United States
Environmental Protection
Agency

Air and Energy Engineering
Research Laboratory
Research Triangle Park NC 27711

Research and Development

EPA/600/SR-92/037 April 1992

EPA

# Project Summary

# Development of an Empirical Model of Methane Emissions from Landfills

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**The U.S. Environmental Protection Agency's (EPA's) Air and Energy Engineering Research Laboratory (AEERL) began a research program in 1990 with the goal of improving global landfill methane ($CH_4$) emissions estimates. Part of this program is a field study to gather information that can be used to develop an empirical model of $CH_4$ emissions. The field study is the subject of this report.**

**Twenty-one U.S. landfills with gas recovery systems were included in the study. Site-specific information includes average $CH_4$ recovery rate, landfill size, tons of refuse (refuse mass), average age of the refuse, and climate. A correlation analysis showed that refuse mass was positively linearly correlated with landfill depth, volume, area, and well depth. Regression of the $CH_4$ recovery rate on depth, refuse mass, and volume was significant, but depth was the best predictive variable ($R^2$ = 0.53). Refuse mass was nearly as good ($R^2$ = 0.50). None of the climate variables—precipitation, average temperature, dewpoint—were correlated with the $CH_4$ recovery rate or with $CH_4$ recovery per metric ton of refuse. Much of the variability in $CH_4$ recovery remains unexplained, and is likely due to between-site differences in landfill construction, operation, and refuse composition. A model for global landfill emissions estimation is proposed.**

***This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).***

## Introduction

The U.S. Environmental Protection Agency's (EPA's) Air and Energy Engineering Research Laboratory (AEERL) began a research program in 1990 with the goal of improving global landfill methane ($CH_4$) emissions estimates. A review of currently available models and data identified several theoretical models and laboratory experiments used to estimate $CH_4$ production in individual landfills. However, adapting these methodologies for global estimates posed several problems, the worst being that site-specific data would be needed for every country. The few global emissions methodologies that were found were reasonable, but were hampered by a paucity of data. In particular, reliable refuse generation rates and waste composition data were not available for many countries. In addition, many landfill experts believe that climate (particularly as it affects moisture input to the landfill) has an effect on $CH_4$ generation rates. No currently available model incorporates climate as a controlling variable.

In order to accurately estimate $CH_4$ generation in landfills on a global basis, a model is needed that is responsive to a wide range of climates, types of waste, and landfill practices. Understanding the effects of climate on $CH_4$ production is especially important to climate modelers who are studying feedback effects of glo-

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bal climate change. Therefore, AEERL initiated a field study to gather data to:

- Identify key variables that affect $CH_4$ generation; and
- Develop an empirical model of $CH_4$ generation based on those variables.

The results of a field study of 21 U.S. landfills are presented. The program was limited to acquisition of $CH_4$ data gathered by on-site monitors. Furthermore, no other sampling or testing was planned. Data acquisition was confined to historical records kept at individual sites.

The objectives of the study were to:

- Develop a statistical model of annual landfill $CH_4$ emissions as a function of climate, refuse mass and age, and other physical characteristics (if warranted);
- Compare the performance of the statistical model to a deterministic kinetics-based model of landfill $CH_4$ production; and,
- Develop a simple model that can be used to estimate global $CH_4$ emissions from landfills.

It is important to note that $CH_4$ recovery is being used as a surrogate for $CH_4$ emissions in this study, thus affording the potential to both underestimate and overestimate emissions. The method may underestimate if gas recovery is not 100% efficient; some $CH_4$ may still be lost through the cap or by lateral gas migration out of the landfill. On the other hand, the method may overestimate if gas recovery circumvents the reoxidation of $CH_4$ by methanotrophs, methanogens, and sulfate-reducing bacteria. Given that strong arguments can be made for both cases and no quantitative data exist for either, the approach used in this study is to assume that both cases are true but the net effect is zero. If data that refute this assumption become available, the model will be adjusted.

## Data Summaries and Statistical Analyses

Table 1 shows the average $CH_4$ recovery rate for each landfill, as well as other summary statistics. The number of measurements available varied a great deal between sites. Table 2 summarizes the landfill statistics used in the analysis and model development.

Climate data were obtained from the Southeast Regional Climate Center for a cooperative National Weather Service (NWS) station nearest each landfill. The monthly average temperature and total rainfall values were summed and converted to average annual temperature and total annual rainfall values for each year. The annual temperature and rainfall values for the years of refuse acceptance were then averaged for comparison to landfill data for each landfill.

***Table 1.*** *Summary Statistics for Methane Recovery Rates Grouped by Measurement Type*

| *Measurements* | | | *Methane Recovery (m³/min)* | | | | | |
|---|---|---|---|---|---|---|---|---|
| *Landfill* | *Type* | *Number* | *Average* | *Median* | *Standard Deviation* | *Minimum Value* | *Maximum Value* | *Range* |
| 1 | daily | 194 | 55.3 | 55.3 | 2.12 | 48.0 | 61.4 | 13.4 |
| 2 | daily | 302 | 18.0 | 18.2 | 1.19 | 12.3 | 20.5 | 8.2 |
| 3 | daily | 314 | 40.0 | 40.3 | 2.32 | 30.2 | 44.6 | 14.4 |
| 4 | daily | 85 | 98.4 | 98.7 | 1.33 | 93.3 | 101.5 | 8.2 |
| 5 | daily | 209 | 24.8 | 24.9 | 1.70 | 20.5 | 27.9 | 7.4 |
| 6 | daily | 37 | 16.7 | 16.8 | 2.07 | 12.6 | 22.6 | 10.0 |
| 7 | monthly | 12 | 9.7 | 10.2 | 2.01 | 4.0 | 12.0 | 8.0 |
| 8 | daily | 626 | 11.7 | 12.4 | 2.46 | 0.5 | 17.1 | 16.6 |
| 9 | daily | 15 | 7.7 | 7.0 | 1.42 | 5.7 | 10.5 | 4.8 |
| 10 | monthly | 6 | 29.3 | 30.5 | 3.34 | 23.4 | 32.4 | 9.0 |
| 11 | monthly | 12 | 11.3 | 11.7 | 1.22 | 9.1 | 12.7 | 3.6 |
| 12 | daily | 232 | 8.0 | 7.7 | 1.02 | 5.4 | 10.4 | 5.0 |
| 13 | daily | 11 | 10.4 | 11.0 | 1.50 | 7.8 | 11.7 | 3.9 |
| 16 | monthly | 15 | 16.0 | 16.6 | 4.13 | 7.4 | 21.6 | 14.2 |
| 17 | minute | 13 | 13.8 | 13.9 | 1.50 | 10.1 | 16.5 | 6.4 |
| 20 | monthly | 12 | 35.0 | 35.1 | 4.75 | 26.5 | 41.3 | 14.8 |
| 21 | daily | 11 | 27.4 | 26.5 | 2.94 | 24.5 | 32.9 | 8.4 |
| 22 | daily | 51 | 33.2 | 31.8 | 7.84 | 21.6 | 60.0 | 38.4 |
| 23 | daily | 202 | 2.2 | 2.3 | 0.51 | 0.3 | 2.9 | 2.6 |
| 24 | daily | 333 | 17.7 | 17.9 | 2.18 | 3.1 | 22.1 | 19.0 |
| 25 | daily | 331 | 20.2 | 20.8 | 2.80 | 1.4 | 24.4 | 23.0 |

In addition to the daily weather data, the 30-year averages of annual mean temperature, mean dewpoint temperature, and total rainfall were obtained for the NWS stations. These 30-year averages of temperature and rainfall are referred to as the 'normal' values.

Dewpoint temperature was included in this analysis because it is a readily available variable that provides a better measure of moisture availability than either temperature or precipitation. Better composite variables could be chosen (such as actual evapotranspiration), but calculating these values was beyond the scope of this project.

Based on the preliminary data analyses, a linear model appeared to be sufficient to model $CH_4$ recovery rate. The SAS regression procedure (PROC REG) was used to generate regression statistics for various models. Two general models were used—one to predict $CH_4$ recovery rate, the other to predict $CH_4$ recovery rate per unit mass. Selection of variables for the regression models was based on the results of the correlation and scatter plots summaries discussed above. In addition, the data distribution of potential regression variables was examined for normality. Although most variables were not normally distributed, the distributions were not so far off as to warrant data transformations.

Table 3 shows the results of several linear regression models. For most of the models that use a single landfill parameter, the intercept term was found to be insignificant. From the regression model results shown in Table 3, landfill depth appears to be the best predictor of $CH_4$ emissions ($P = 0.0002$, $R^2 = 0.53$). However, refuse mass is very nearly as good ($P = 0.0003$, $R^2 = 0.50$). The best model used both depth and mass as predictive variables ($P = 0.0001$, $R^2 = 0.65$). Because waste production data are much more widely available than landfill depth data on a global basis, the no-intercept regression of $CH_4$ recovery on refuse mass is the better model choice. This model is:

$$CH_4 = 4.52W$$

where:

$CH_4$ = methane flow rate (m³/min); and
W = mass of refuse ($10^6$ Mg).

Figure 1 shows the regression line for $CH_4$ recovery rate as a function of refuse mass. The 95-% confidence interval of the regression line is shown by the dashed lines.

No other variables were found to have any effect on $CH_4$ production. In particular, no functional model was found linking $CH_4$ production to climate variables. This does not mean that climate is not important. Given the unexplained variability in the $CH_4$-versus-tons regression, some aspect of climate may actually play a controlling role. However, as shown in this study, site-specific factors and difficulties in accurately quantifying key parameters confound the problem.

**Table 2.** *Summary of Landfill Parameters Used in the Statistical Analyses*

| Landfill Identification Code | | Refuse Mass ($10^6$ Mg) | Average Refuse Age (yrs) | Landfill Area (hectares) | Average Landfill Depth (meters) | Average Well Depth (meters) | Number of Wells | Landfill Volume ($10^6$ $m^3$) | Average Methane Recovery Rate ($m^3$/min) | Average Methane Recovery Rate Per Unit Mass ($m^3$/min/$10^6$ Mg) | Gas End Use |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Number | Letter | | | | | | | | | | |
| 1 | A | 6.35 | 8.0 | 34.80 | 67.06 | 13.72 | 45 | 23.34 | 55.3 | 8.71 | ELEC.-TURBINE |
| 2 | B | 6.12 | 10.0 | 54.64 | 25.91 | 14.33 | 44 | 14.15 | 18.0 | 2.94 | ELEC.-TURBINE |
| 3 | C | 7.35 | 10.0 | 50.99 | 66.14 | 23.47 | 31 | 33.73 | 40.0 | 5.45 | ELEC.-TURBINE |
| 4 | D | 13.79 | 9.5 | 56.66 | 56.39 | 21.34 | 111 | 31.95 | 98.4 | 7.14 | ELEC.-TURBINE |
| 5 | E | 10.89 | 15.0 | 32.38 | 45.72 | 34.14 | 102 | 14.80 | 24.8 | 2.28 | FLARE |
| 6 | F | 2.40 | 7.0 | 40.31 | 9.83 | 9.83 | 68 | 3.96 | 16.7 | 6.97 | ELEC.-IC ENGINE |
| 7 | G | 2.95 | 10.0 | 50.59 | 18.29 | 12.19 | 48 | 9.25 | 9.7 | 3.28 | BOILER FUEL |
| 8 | H | 2.72 | 10.0 | 22.26 | 16.76 | 16.76 | 107 | 3.73 | 11.7 | 4.32 | HIGH BTU |
| 9 | I | 1.63 | 7.0 | 12.14 | 15.24 | 15.24 | 32 | 1.85 | 7.7 | 4.71 | FLARE |
| 10 | J | 5.26 | 12.0 | 32.38 | 21.34 | 13.72 | 96 | 6.91 | 29.3 | 5.57 | HIGH BTU |
| 11 | K | 1.81 | 10.0 | 27.92 | 24.38 | 13.72 | 39 | 6.81 | 11.3 | 6.22 | BRICK KILN FUEL |
| 12 | L | 2.78 | 8.5 | 34.40 | 10.67 | 10.67 | 78 | 3.67 | 8.0 | 2.87 | HIGH BTU |
| 13 | M | 0.96 | 7.0 | 14.17 | 12.19 | 12.19 | 51 | 1.73 | 10.4 | 10.87 | FLARE |
| 16 | P | 3.38 | 5.5 | 30.35 | 27.43 | 18.29 | 36 | 8.33 | 16.0 | 4.74 | ELEC.-TURBINE |
| 17 | Q | 5.17 | 10.0 | 16.19 | 18.29 | 18.29 | 41 | 2.96 | 13.8 | 2.67 | FLARE |
| 20 | T | 9.71 | 11.0 | 72.85 | 18.29 | 17.37 | 69 | 13.32 | 35.0 | 3.61 | FLARE |
| 21 | U | 2.60 | 13.0 | 26.71 | 27.43 | 18.29 | 56 | 7.33 | 27.4 | 10.52 | FLARE |
| 22 | V | 3.97 | 12.0 | 40.47 | 24.38 | 24.38 | 40 | 9.87 | 33.2 | 8.35 | FLARE |
| 23 | W | 2.87 | 10.7 | 40.47 | 21.34 | 19.81 | 19 | 8.63 | 2.2 | 0.78 | ELEC.-IC ENGINE |
| 24 | X | 6.21 | 5.6 | 109.27 | 30.48 | 15.24 | 23 | 33.30 | 17.7 | 2.85 | ELEC.-TURBINE |
| 25 | Y | 10.65 | 12.0 | 74.87 | 22.86 | 21.34 | 43 | 17.11 | 20.2 | 1.90 | ELEC.-TURBINE |

*Table 3. Landfill Regression Summary*

| Regression Model* | Prob > F | $R^2$ | b0 | b1 | b2 | Comments |
|---|---|---|---|---|---|---|
| methane = depth | 0.0002 | 0.53 | -1.09 | 9.13E-1 | — | intercept not significant |
| methane = depth | 0.0001 | — | — | 8.84E-1 | — | no intercept in model |
| methane = $10^6$ Mg | 0.0003 | 0.50 | 1.89 | 4.27 | — | intercept not significant |
| methane = $10^6$ Mg | 0.0001 | — | — | 4.52 | — | no intercept in model |
| methane = volume | 0.0011 | 0.44 | 7.38 | 1.37E-6 | — | intercept not significant |
| methane = volume | 0.0001 | — | — | 1.73E-6 | — | no intercept in model |
| methane = wells | 0.0701 | 0.16 | 6.87 | 3.08E-1 | — | model fit & wells borderline; intercept not significant |
| methane = wells | 0.0001 | — | — | 4.07E-1 | — | no intercept in model |
| methane = depth + $10^6$ Mg | 0.0001 | 0.65 | -5.96 | 2.36 | 0.18 | intercept not significant |
| methane = depth + $10^6$ Mg | 0.0001 | — | — | 2.056 | 0.15 | no intercept in model |
| methane = $10^6$ Mg + mean rain | 0.0011 | 0.53 | -10.31 | 4.32 | 1.22E-1 | intercept & mean rain not significant |
| methane = $10^6$ Mg + mean temp | 0.0015 | 0.52 | -4.67 | 4.11 | 5.61E-1 | intercept & mean temp not significant |
| methane = $10^6$ Mg + dewpoint 30 | 0.0009 | 0.54 | -2.98 | 3.97 | 9.49E-1 | intercept & dewpoint 30 not significant |
| methane/Mg = mean rain | 0.7688 | 0.00 | 4.48 | 6.19E-3 | — | poor model fit; mean rain not significant |
| methane/Mg = mean temp | 0.7607 | 0.01 | 6.64 | -4.21E-2 | — | poor model fit; mean temp not significant |
| methane/Mg = dewpoint 30 | 0.6127 | 0.01 | 4.61 | 7.03E-2 | — | poor model fit; dewpoint 30 not significant |

* *Methane = b0 + b1 • variable 1 + b2 • variable 2.*

In order to validate the statistical model, its performance was compared to that of the U.S. EPA's Landfill Air Emissions Estimation Model, which is a deterministic computer model that was developed for regulatory purposes. Assuming that the refuse has been accepted at the same annual rate over time (i.e., all submasses are of the same size), the model equation is as follows:

$$Q_{CH4} = L_0 R \{\exp\{-kc\} - \exp(-kt)\}$$

where:

- $Q_{CH4}$ = $CH_4$ generation rate at time t, ft³/yr
- $L_0$ = potential $CH_4$ generation capacity of the refuse, ft³/Mg refuse
- R = average annual refuse acceptance rate during active life, Mg/yr
- k = $CH_4$ generation rate constant, 1/yr
- c = time since landfill closure, year (c = 0 for an active landfill)
- t = time since initial refuse placement, year

The Landfill Model methodology is based on the Scholl Canyon model, which is a first order decay equation. Because site-specific characteristics are required as model input, the Landfill Model is impractical for use on a global scale.

The relative performances of the models were compared using a ratio of predicted $CH_4$ emissions to actual $CH_4$ recovered. The mean value of the ratio for all 21 landfills provides a measure of the model's relative accuracy.

The results of the Landfill Model and regression model comparisons are shown in Table 4. As shown by the mean of the ratios, the Landfill Model with $L_0$ of 50 m³/Mg tends to underpredict (ratio less than 1). When $L_0$ is set to 162 m³/Mg, the model, on average, is very accurate (the mean ratio of 1.07 approximates 1); the model default $L_0$ (298 m³/Mg) tends to overestimate $CH_4$ (mean ratio = 1.97). The regression model's mean ratio of 1.39 falls between Landfill Model runs 1 and 3.

The regression model performs reasonably well compared to the Landfill Model. One particular advantage of using a statistical model is that only one variable is required. Furthermore, it is relatively easy to add new observations and further refine the model, as only average $CH_4$ recovery and refuse mass are required. The confidence limits of the regression coefficient can be used to bound estimated $CH_4$ emissions. The upper and lower 95-% confidence limits are 6.52 and 2.52 m³ $CH_4$/Mg refuse, respectively.

## Summary and Conclusions

This research program had as its goal the development of an empirical model of $CH_4$ emissions from landfills. It was successful in meeting its major objectives, but much remains to be learned. The main objective—developing a model for global emissions—was achieved. The strengths and successes of this program include:

- Development of a model that accurately reflects real world variability of landfill $CH_4$ recovery;
- The model is very simple and easily adapted to global emissions estimation;
- The uncertainty associated with $CH_4$ recovery was quantified; and,
- The program was cost-effective, allowing maximization of sample size.

The weaknesses of this approach are:

- The model is not mechanistic, and is therefore limited in its usefulness.
- Between-site variability is high, and much of the variability remains unexplained by the model.
- Recovery is used as a surrogate for emissions. The validity of this substitution is unknown.

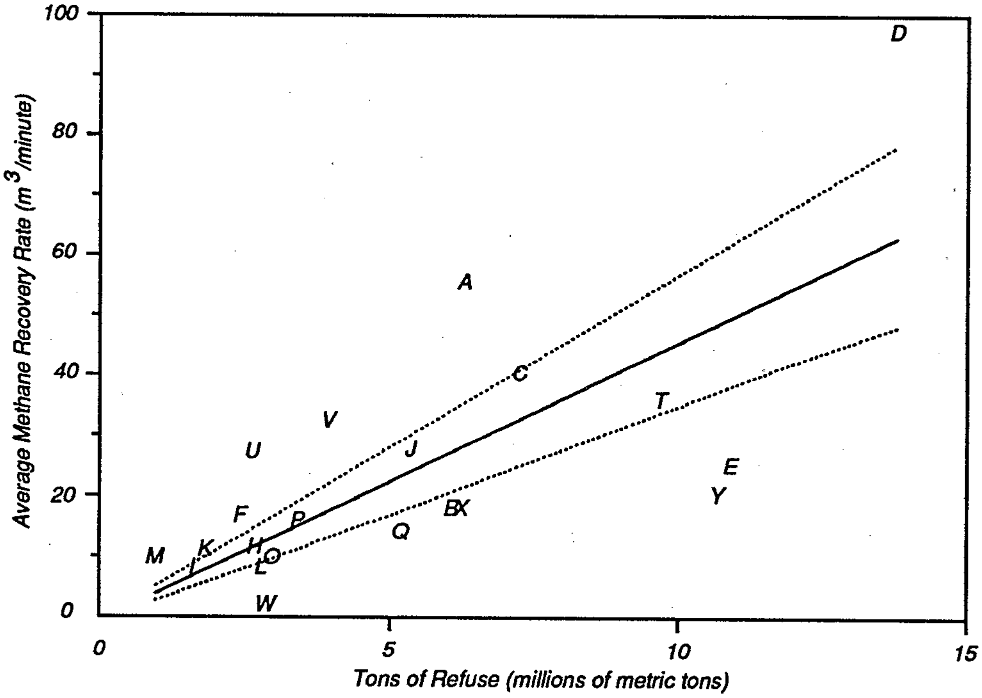


*Figure 1. Methane recovery regression with 95% confidence interval of regression coefficient.*

A factor for estimating landfill $CH_4$ emissions can be proposed based on the $CH_4$ per refuse mass regression model. The intercept was not significant, so the simpler model (with the line forced through the origin) can be used. The slope for this line is 4.52 $m^3$ $CH_4$ per min/$10^6$ Mg of refuse; this factor can be used to estimate annual $CH_4$ emissions by multiplying it by the total refuse landfilled each year.

On a global basis, this factor may overestimate $CH_4$ production for many countries. The composition of wastes from less-developed countries in particular is lower in paper and therefore less likely to produce $CH_4$. Also, global landfilling practices vary much more than those of the sample population of U.S. sites. On the other hand, if waste decays more slowly than assumed in this study (20 years), then this factor underestimates $CH_4$ per ton of refuse.

Despite these concerns, the $CH_4$ potential factor developed in this study should yield more reasonable estimates of global landfill $CH_4$ emissions than are currently available because the factor is based on actual landfill data rather than theoretical models. By careful consideration of all the mitigating effects, some of which are discussed in this report, this simple model can be used to quantify and reduce some of the uncertainty in global estimates.

***Table 4.*** *Comparison of Model Performances*

| | Landfill Air Emissions Estimation Model | | | Regression |
|---|---|---|---|---|
| Site Number | Run 1 Pred./Actual | Run 2 Pred./Actual | Run 3 Pred./Actual | Pred./Actual |
| 1 | 0.16 | 0.40 | 0.73 | 0.52 |
| 2 | 0.48 | 1.21 | 2.23 | 1.55 |
| 3 | 0.28 | 0.71 | 1.31 | 0.83 |
| 4 | 0.22 | 0.55 | 1.01 | 0.62 |
| 5 | 0.58 | 1.44 | 2.66 | 1.95 |
| 6 | 0.24 | 0.60 | 1.10 | 0.73 |
| 7 | 0.46 | 1.16 | 2.14 | 1.50 |
| 8 | 0.37 | 0.93 | 1.71 | 1.15 |
| 9 | 0.36 | 0.90 | 1.67 | 1.15 |
| 10 | 0.25 | 0.64 | 1.17 | 0.83 |
| 11 | 0.23 | 0.57 | 1.05 | 0.85 |
| 12 | 0.54 | 1.34 | 2.47 | 1.72 |
| 13 | 0.16 | 0.39 | 0.72 | 0.57 |
| 16 | 0.33 | 0.82 | 1.52 | 1.02 |
| 17 | 0.49 | 1.23 | 2.26 | 1.73 |
| 20 | 0.41 | 1.02 | 1.88 | 1.24 |
| 21 | 0.15 | 0.36 | 0.67 | 0.47 |
| 22 | 0.19 | 0.47 | 0.87 | 0.57 |
| 23 | 1.74 | 4.35 | 8.00 | 6.32 |
| 24 | 0.54 | 1.34 | 2.46 | 1.60 |
| 25 | 0.82 | 2.06 | 3.79 | 2.34 |
| Mean | 0.43 | 1.07 | 1.97 | 1.39 |
| Standard Deviation | 0.34 | 0.85 | 1.56 | 1.24 |



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*The complete report, entitled "Development of an Empirical Model of Methane Emissions from Landfills," (Order No. PB92-152875/AS; Cost: $26.00, subject to change) will be available only from:*

*National Technical Information Service*
*5285 Port Royal Road*
*Springfield, VA 22161*
*Telephone: 703-487-4650*

*The EPA Project Officer can be contacted at:*

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