ORIGINAL ARTICLE

A New Empirical Model to Estimate Landfill Gas Pollution

Hamidreza Kamalan

Abstract

Background: Landfills are the most important producers of methane as human source. So, prediction of landfill gas generation is by far the most important concern of scientists, decision makers, and landfill owners as well as health authorities. Almost all the currently used models are based on Monod equation first order decay rate which is experimental while the main purpose of this research is to develop a numerical model.

Methods: A real scale pilot landfill with 4500 tons of municipal solid waste has been designed, constructed, and operated for two years. Required measurements have been done to provide proper data on greenhouse gases emitted by the landfill and monitor its status such as internal temperature, leachate content, and its settlement during two years. Afterwards, weighted residual method has been used to develop the numerical model. Then, the newly mathematical method has been verified with data from another landfill.

Results: Measurements showed that the minimum and maximum percentages of methane among landfill gas were 22.3 and 46.1%, respectively. These values for velocity of landfill gas are 0.3 and 0.48 meters per second, in that order.

Conclusion: Since there is just 0.6 percent error in calculation as compared to real measurements from a landfill in California and most of the models used have ten percent error, this simple empirical numerical model is suggested to be utilized by scientists, decision makers, and landfill owners.

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Assistant Professor, Department of Civil Engineering, Pardis Branch, Islamic Azad University, Pardis, Iran

Correspondence:
Hamidreza Kamalan,
#2, Second West Ave., Seond Golzar Ave.,
Shahrak-e-Aghdasiyeh, Oushan Blvd., Imam Ali Highway,
Tehran, Iran
Tel/Fax: +98 21 22443868
Emails: hkamalan@yahoo.com
hkamalan@pardisiau.a.cir
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Introduction

Landfilling is an inevitable part of solid waste management chain which causes emission of greenhouse gases.[1] The gases produced in the landfills are mainly methane and carbon dioxide.[2] Meanwhile, the concentration of atmospheric methane has been increased within last 2 decades.[3] By mass, methane has 21 times the global warming potential of carbon dioxide over a 100-year time frame.[4] On the other hand, methane is a valuable energy element which has 15.1 Mj/m3 energy.[5] On these bases, methane generation rates have been estimated (1) to assess the impact of landfill-generated methane on global warming, (2) to introduce it as part of the design of methane control systems; and (3) to provide the information necessary to evaluate and design new energy projects.[6]

Methane is generated in the landfills during anaerobic digestion process which has been phased out as non-methanogenic, unsteady methanogenic, steady methanogenic, and transition to aerobic phase.[7]

Scientific studies on methane prediction have been performed based on Darcy's Law; physical characteristics such as climate, refuse mass and age; the Gompertz Equation; and environmental factors such as moisture content, sulfate and volatile solids.[8] Thus, almost all of the current worldwide used models are first order decay ones.[9] In these models, generated methane has a direct relationship with carbon content of the waste and exponential function of the decay rate multiplied by time as follows.[10] TNO, LandGEM, Gassim, Afvalzorg, EPER, IPCC, and LFGEEN are the models used around the world for prediction of methane generation from landfills and all are first order decay models.[11] TNO model calculates LFG generation based on the degradation of organic carbon in the waste.[12] USEPA has developed a software entitled LandGEM which uses almost the same formula as the first order decay for municipal solid waste.[13] Since there are different fractions of organic carbon in different materials (i.e. the fraction degradable of paper, garden waste, and food waste are different from each other),[14] it seems that the models should be revised. Therefore, multiphase models have been provided to consider the composition of the wastes. Gassim, the software provided by UK environmental agency, works by multiphase model concept.[15] Afvalzorg is another multiphase model on predicting methane production which considers eight waste categories and three fractions.[4] EPER France is another multiphase model which considers three different degradation rate for the waste composition.[12]

Numerical method is a strong tool to simulate and model all phenomena if there is a good general understanding of them.[16] So, it can be used to estimate methane generation in a simpler method. On these bases, a study has been done to check if Weighted Residual Method (WRM) can be used in this regard successfully. Result on a real landfill with few observed data has shown a reasonable perdition.[4] This study was carried out to develop a simple numerical model with the most accuracy to predict methane generation out of landfills.

Material and Methods

There are lots of numerical methods such as finite difference, finite element, and finite volume. Also, there are a great number of approximation methods, i.e. least summation of error square and WRM (point collocation, Galerkin, …).[17] Since weighted residual method (WRM) is a comprehensive numerical one to approximate an unknown value analytically,[18] it can develop a function for methane generation against time and amount of landfilled waste which contains organic material. In order to utilize WRM method, the approximation of the generated methane can be written mathematically by equation 1, as follows:[19]

$$G \cong \psi + \sum_{n,m=1}^{K} (a_{mn} N_{mn}) \qquad \text{(Eq. 1)}$$

Where "ψ" is a function to satisfy boundary condition, "N_{mn}" is trail function which should be zero on boundaries, and "a_{mn}" is a coefficient which should be determined. The goal of WRM is to choose "a_{mn}" such that residue (R) becomes small over a specific domain. In fact, "R" is the difference between the right side and the left side of equation 1. Weighting function (w) is multiplied by "R" to determine the coefficient "a" appropriately. On this basis, integration of the product of weighting function by residue in the domain is to be zero. All functions in equation 1 are known, except "a" which should be obtained through utilizing equation 2 method.[4]

$$\iint_{domain} w_{lp}(G-\psi)\,dt\,dw = \iint_{domain} a_{mn}\Big(w_{lp}\sum_{n,m=1} N_{mn}\Big) \Leftrightarrow f_l = k_{lm}\sum a_{mn} \qquad \text{(Eq. 2)}$$

Where "w_{lp}" is weighting function and "k" is coefficient matrices which are known, "f_l" is right hand side matrix which is known, and "a_{mn}" is the unknown matrix.

To apply the WRM method to develop a model for predicting methane out of landfills, a database of landfilled waste, time and methane produced is needed. To reach the research goal, the first sanitary real scale pilot landfill was designed, constructed and operated with capacity of 4750 tons of municipal solid waste. It consists of geotechnical barrier, bottom layer, leachate collection system, cover, waste compaction, gas collection system, and top layer. Construction of the cell took about 4 months and total waste disposal lasted about 3 months. The landfill was operated for more than two years and landfill gas generated was measured. The base liner of landfill cell was 60cm of compacted clay and 1.5mm HDPE geomembrane which was covered by a 500gr/m2 geotextile and 15cm of fine sand as protection layers. For drainage layer, 45cm of gravel was used over protection sand. The final cover was 40cm of compacted clay. The pilot had dimensions of nearly 35 by 57m and 5.2m height in 3 lifts. A leachate collection grading, pipes, and gas collection system were prepared. Gas collection system was a passive one containing two 16cm diameter and 6m length pipe with 10mm holes on them.

Temperature of the pilot were measured in 3 levels at 8 points, i.e. min, max, and average daily temperature, daily precipitation and evaporation, leachate produced, landfill gas (LFG) velocity, percentage of methane, and CO_2 within the LFG by a TESTO 350 test/analyzer and probe from 2/3 of gas pipe diameter in a period of two years.

It is notable that this real scale pilot was designed, constructed, and operated for two years in 2006 in Arad Kuh Landfill site, an arid area, located in 35Km South-West of Tehran, Iran (35°, 28',00.08" N, 51°, 20', 04.06" E).

Results

The pilot has experienced 8 seasons during two years. Thus, the results and observed data are as accurate as possible. Min and Max of daily temperature were measured between -7 and 40 Celsius degree while the average temperature of the pilot remained at 45.4 with max tolerance of 2 degrees. This temperature is suitable for anaerobic digestion. Min and Max of methane percentage among LFG was measured at 22.3 and 46.1%, respectively. These values for velocity of LFG were 0.3 and 0.48 m/s, respectively. Figure 1 shows the measured methane percentage within LFG from the pilot at a glance. Also, Figure 2 shows the actual measured methane generation from the pilot in terms of cubic meter per day.

To develop a model to predict the methane produced from landfills, WRM was used and a code in Visual Fortran 6.0 was developed. The code wass able to receive time, produced methane, time split (desirable time sections for integral calculating), three different shape functions, three different functions to satisfy boundaries, and method of WRM, i.e. Galerkin or point collocation. So, 18 different sets of output could be produced in each run. Each output set consisted of values of "a_{mn}".

Functions satisfying the boundaries used in the code are linear and second order polynomial as well as exponential functions as listed within equations 3 to 5.

$$\Psi=Q_1+(t-t_1)*(Q_{End}-Q_1)/(t_{End}-t_1) \quad \text{(Eq. 3)}$$

$$\Psi=-t^2+(-Q_{End}+Q_1-t_{End}^2+t_1^2)*t+(Q_1+t_1^2-(-Q_{End}+Q_1-t_{End}^2+t_1^2)*t_1) \quad \text{(Eq. 4)}$$

$$\Psi=Q_{End}*Exp((Ln(Q_{End}/Q_1))*t_{End}/(t_1-t_{End}))*Exp((Ln(Q_{End}/Q_1))*t/(t_1-t_{End})) \quad \text{(Eq. 5)}$$

Where: "Q" is methane generation in terms of cubic meter per day, "t" is time in terms of day, "1" relates to the first time of measuring, and "$_{END}$" relates to the last day of measuring.

The most accurate model developed by 18 different runs of the code was obtained through Galerkin method, equation 5 as the function to satisfy the boundaries and shape function as equation 6.

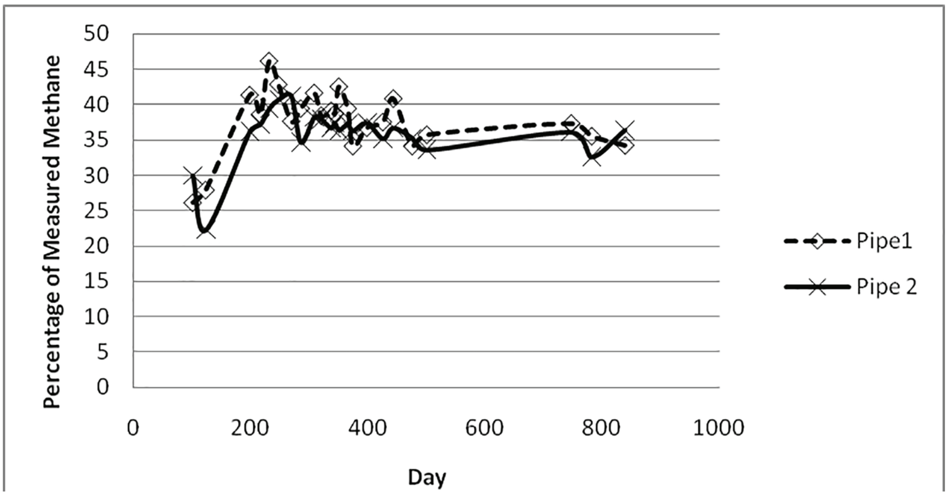

Figure 1: Observed Methane Portion among LFG of the Pilot

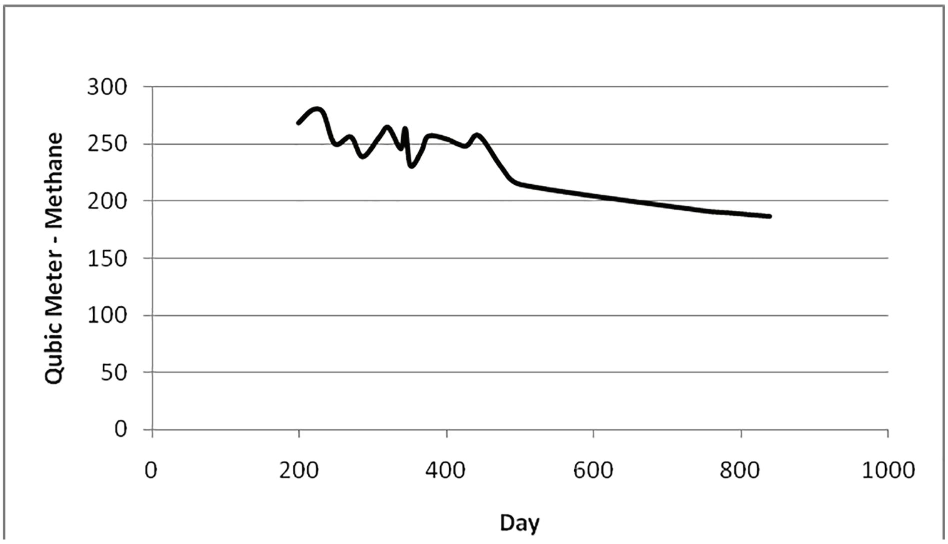

Figure 2: Observed Methane Rate of the Pilot

$N_m = (Exp(-mt/3650))\ (t-102)(t-839))^m$ (Eq. 6)

Where “m” is the inplaced waste in tons.

Although the Correlation Coefficient of the results of the model compared to the measured data was more than 93%, as Figure 3 shows, the trend of the curve was conformity with the physical trend of the phenomena. So, this model cannot be considered a model for prediction of methane from municipal solid waste landfills.

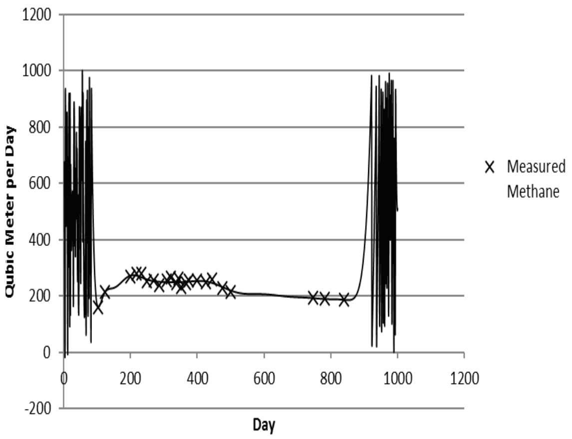

Figure 3: A Sample of Code Result

Since the results did not comply with the fact, in addition to the function, satisfying the boundaries had a very minor effect on the results; Ψ was omitted in the code. So, the boundaries should be satisfied by shape functions. This led to better estimations both based on numerical analysis and trend in comparison to the methane generation phenomena. Accordingly, we compared 15 different shape functions, two WRM methods and 36 series of outputs; the developed model can be defined by utilizing shape function as equation 7, Galerkin method, and the results are displayed in Table 1.

$N_m = t^{m}$ (Eq. 7)

To have a model to use for different landfills, the result should be divided into 4750 ton which results in a model predict methane generation per ton of municipal solid waste as equation 8 and Figure 4.

$$Q=[(-151989.942898877t^{-1})+(1.56E9^{-2.0})+(-2.4E+12t^{3.0}) +(1.51E+15t^{4.0})+(-3.3E+17t^{5.0}) + -1.1E+20t^{6.0}) + (8.69E+22t^{7.0})+ (-2.2E+25t^{8.0}) + (2.08E+27t^{9.0}) +(1.25E+29t^{10.0}) + (-4.5E+31t^{11.0}) +(2.39E+33t^{12.0}) +(2.26E+35t^{13.0})+ (-3.1E+37t^{14.0}) + (5.47E+38t^{15.0}) +(2.32E+41t^{16.0}) +(-4.4E+43t^{17.0}) +(2.97E+45t^{18.0}) +(1.23E+47t^{19.0})+ (-2.9E+49t^{20.0}) +(1.53E+51t^{21.0}) + (-2.6E+52t^{22.0})]/ 4750$$ (Eq. 8)

For better understanding of Methane generation prediction by the new empirical model, Figure 5 shows the fluctuations from day 100 to 850 as follows:

Table 1: Values for “a_{mn}”

a1=	-151990
a2=	1.56E+09
a3=	-2.4E+12
a4=	1.51E+15
a5=	-3.3E+17
a6=	-1.1E+20
a7=	8.69E+22
a8=	-2.2E+25
a9=	2.08E+27
a10=	1.25E+29
a11=	-4.5E+31
a12=	2.39E+33
a13=	2.26E+35
a14=	-3.1E+37
a15=	5.47E+38
a16=	2.32E+41
a17=	-4.4E+43
a18=	2.97E+45
a19=	1.23E+47
a20=	-2.9E+49
a21=	1.53E+51
a22=	-2.6E+52

Discussion

As Figure 1 represents, from the 102nd day, the rate of methane generation was steady. This steady trend as well as the constant temperature about 45C confirms that anaerobic methanogenic steady phase has started from that day. The dramatic decrease in methane generation on day 199 was related to the fact that leachate pumping out of landfill was not performed in a duration of 10 days.

Methane generation has an upward trend until day 199. Afterwards, it has a fluctuation in methane generation with a downward trend till the 500th day. From then, the trend of methane generation is seen as linear descending movement. Figure 2 shows the trend clearly.

Also, as Figure 4 and equation 7 shows, the model format has a general coloration with the phenomena. At the beginning, there is a quickly increasing trend and then a timely decreasing trend. This is exactly according to the four different phases of anaerobic digestion. So, it meets the physical and actual trend, but for utilizing this model, accuracy and its verification is a must.

Since there are measured figures of methane production, as presented in Figures 1 and 2, they can be used as a benchmark of observed data and compared to the predicted data by the model. Correlation Coefficient in this case remains at 96%. On this basis, model has a nice estimation for its own real scale pilot data.

To verify the model, another code has been developed in Visual Fortran 6.0 to calculate

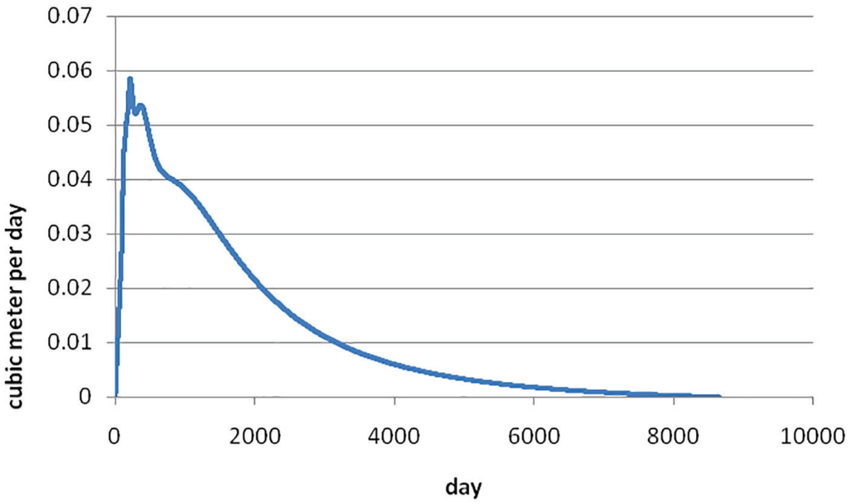

Figure 4: New imperial model to predict methane generation per ton of waste

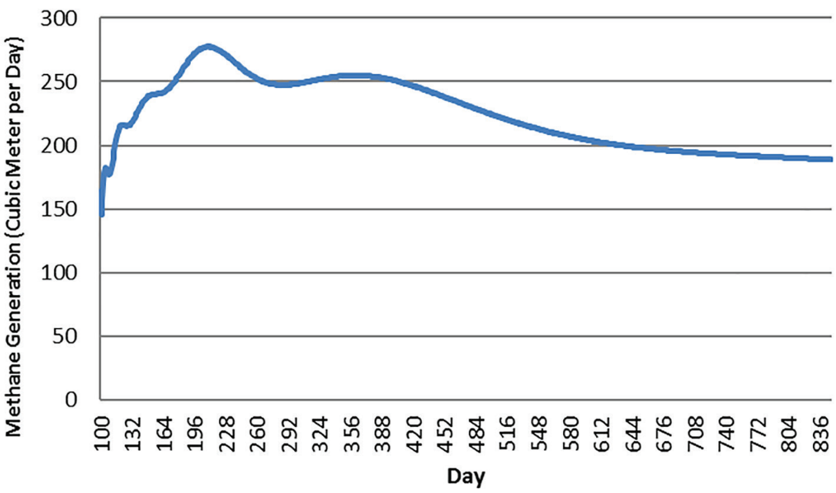

Figure 5: Predicted Methane Generated from Landfills between days 100 and 850

communicative methane generation against the landfill history and different buried solid wastes in different years. Inputs of this model are time and volume of buried wastes, desired year in which the calculations should be continued, time split based on which the calculation should be done based on it (for example 365 to calculate annually, 30 to calculate monthly, …), desired day to calculate daily methane generation in the specific desired day. Outputs are annual methane produced until the due year (or any other time span selected) and daily methane produced on the due day.

Utilizing the model and data base from Borogo landfill in California as shown in Table 2, the result of measurement of methane in the summer of 2008 (32 fpm), and calculation by the model (1296.87 cubic meter per day) resulted in just 0.6% error.

Since the models are to be verified via utilizing more databases, some data taken from Nauerna Landfill in the Netherlands were introduced to newly developed model. Figure 6 represents the characteristics of inplaced wastes in this landfill.

Table 2: Brogo landfill history

Year	Buried waste (ton)
1995	2053
1996	2086
1997	2436
1998	3514
1999	3071
2000	3741
2001	5470
2002	4256
2003	4469
2004	4692
2005	4927
2006	5173
2007	5432

There is a series of Methane measurements in this landfill taken in 2001 about 2.5 Gg/y[12] which is equal to 3.81Mm^3. Utilizing landfill history into the model of this research resulted in estimation of 3.48 Mm^3. Error remained at 8.7%. It can be noticed that 5 different models (TNO, LandGEM, GasSim, Afvalzorg, and

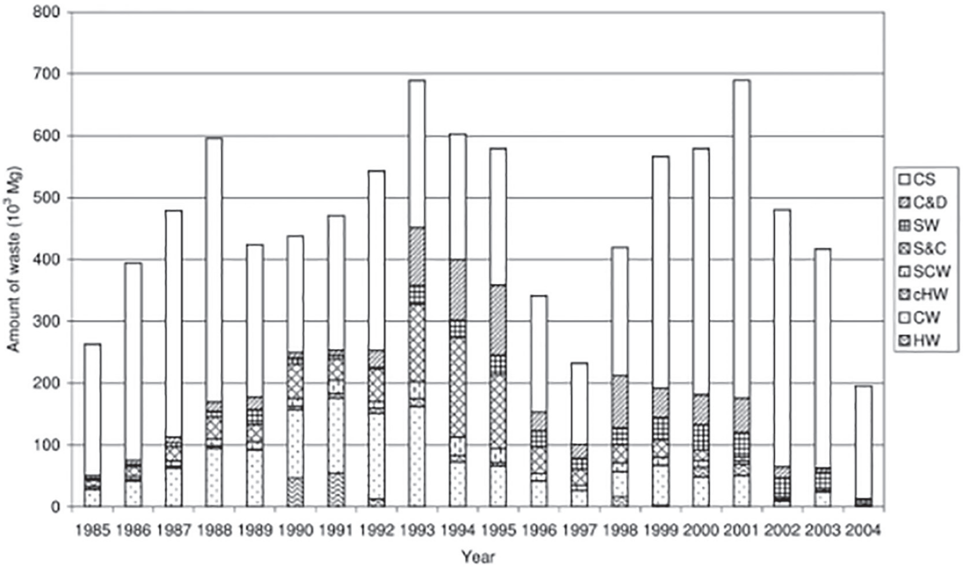

Figure 6: Inplaced wastes in Nauerna Landfill

EPER) were applied on this database and resulted in 40% up to 570% error.[12]

So, this model have a nice prediction which is quite near to observed data from the research pilot as well as a real landfill data in a non-arid area which can prove the results of the model.

Conclusion

To conclude, methane, as the most important component of greenhouse gases which is mainly produced from municipal landfills, should be predicted based on international protocols. On this basis, this study aimed to develop more accurate approach utilizing the numerical method to predict methane generation from landfills.

In this study, two models have been developed. The first one resulted in developing a numerical model of methane generation by a ton of municipal waste in different years during time. The second model which used the results of the first one led to prediction of accumulated methane produced until the due year (by frequency of selected time span) and daily methane produced in a due day. This is the ability of this model and no model in the world is able to calculate the methane generation on a specific day. They all calculate methane generation over a year.

The model developed in this study was developed utilizing the measured data obtained from a real scale pilot over two years of operation. The model was verified by data from a landfill in California and the Netherlands and resulted in 0.6 and 8.7% error, respectively. Thus, this empirical model can be utilized in any kind of climate easily by entering the landfilled waste in tons in each year and get the result from the model as the amount of methane generation in a specific date (which can be found just in this model), and the amount of cumulative methane production per time with more accuracy than the existing models.

The limitations of the model can be summarized as: (1) it is just used for sanitary landfills and cannot cover open dumping; and (2) it is just used for mixed municipal solid waste.

Conflict of Interest: None declared.

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