.0100341	33.999636	#########	23.477339	6507.3273	4127.2756	2880.8682	1301.2421
25.3	25.25	0.0099778	33.294914	43.220816	23.319647	6507.3283	4130.6051	2885.1903	1303.574
25.4	25.35	0.0099218	32.59727	42.880295	23.162924	6507.3293	4133.8648	2889.4783	1305.8903
25.5	25.45	0.0098661	31.906641	42.542331	23.007167	6507.3302	4137.0555	2893.7325	1308.1911
25.6	25.55	0.0098108	31.222968	42.206909	22.852369	6507.3312	4140.1778	2897.9532	1310.4763
25.7	25.65	0.0097557	30.54619	41.874011	22.698527	6507.3322	4143.2324	2902.1406	1312.7461
25.8	25.75	0.009701	29.876247	41.543623	22.545637	6507.3332	4146.22	2906.295	1315.0007
25.9	25.85	0.0096466	29.213079	41.215728	22.393692	6507.3341	4149.1413	2910.4166	1317.2401
26.0	25.95	0.0095925	28.556629	40.890312	22.24269	6507.3351	4151.997	2914.5056	1319.4643
26.1	26.05	0.0095386	27.906836	40.567357	22.092625	6507.336	4154.7877	2918.5623	1321.6736
26.2	26.15	0.0094851	27.263644	40.24685	21.943492	6507.337	4157.514	2922.587	1323.868
26.3	26.25	0.0094319	26.626993	39.928773	21.795288	6507.3379	4160.1767	2926.5799	1326.0475
26.4	26.35	0.009379	25.996826	39.613112	21.648007	6507.3389	4162.7764	2930.5412	1328.2123

26.5	26.45	0.0093264	25.373087	39.299851	21.501645	6507.3398	4165.3137	2934.4712	1330.3625
26.6	26.55	0.009274	24.755718	38.988975	21.356198	6507.3407	4167.7893	2938.3701	1332.4981
26.7	26.65	0.009222	24.144662	38.680469	21.21166	6507.3417	4170.2038	2942.2381	1334.6192
26.8	26.75	0.0091703	23.539864	38.374316	21.068027	6507.3426	4172.5577	2946.0756	1336.726
26.9	26.85	0.0091188	22.941268	38.070503	20.925295	6507.3435	4174.8519	2949.8826	1338.8186
27.0	26.95	0.0090677	22.348817	37.769013	20.783459	6507.3444	4177.0868	2953.6595	1340.8969
27.1	27.05	0.0090168	21.762456	37.469831	20.642514	6507.3453	4179.263	2957.4065	1342.9612
27.2	27.15	0.0089662	21.182131	37.172943	20.502457	6507.3462	4181.3812	2961.1238	1345.0114
27.3	27.25	0.0089159	20.607785	36.878334	20.363281	6507.3471	4183.442	2964.8116	1347.0477
27.4	27.35	0.0088659	20.039366	36.585988	20.224984	6507.348	4185.4459	2968.4702	1349.0702
27.5	27.45	0.0088161	19.476817	36.295891	20.087559	6507.3489	4187.3936	2972.0998	1351.079
27.6	27.55	0.0087667	18.920084	36.008027	19.951004	6507.3497	4189.2856	2975.7006	1353.0741
27.7	27.65	0.0087175	18.369114	35.722382	19.815312	6507.3506	4191.1225	2979.2729	1355.0556
27.8	27.75	0.0086686	17.823852	35.438941	19.680481	6507.3515	4192.9049	2982.8168	1357.0237
27.9	27.85	0.0086199	17.284244	35.157144	19.546504	6507.3523	4194.6333	2986.3325	1358.9783
28.0	27.95	0.0085716	16.750236	34.869175	19.413379	6507.3532	4196.3084	2989.8194	1360.9197
28.1	28.05	0.0085235	16.221774	34.583498	19.281099	6507.354	4197.9305	2993.2777	1362.8478
28.2	28.15	0.0084757	15.698803	34.300097	19.149661	6507.3549	4199.5004	2996.7078	1364.7627
28.3	28.25	0.0084281	15.18127	34.018955	19.019061	6507.3557	4201.0185	3000.1096	1366.6646
28.4	28.35	0.0083808	14.66912	33.740057	18.889293	6507.3566	4202.4855	3003.4837	1368.5536
28.5	28.45	0.0083338	14.162299	33.463388	18.760354	6507.3574	4203.9017	3006.83	1370.4296
28.6	28.55	0.0082871	13.66075	33.188931	18.632238	6507.3582	4205.2678	3010.1489	1372.2928
28.7	28.65	0.0082406	13.16442	32.91667	18.504942	6507.3591	4206.5842	3013.4406	1374.1433
28.8	28.75	0.0081943	12.673252	32.646592	18.378462	6507.3599	4207.8515	3016.7052	1375.9812
28.9	28.85	0.0081484	12.187189	32.378679	18.252791	6507.3607	4209.0702	3019.9431	1377.8065
29.0	28.95	0.0081026	11.706174	32.112916	18.127928	6507.3615	4210.2409	3023.1544	1379.6192
29.1	29.05	0.0080572	11.230148	31.849289	18.003866	6507.3623	4211.3639	3026.3393	1381.4196
29.2	29.15	0.008012	10.759052	31.587781	17.880601	6507.3631	4212.4398	3029.4981	1383.2077
29.3	29.25	0.007967	10.292825	31.328379	17.75813	6507.3639	4213.4691	3032.6309	1384.9835
29.4	29.35	0.0079223	9.8314032	31.071066	17.636447	6507.3647	4214.4522	3035.738	1386.7472

29.5	29.45	0.0078779	9.3747222	30.815829	17.51555	6507.3655	4215.3897	3038.8196	1388.4987
29.6	29.55	0.0078337	8.922714	30.562651	17.395432	6507.3663	4216.282	3041.8759	1390.2383
29.7	29.65	0.0077897	8.4753078	30.311518	17.27609	6507.367	4217.1295	3044.907	1391.9659
29.8	29.75	0.007746	8.0324288	30.062415	17.157519	6507.3678	4217.9327	3047.9133	1393.6816
29.9	29.85	0.0077026	7.5939972	29.815328	17.039716	6507.3686	4218.6921	3050.8948	1395.3856
30.0	29.95	0.0076594	7.1599274	29.570242	16.922676	6507.3694	4219.4081	3053.8518	1397.0779
30.1	30.05	0.0076164	6.7301263	29.327143	16.806395	6507.3701	4220.0811	3056.7845	1398.7585
30.2	30.15	0.0075737	6.304491	29.086016	16.690868	6507.3709	4220.7116	3059.6931	1400.4276
30.3	30.25	0.0075312	5.8829067	28.846846	16.576091	6507.3716	4221.2999	3062.5778	1402.0852
30.4	30.35	0.0074889	5.4652427	28.60962	16.462061	6507.3724	4221.8464	3065.4388	1403.7314
30.5	30.45	0.0074469	5.0513471	28.374323	16.348772	6507.3731	4222.3515	3068.2762	1405.3663
30.6	30.55	0.0074051	4.6410401	28.140942	16.236221	6507.3739	4222.8156	3071.0903	1406.9899
30.7	30.65	0.0073636	4.2341029	27.909461	16.124404	6507.3746	4223.239	3073.8813	1408.6023
30.8	30.75	0.0073223	3.8302613	27.679867	16.013316	6507.3753	4223.6221	3076.6492	1410.2037
30.9	30.85	0.0072812	3.4291604	27.452147	15.902953	6507.3761	4223.965	3079.3945	1411.794
31.0	30.95	0.0072403	3.0303218	27.226286	15.793311	6507.3768	4224.268	3082.1171	1413.3733
31.1	31.05	0.0071997	2.6330678	27.002271	15.684386	6507.3775	4224.5313	3084.8173	1414.9417
31.2	31.15	0.0071593	2.2363781	26.780087	15.576173	6507.3782	4224.755	3087.4953	1416.4993
31.3	31.25	0.0071191	1.8385835	26.559722	15.46867	6507.3789	4224.9388	3090.1513	1418.0462
31.4	31.35	0.0070792	1.4366106	26.341162	15.361871	6507.3796	4225.0825	3092.7854	1419.5824
31.5	31.45	0.0070395	1.0236066	26.124393	15.255773	6507.3803	4225.1848	3095.3979	1421.108
31.6	31.55	0.007	0.4816943	25.909403	15.150372	6507.381	4225.233	3097.9888	1422.623
31.7	31.65	0.0069607	0.0007861	25.696177	15.045663	6507.3817	4225.2331	3100.5584	1424.1276
31.8	31.75	0.0069217	0.0007817	25.484703	14.941642	6507.3824	4225.2332	3103.1069	1425.6217
31.9	31.85	0.0068828	0.0007773	25.274967	14.838306	6507.3831	4225.2332	3105.6344	1427.1056
32.0	31.95	0.0068442	0.000773	25.066957	14.735651	6507.3838	4225.2333	3108.1411	1428.5791
32.1	32.05	0.0068058	0.0007686	24.860659	14.633672	6507.3845	4225.2334	3110.6271	1430.0425
32.2	32.15	0.0067676	0.0007643	24.656061	14.532366	6507.3852	4225.2335	3113.0927	1431.4957
32.3	32.25	0.0067297	0.00076	24.453149	14.431729	6507.3858	4225.2336	3115.5381	1432.9389
32.4	32.35	0.0066919	0.0007558	24.251912	14.331757	6507.3865	4225.2336	3117.9632	1434.3721

32.5	32.45	0.0066544	0.0007515	24.052336	14.232445	6507.3872	4225.2337	3120.3685	1435.7953
32.6	32.55	0.006617	0.0007473	23.854408	14.13379	6507.3878	4225.2338	3122.7539	1437.2087
32.7	32.65	0.0065799	0.0007431	23.658117	14.035789	6507.3885	4225.2339	3125.1197	1438.6123
32.8	32.75	0.006543	0.000739	23.46345	13.938437	6507.3891	4225.2339	3127.4661	1440.0061
32.9	32.85	0.0065063	0.0007348	23.270394	13.84173	6507.3898	4225.234	3129.7931	1441.3903
33.0	32.95	0.0064698	0.0007307	23.078937	13.745665	6507.3904	4225.2341	3132.101	1442.7649
33.1	33.05	0.0064335	0.0007266	22.889067	13.650238	6507.3911	4225.2341	3134.3899	1444.1299
33.2	33.15	0.0063974	0.0007225	22.700772	13.555445	6507.3917	4225.2342	3136.66	1445.4854
33.3	33.25	0.0063615	0.0007185	22.51404	13.461282	6507.3924	4225.2343	3138.9114	1446.8316
33.4	33.35	0.0063258	0.0007144	22.328858	13.367746	6507.393	4225.2344	3141.1443	1448.1684
33.5	33.45	0.0062903	0.0007104	22.145215	13.274832	6507.3936	4225.2344	3143.3588	1449.4958
33.6	33.55	0.006255	0.0007064	21.963099	13.182537	6507.3942	4225.2345	3145.5551	1450.8141
33.7	33.65	0.0062199	0.0007025	21.782498	13.090858	6507.3949	4225.2346	3147.7334	1452.1232
33.8	33.75	0.006185	0.0006985	21.603401	12.999791	6507.3955	4225.2346	3149.8937	1453.4232
33.9	33.85	0.0061503	0.0006946	21.425795	12.909331	6507.3961	4225.2347	3152.0363	1454.7141
34.0	33.95	0.0061158	0.0006907	21.24967	12.819476	6507.3967	4225.2348	3154.1613	1455.996
34.1	34.05	0.0060815	0.0006868	21.075013	12.730222	6507.3973	4225.2348	3156.2688	1457.2691
34.2	34.15	0.0060474	0.000683	20.901814	12.641564	6507.3979	4225.2349	3158.3589	1458.5332
34.3	34.25	0.0060135	0.0006792	20.730061	12.5535	6507.3985	4225.235	3160.4319	1459.7886
34.4	34.35	0.0059797	0.0006754	20.559743	12.466026	6507.3991	4225.2351	3162.4879	1461.0352
34.5	34.45	0.0059462	0.0006716	20.390848	12.379138	6507.3997	4225.2351	3164.527	1462.2731
34.6	34.55	0.0059128	0.0006678	20.223365	12.292833	6507.4003	4225.2352	3166.5493	1463.5024
34.7	34.65	0.0058797	0.000664	20.057284	12.207107	6507.4009	4225.2353	3168.5551	1464.7231
34.8	34.75	0.0058467	0.0006603	19.892594	12.121957	6507.4015	4225.2353	3170.5443	1465.9353
34.9	34.85	0.0058139	0.0006566	19.729283	12.037378	6507.4021	4225.2354	3172.5173	1467.139
35.0	34.95	0.0057812	0.0006529	19.56734	11.953369	6507.4026	4225.2354	3174.474	1468.3343
35.1	35.05	0.0057488	0.0006493	19.406755	11.869924	6507.4032	4225.2355	3176.4147	1469.5213
35.2	35.15	0.0057166	0.0006456	19.247518	11.787042	6507.4038	4225.2356	3178.3394	1470.7
35.3	35.25	0.0056845	0.000642	19.089617	11.704717	6507.4044	4225.2356	3180.2484	1471.8705
35.4	35.35	0.0056526	0.0006384	18.933042	11.622948	6507.4049	4225.2357	3182.1417	1473.0328

35.5	35.45	0.0056209	0.0006348	18.777782	11.54173	6507.4055	4225.2358	3184.0195	1474.187
35.6	35.55	0.0055893	0.0006313	18.623827	11.46106	6507.406	4225.2358	3185.8818	1475.3331
35.7	35.65	0.005558	0.0006277	18.471167	11.380934	6507.4066	4225.2359	3187.729	1476.4712
35.8	35.75	0.0055268	0.0006242	18.319792	11.30135	6507.4072	4225.236	3189.5609	1477.6013
35.9	35.85	0.0054958	0.0006207	18.16969	11.222304	6507.4077	4225.236	3191.3779	1478.7235
36.0	35.95	0.005465	0.0006172	18.020852	11.143792	6507.4083	4225.2361	3193.18	1479.8379
36.1	36.05	0.0054343	0.0006137	17.873269	11.065812	6507.4088	4225.2361	3194.9673	1480.9445
36.2	36.15	0.0054038	0.0006103	17.726929	10.98836	6507.4093	4225.2362	3196.74	1482.0433
36.3	36.25	0.0053735	0.0006069	17.581823	10.911432	6507.4099	4225.2363	3198.4982	1483.1345
36.4	36.35	0.0053433	0.0006035	17.437941	10.835026	6507.4104	4225.2363	3200.242	1484.218
36.5	36.45	0.0053134	0.0006001	17.295274	10.759139	6507.4109	4225.2364	3201.9715	1485.2939
36.6	36.55	0.0052836	0.0005967	17.15381	10.683766	6507.4115	4225.2364	3203.6869	1486.3623
36.7	36.65	0.0052539	0.0005934	17.013542	10.608905	6507.412	4225.2365	3205.3883	1487.4232
36.8	36.75	0.0052244	0.00059	16.874458	10.534552	6507.4125	4225.2366	3207.0757	1488.4766
36.9	36.85	0.0051951	0.0005867	16.736551	10.460705	6507.413	4225.2366	3208.7494	1489.5227
37.0	36.95	0.005166	0.0005834	16.599809	10.38736	6507.4136	4225.2367	3210.4093	1490.5614
37.1	37.05	0.005137	0.0005802	16.464224	10.314515	6507.4141	4225.2367	3212.0558	1491.5929
37.2	37.15	0.0051082	0.0005769	16.329786	10.242165	6507.4146	4225.2368	3213.6887	1492.6171
37.3	37.25	0.0050795	0.0005737	16.196486	10.170308	6507.4151	4225.2369	3215.3084	1493.6341
37.4	37.35	0.005051	0.0005705	15.965248	10.098941	6507.4156	4225.2369	3216.9049	1494.644
37.5	37.45	0.0050227	0.0005673	15.704295	10.02806	6507.4161	4225.237	3218.4753	1495.6468
37.6	37.55	0.0049945	0.0005641	15.445853	9.9576633	6507.4166	4225.237	3220.0199	1496.6426
37.7	37.65	0.0049665	0.0005609	15.1899	9.8877468	6507.4171	4225.2371	3221.5389	1497.6314
37.8	37.75	0.0049386	0.0005578	14.936416	9.8183079	6507.4176	4225.2371	3223.0326	1498.6132
37.9	37.85	0.0049109	0.0005546	14.685381	9.7493434	6507.4181	4225.2372	3224.5011	1499.5881
38.0	37.95	0.0048834	0.0005515	14.436774	9.6808504	6507.4186	4225.2372	3225.9448	1500.5562
38.1	38.05	0.004856	0.0005484	14.190575	9.6128259	6507.419	4225.2373	3227.3638	1501.5175
38.2	38.15	0.0048287	0.0005454	13.946763	9.5452668	6507.4195	4225.2374	3228.7585	1502.472
38.3	38.25	0.0048016	0.0005423	13.705319	9.4781704	6507.42	4225.2374	3230.129	1503.4198
38.4	38.35	0.0047747	0.0005393	13.466223	9.4115335	6507.4205	4225.2375	3231.4757	1504.361

38.5	38.45	0.0047479	0.0005362	13.229454	9.3453533	6507.421	4225.2375	3232.7986	1505.2955
38.6	38.55	0.0047213	0.0005332	12.994995	9.2796268	6507.4214	4225.2376	3234.0981	1506.2235
38.7	38.65	0.0046948	0.0005302	12.762825	9.2143513	6507.4219	4225.2376	3235.3744	1507.1449
38.8	38.75	0.0046684	0.0005273	12.532924	9.1495237	6507.4224	4225.2377	3236.6277	1508.0599
38.9	38.85	0.0046422	0.0005243	12.305275	9.0851413	6507.4228	4225.2377	3237.8582	1508.9684
39.0	38.95	0.0046162	0.0005214	12.079857	9.0212011	6507.4233	4225.2378	3239.0662	1509.8705
39.1	39.05	0.0045903	0.0005184	11.856653	8.9577004	6507.4238	4225.2378	3240.2519	1510.7663
39.2	39.15	0.0045645	0.0005155	11.635643	8.8946363	6507.4242	4225.2379	3241.4154	1511.6558
39.3	39.25	0.0045389	0.0005126	11.416809	8.832006	6507.4247	4225.2379	3242.5571	1512.539
39.4	39.35	0.0045135	0.0005098	11.200132	8.7698068	6507.4251	4225.238	3243.6771	1513.4159
39.5	39.45	0.0044881	0.0005069	10.985595	8.7080359	6507.4256	4225.238	3244.7757	1514.2867
39.6	39.55	0.004463	0.000504	10.773179	8.6466905	6507.426	4225.2381	3245.853	1515.1514
39.7	39.65	0.0044379	0.0005012	10.562866	8.5857678	6507.4265	4225.2381	3246.9093	1516.01
39.8	39.75	0.004413	0.0004984	10.354638	8.5252652	6507.4269	4225.2382	3247.9447	1516.8625
39.9	39.85	0.0043883	0.0004956	10.148477	8.4651799	6507.4273	4225.2382	3248.9596	1517.709
40.0	39.95	0.0043637	0.0004928	9.9443666	8.4055092	6507.4278	4225.2383	3249.954	1518.5496
40.1	40.05	0.0043392	0.0004901	9.7422884	8.3462506	6507.4282	4225.2383	3250.9283	1519.3842
40.2	40.15	0.0043148	0.0004873	9.5422251	8.2874012	6507.4286	4225.2384	3251.8825	1520.2129
40.3	40.25	0.0042906	0.0004846	9.3441595	8.2289584	6507.4291	4225.2384	3252.8169	1521.0358
40.4	40.35	0.0042665	0.0004819	9.1480745	8.1709197	6507.4295	4225.2385	3253.7317	1521.8529
40.5	40.45	0.0042426	0.0004792	8.953953	8.1132823	6507.4299	4225.2385	3254.6271	1522.6643
40.6	40.55	0.0042188	0.0004765	8.7617783	8.0560437	6507.4303	4225.2386	3255.5033	1523.4699
40.7	40.65	0.0041951	0.0004738	8.5715334	7.9992013	6507.4308	4225.2386	3256.3604	1524.2698
40.8	40.75	0.0041716	0.0004711	8.3832017	7.9427524	6507.4312	4225.2387	3257.1987	1525.0641
40.9	40.85	0.0041482	0.0004685	8.1967666	7.8866947	6507.4316	4225.2387	3258.0184	1525.8527
41.0	40.95	0.0041249	0.0004659	8.0122118	7.8310254	6507.432	4225.2388	3258.8196	1526.6358
41.1	41.05	0.0041018	0.0004633	7.8295207	7.7757421	6507.4324	4225.2388	3259.6026	1527.4134
41.2	41.15	0.0040788	0.0004607	7.6486773	7.7208422	6507.4328	4225.2389	3260.3675	1528.1855
41.3	41.25	0.0040559	0.0004581	7.4696652	7.6663232	6507.4332	4225.2389	3261.1144	1528.9521
41.4	41.35	0.0040331	0.0004555	7.2924685	7.6121827	6507.4336	4225.2389	3261.8437	1529.7133

41.5	41.45	0.0040105	0.0004529	7.1170713	7.5584181	6507.434	4225.239	3262.5554	1530.4692
41.6	41.55	0.003988	0.0004504	6.9434575	7.5050271	6507.4344	4225.239	3263.2497	1531.2197
41.7	41.65	0.0039656	0.0004479	6.7716115	7.4520071	6507.4348	4225.2391	3263.9269	1531.9649
41.8	41.75	0.0039434	0.0004454	6.6015175	7.3993557	6507.4352	4225.2391	3264.587	1532.7048
41.9	41.85	0.0039213	0.0004429	6.43316	7.3470705	6507.4356	4225.2392	3265.2304	1533.4395
42.0	41.95	0.0038993	0.0004404	6.2665233	7.2951491	6507.436	4225.2392	3265.857	1534.169
42.1	42.05	0.0038774	0.0004379	6.1015921	7.2435891	6507.4364	4225.2393	3266.4672	1534.8934
42.2	42.15	0.0038556	0.0004355	5.9383508	7.1923881	6507.4368	4225.2393	3267.061	1535.6126
42.3	42.25	0.003834	0.000433	5.7767842	7.1415438	6507.4372	4225.2393	3267.6387	1536.3268
42.4	42.35	0.0038125	0.0004306	5.616877	7.0910537	6507.4375	4225.2394	3268.2004	1537.0359
42.5	42.45	0.0037911	0.0004282	5.4586138	7.0409157	6507.4379	4225.2394	3268.7462	1537.74
42.6	42.55	0.0037698	0.0004258	5.3019796	6.9911272	6507.4383	4225.2395	3269.2764	1538.4391
42.7	42.65	0.0037487	0.0004234	5.1469591	6.9416861	6507.4387	4225.2395	3269.7911	1539.1333
42.8	42.75	0.0037276	0.000421	4.9935371	6.8925901	6507.439	4225.2396	3270.2905	1539.8225
42.9	42.85	0.0037067	0.0004186	4.8416987	6.8438367	6507.4394	4225.2396	3270.7747	1540.5069
43.0	42.95	0.0036859	0.0004163	4.6914286	6.7954239	6507.4398	4225.2396	3271.2438	1541.1865
43.1	43.05	0.0036653	0.000414	4.5427116	6.7473493	6507.4401	4225.2397	3271.6981	1541.8612
43.2	43.15	0.0036447	0.0004116	4.3955327	6.6996106	6507.4405	4225.2397	3272.1376	1542.5312
43.3	43.25	0.0036242	0.0004093	4.2498766	6.6522057	6507.4409	4225.2398	3272.5626	1543.1964
43.4	43.35	0.0036039	0.000407	4.1057281	6.6051324	6507.4412	4225.2398	3272.9732	1543.8569
43.5	43.45	0.0035837	0.0004047	3.9630719	6.5583883	6507.4416	4225.2398	3273.3695	1544.5127
43.6	43.55	0.0035636	0.0004025	3.8218924	6.5119714	6507.442	4225.2399	3273.7517	1545.1639
43.7	43.65	0.0035436	0.0004002	3.6821742	6.4658795	6507.4423	4225.2399	3274.1199	1545.8105
43.8	43.75	0.0035237	0.000398	3.5439014	6.4201103	6507.4427	4225.24	3274.4743	1546.4525
43.9	43.85	0.0035039	0.0003957	3.4070583	6.3746618	6507.443	4225.24	3274.815	1547.09
44.0	43.95	0.0034843	0.0003935	3.2716285	6.3295318	6507.4434	4225.24	3275.1422	1547.7229
44.1	44.05	0.0034647	0.0003913	3.1375956	6.2847182	6507.4437	4225.2401	3275.4559	1548.3514
44.2	44.15	0.0034453	0.0003891	3.0049427	6.2402188	6507.444	4225.2401	3275.7564	1548.9754
44.3	44.25	0.003426	0.0003869	2.8736527	6.1960316	6507.4444	4225.2402	3276.0438	1549.595
44.4	44.35	0.0034067	0.0003848	2.7437076	6.1521544	6507.4447	4225.2402	3276.3181	1550.2103

44.5	44.45	0.0033876	0.0003826	2.6150889	6.1085853	6507.4451	4225.2402	3276.5797	1550.8211
44.6	44.55	0.0033686	0.0003805	2.4877776	6.065322	6507.4454	4225.2403	3276.8284	1551.4276
44.7	44.65	0.0033497	0.0003783	2.3617532	6.0223627	6507.4457	4225.2403	3277.0646	1552.0299
44.8	44.75	0.0033309	0.0003762	2.2369946	5.9797052	6507.4461	4225.2404	3277.2883	1552.6279
44.9	44.85	0.0033122	0.0003741	2.1134787	5.9373475	6507.4464	4225.2404	3277.4997	1553.2216
45.0	44.95	0.0032937	0.000372	1.9911811	5.8952877	6507.4467	4225.2404	3277.6988	1553.8111
45.1	45.05	0.0032752	0.0003699	1.8700748	5.8535236	6507.4471	4225.2405	3277.8858	1554.3965
45.2	45.15	0.0032568	0.0003678	1.75013	5.8120533	6507.4474	4225.2405	3278.0608	1554.9777
45.3	45.25	0.0032385	0.0003658	1.6313133	5.7708749	6507.4477	4225.2405	3278.2239	1555.5548
45.4	45.35	0.0032204	0.0003637	1.5135864	5.7299863	6507.448	4225.2406	3278.3753	1556.1278
45.5	45.45	0.0032023	0.0003617	1.3969045	5.6893856	6507.4484	4225.2406	3278.515	1556.6967
45.6	45.55	0.0031843	0.0003596	1.2812143	5.6490709	6507.4487	4225.2406	3278.6431	1557.2616
45.7	45.65	0.0031665	0.0003576	1.1664504	5.6090403	6507.449	4225.2407	3278.7597	1557.8225
45.8	45.75	0.0031487	0.0003556	1.05253	5.5692918	6507.4493	4225.2407	3278.865	1558.3794
45.9	45.85	0.003131	0.0003536	0.9393452	5.5298234	6507.4496	4225.2408	3278.9589	1558.9324
46.0	45.95	0.0031135	0.0003516	0.8267481	5.4906335	6507.4499	4225.2408	3279.0416	1559.4815
46.1	46.05	0.003096	0.0003497	0.7145265	5.4517199	6507.4502	4225.2408	3279.1131	1560.0267
46.2	46.15	0.0030786	0.0003477	0.6023545	5.4130809	6507.4505	4225.2409	3279.1733	1560.568
46.3	46.25	0.0030614	0.0003457	0.489684	5.3747146	6507.4509	4225.2409	3279.2223	1561.1054
46.4	46.35	0.0030442	0.0003438	0.3754631	5.3366192	6507.4512	4225.2409	3279.2598	1561.6391
46.5	46.45	0.0030271	0.0003419	0.2571653	5.2987928	6507.4515	4225.241	3279.2855	1562.169
46.6	46.55	0.0030101	0.00034	0.0795803	5.2612336	6507.4518	4225.241	3279.2935	1562.6951
46.7	46.65	0.0029932	0.0003381	0.000161	5.2239398	6507.4521	4225.241	3279.2935	1563.2175
46.8	46.75	0.0029764	0.0003362	0.0001601	5.1869096	6507.4524	4225.2411	3279.2935	1563.7362
46.9	46.85	0.0029597	0.0003343	0.0001592	5.1501411	6507.4527	4225.2411	3279.2935	1564.2512
47.0	46.95	0.0029431	0.0003324	0.0001583	5.1136327	6507.4529	4225.2411	3279.2935	1564.7626
47.1	47.05	0.0029266	0.0003305	0.0001574	5.0773824	6507.4532	4225.2412	3279.2936	1565.2703
47.2	47.15	0.0029102	0.0003287	0.0001565	5.0413887	6507.4535	4225.2412	3279.2936	1565.7744
47.3	47.25	0.0028939	0.0003268	0.0001556	5.0056497	6507.4538	4225.2412	3279.2936	1566.275
47.4	47.35	0.0028776	0.000325	0.0001548	4.9701636	6507.4541	4225.2413	3279.2936	1566.772

47.5	47.45	0.0028615	0.0003232	0.0001539	4.9349289	6507.4544	4225.2413	3279.2936	1567.2655
47.6	47.55	0.0028454	0.0003214	0.000153	4.8999437	6507.4547	4225.2413	3279.2936	1567.7555
47.7	47.65	0.0028295	0.0003196	0.0001522	4.8652063	6507.455	4225.2414	3279.2937	1568.242
47.8	47.75	0.0028136	0.0003178	0.0001513	4.8307151	6507.4552	4225.2414	3279.2937	1568.7251
47.9	47.85	0.0027978	0.000316	0.0001505	4.7964683	6507.4555	4225.2414	3279.2937	1569.2047
48.0	47.95	0.0027821	0.0003142	0.0001496	4.7624644	6507.4558	4225.2415	3279.2937	1569.681
48.1	48.05	0.0027665	0.0003124	0.0001488	4.7287015	6507.4561	4225.2415	3279.2937	1570.1539
48.2	48.15	0.002751	0.0003107	0.0001479	4.6951782	6507.4564	4225.2415	3279.2937	1570.6234
48.3	48.25	0.0027356	0.000309	0.0001471	4.6618927	6507.4566	4225.2415	3279.2937	1571.0896
48.4	48.35	0.0027202	0.0003072	0.0001463	4.6288434	6507.4569	4225.2416	3279.2938	1571.5525
48.5	48.45	0.0027049	0.0003055	0.0001455	4.5960286	6507.4572	4225.2416	3279.2938	1572.0121
48.6	48.55	0.0026898	0.0003038	0.0001446	4.5634469	6507.4574	4225.2416	3279.2938	1572.4684
48.7	48.65	0.0026747	0.0003021	0.0001438	4.5310965	6507.4577	4225.2417	3279.2938	1572.9215
48.8	48.75	0.0026597	0.0003004	0.000143	4.4989759	6507.458	4225.2417	3279.2938	1573.3714
48.9	48.85	0.0026448	0.0002987	0.0001422	4.4670835	6507.4582	4225.2417	3279.2938	1573.8181
49.0	48.95	0.0026299	0.000297	0.0001414	4.4354178	6507.4585	4225.2418	3279.2938	1574.2617
49.1	49.05	0.0026152	0.0002954	0.0001406	4.4039771	6507.4588	4225.2418	3279.2939	1574.7021
49.2	49.15	0.0026005	0.0002937	0.0001398	4.37276	6507.459	4225.2418	3279.2939	1575.1393
49.3	49.25	0.0025859	0.0002921	0.0001391	4.3417648	6507.4593	4225.2418	3279.2939	1575.5735
49.4	49.35	0.0025714	0.0002904	0.0001383	4.3109901	6507.4595	4225.2419	3279.2939	1576.0046
49.5	49.45	0.002557	0.0002888	0.0001375	4.2804343	6507.4598	4225.2419	3279.2939	1576.4327
49.6	49.55	0.0025426	0.0002872	0.0001367	4.2500959	6507.46	4225.2419	3279.2939	1576.8577
49.7	49.65	0.0025284	0.0002856	0.000136	4.2199735	6507.4603	4225.242	3279.2939	1577.2797
49.8	49.75	0.0025142	0.0002839	0.0001352	4.1900654	6507.4606	4225.242	3279.294	1577.6987
49.9	49.85	0.0025001	0.0002824	0.0001344	4.1603703	6507.4608	4225.242	3279.294	1578.1147
50.0	49.95	0.002486	0.0002808	0.0001337	4.1308867	6507.4611	4225.242	3279.294	1578.5278

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