PVC\'s role in dioxin emissions from open burning: New analysis of US EPA data

Christopher Neurath[1]

[1]Work on Waste, Canton NY

Introduction

Experimental studies have revealed high rates of dioxin emission from open burning of domestic waste. Based on these studies and estimates of activity level, the US Environmental Protection Agency (EPA) dioxin inventory now projects that open burning is the single largest source of dioxin to the atmosphere in the US[1]. They estimate it is ten times greater than the next largest source category (incineration) and that open burning produces more airborne dioxin than all other categories combined. Beginning in 1997, the EPA has published five reports of their experimental studies on open burning emissions[2, 3, 4, 5, 6]. The latest report includes complete data from 25 test runs.

An important question the EPA set out to answer was: What conditions of open burning most affect dioxin emissions? The results of their first screening level experiments suggested that the polyvinyl chloride (PVC) plastic content of the waste might have been a key determinant of dioxin levels[2].

Later experiments were designed to determine the effect of varying PVC and inorganic chlorine content of waste input on dioxin emissions. Other variables investigated were the effect of waste moisture content, waste density, total waste load, level of copper, and whether the waste was burned in a steel “burn barrel” or in an open pile.

The EPA also measured many variables such as temperatures and gas concentrations during the runs. They conducted statistical analysis to determine correlations between these measurements and dioxin emissions. The EPA presented three main conclusions about the role of chlorine (Cl) and PVC input in creating dioxin[6]:

> “In summary, although Cl in the waste does appear to influence emissions of PCDDs/Fs from burn barrels, [1] this effect can be observed only at high levels of Cl, atypical of household trash, [2] and is independent of the source of the Cl (organic or inorganic). [3] At moderate levels of Cl, a statistically significant effect of waste Cl concentration is not observed, because other more important variables have a much greater influence on the emissions of PCDDs/Fs.”

These three conclusions contradict the findings of other studies[2, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. Also, some EPA analyses used less powerful statistical methods than were possible. For these reasons, a re-evaluation of the EPA data was undertaken.

Methods

To determine the strength of relationships between variables, regression analysis was used. Analysis of variance (ANOVA) was used to compare PVC with $CaCl_2$ as chlorine sources. All statistical analyses were performed with JMP software from SAS.

The controlled independent variables in the 25 runs conducted by EPA were:

polyvinyl chloride (PVC) level in waste (0, 0.2, 1.0, 7.5%)
calcium chloride ($CaCl_2$ an inorganic chlorine) level (0, 7.0%)
Cl level from added PVC (60% Cl) or $CaCl_2$ (64% Cl) (0. 0.12, 0.60, 4.50%)
copper (Cu) level (Cu is thought to be a catalyst for dioxin formation) (0.07, 2%)
moisture content (no added water, added water)
density (not compressed, compressed)
total mass placed in barrel or in pile (single load, double load)
burning inside a barrel or in an open pile (steel barrel, open pile)

The uncontrolled dependent variables measured during burning were:

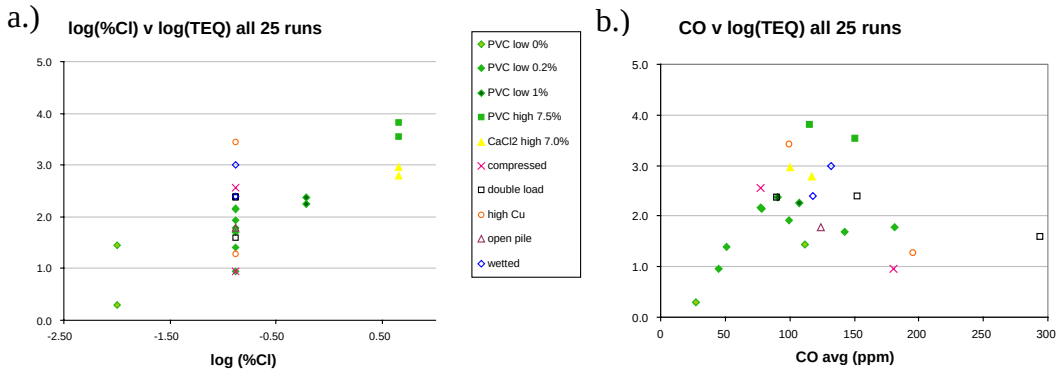
dioxin/furan/PCB air emissions (by congener, totaled, and calculated TEQ)
HCl emissions (hydrogen chloride)
CO emissions (carbon monoxide)
O_2 emissions (oxygen)
CO_2 emissions (carbon dioxide)
Cu emissions (copper)
temperatures at various locations within and above the burning waste (e.g. TC6max)

The EPA also derived additional variables. For example, the lengths of time parts of the barrel were within a certain temperature window. We looked at all variables in our analysis. To prevent indeterminate logarithms of zero %Cl values were transformed by adding 0.01.

Results and Discussion

To put statistical results in context Figure 1a shows all the runs in a scatterplot of dioxin emissions factors against chlorine input. For comparison a scatterplot between CO emissions and TEQ is shown in Figure 1b. CO is a variable that the EPA suggests predicts log(TEQ) better than %Cl.

Figure 1. Dioxin emission factors for all runs plotted against: a.) chlorine content; b.) CO. Each variation of initial test conditions is indicated by a unique symbol.



For each of EPA's three conclusions, details of statistical re-analysis are presented:

EPA conclusion 1: "In summary, although Cl in the waste does appear to influence emissions of PCDDs/Fs from burn barrels, this effect can be observed only at high levels of Cl, atypical of household trash …."

To test this conclusion, least squares regression analysis was performed on subsets of test runs where PVC was 1% or less. The EPA considers these "moderate" levels of chlorine. See Table 1. A high correlation coefficient was found (R^2=0.54, p=0.01) for the sub-subset of such runs where PVC was the only variable. Even when all runs with "moderate" Cl levels were examined, which introduced much more variability, the correlation was still R^2=0.23 at p=0.028. The effect of PVC on dioxin emissions is observable at these lower PVC levels, contrary to the EPA conclusion.

How large a reduction in dioxin could be expected from a reduction in PVC open burning? The strength of the effect is noteworthy. The relationship from the EPA data is:
$\log_{10}(TEQ) = 2.71 + 0.85 \log_{10}(\%Cl)$
Reducing PVC by half reduces dioxin emissions by almost half. For example, at 0.4% PVC 156 ngTEQ/kg would be expected, whereas at 0.2% PVC, only 89 ngTEQ/kg. This holds across the entire range of PVC (0 to 7.5%) examined by the EPA. The equation is similar no matter which of the four sets of runs are used in the regression.

Table 1. Regression of log(TEQ) with log(%Cl) for various data set choices.

runs included	N	R^2	p-value
all	25	0.50	>0.0001
all with "moderate" Cl	21	0.23	0.028
all with only PVC varied	13	0.80	>0.0001
all with "moderate" Cl and only PVC varied	11	0.54	0.01

The EPA acknowledges the effect of %Cl on dioxin becomes extremely clear if the runs with higher levels of PVC (7.5% PVC) are included. But they argue that levels of PVC above 1% are atypical in household trash. Yet their own original burn barrel study assumes there may be common situations where higher levels of PVC are burned[2]. For this study they made up a waste composition for an "avid recycler". The mix had 4.5% PVC because most of the recyclable glass, metal, and paper was removed before burning thereby enriching the remaining materials in non-recyclable PVC plastic. Among European countries France, Switzerland, Spain and the UK all have levels of PVC in waste greater than 1%[20].

EPA conclusion 2: "In summary, although Cl in the waste does appear to influence emissions of PCDDs/Fs from burn barrels, this effect can be observed only at high levels of Cl, … and is independent of the source of the Cl (organic or inorganic)."

Statistical analysis (ANOVA) of the dioxin emissions from organic Cl (from PVC) compared to inorganic Cl (from $CaCl_2$) contradicts the EPA conclusion that there is no difference between these forms of Cl. The data show that emissions as log(TEQ) are significantly different with p=0.04. The EPA uses the logarithm of TEQ for all their regression analyses. For emissions as TEQ (not log transformed), the small number of runs does not provide sufficient power to show a "statistically significant" difference at the p=0.05 level. However, at the p=0.11 level there is a significant difference. Furthermore, the mean dioxin emissions from the PVC runs were more than 6 times greater than from $CaCl_2$ runs with equivalent Cl content. This suggests that to reduce dioxin emissions, limiting the PVC input is much more effective than limiting inorganic Cl sources.

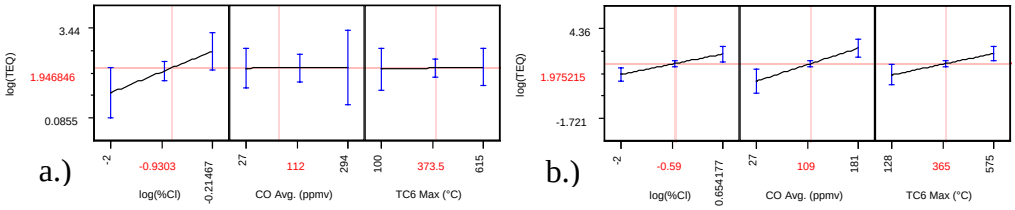
EPA conclusion 3: "At moderate levels of Cl, a statistically significant effect of waste Cl concentration is not observed, because other more important variables have a much greater influence on the emissions of PCDDs/Fs."

Amongst independent controlled variables only PVC and chlorine level clearly predicted dioxin emissions. Virtually no relationship was shown with density, total mass, or open versus barrel burning. Very slight relationships were found with moisture and copper level. Statistical analysis does not support the EPA conclusion that %Cl shows no effect on dioxin or less effect than other variables. Table 2 compares single variable regression models and a three variable multiple regression model with terms: log(%Cl), CO, TC6max. This three variable model was identified by EPA has having the best fit from their stepwise model selection procedure.

Results depend heavily on what runs are excluded from the regression. When 20 runs with "moderate" %Cl are included %Cl has a very strong positive correlation with dioxin whereas CO and TC6max have virtually no correlation and no effect (see Figure 2a). When all 25 runs are included, the dominance of %Cl is even stronger.

A smaller subset of runs where CO and TC6max seem to dominate is those 15 runs where only %Cl was varied (see Figure 2b). The EPA seems to have selectively chosen this subset of their data to bolster their conclusion. Yet even for this subset of runs, although CO and TC6max are better predictors of dioxin, the %Cl still has an effect that is of practical importance. When the %Cl is halved, the dioxin is reduced by more than one quarter.

Figure 2. Prediction Profilers: a.) 20 runs with "moderate" Cl; b.) 15 runs where only %Cl was varied.



Another way to examine the relative importance of "combustion" variables versus %Cl is to see which consistently provide a good model fit for dioxin emissions regardless of the subset of data used. No matter which subset of runs are chosen, %Cl does have a significant and clear effect on dioxin emissions. But EPA's preferred "combustion" variables only provide a good fit and strong effect when many of the runs are excluded (e.g. Figure 2b). Table 2 demonstrates that only %Cl has a clear effect on dioxin over all sets of data.

Finally, when the runs included in the regression are limited to just those where PVC is varied, the relationship between PVC and dioxin is very strong and highly significant (R^2=0.80, p=0.0001). This holds even when the runs are further limited to those with just "moderate" Cl levels. The multiple variable model improves the correlation somewhat.

Table 2. Effect of data set choice on strength and significance of relationships for various models. Dioxin emissions as log(TEQ).

variable(s) in model	runs included in regression	N	R^2	p-value signif. level	model effect strength	relative effect strength on TEQ emissions by variable
log(%Cl)	all	25	0.50	0.001	high	
log(%Cl), CO, TC6max	all	24	0.51	0.002	high	log(%Cl) >> CO , TC6max
CO	all	25	0.00	0.90	none	
TC6max	all	24	0.07	0.23	none	
log(%Cl)	"moderate" Cl	21	0.19	0.05	medium	
log(%Cl), CO, TC6max	"moderate" Cl	20	0.25	0.20	low	all low or none
CO	"moderate" Cl	21	0.00	0.98	none	
TC6max	"moderate" Cl	20	0.00	0.80	none	
log(%Cl)	only PVC varied	13	0.80	0.0001	high	
log(%Cl), CO, TC6max	only PVC varied	13	0.90	0.0001	high	CO > TC6max > log(%Cl)
CO	only PVC varied	13	0.23	0.06	medium	
TC6max	only PVC varied	13	0.08	0.36	none	
log(%Cl)	"moderate" Cl; only PVC varied	11	0.54	0.01	high	
log(%Cl), CO, TC6max	"moderate" Cl; only PVC varied	11	0.81	0.007	high	CO > TC6max > log(%Cl)
CO	"moderate" Cl; only PVC varied	11	0.25	0.12	low	
TC6max	"moderate" Cl; only PVC varied	11	0.00	0.86	none	

Notes: There was a run with a missing value for TC6max so models with TC6max may have one less N. All these analyses are with log(TEQ) but the results with log(Total PCDD/F) are very similar. Effect strengths: "high"—doubling variable doubles TEQ or more; "medium"—doubling variable increases dioxin by about 50%; "low"—doubling variable increases dioxin by about 25%.

The EPA repeatedly tries to emphasize the importance of "combustion variables" such as CO and TC6max and suggests they are more important than %Cl or %PVC. A careful statistical re-analysis of the data has shown that %Cl and especially %PVC are actually the most important predictors of dioxin emissions. Combustion variables do play a role but they are likely to be subsidiary to %PVC when practical methods of controlling dioxin are sought. Uncontrolled open burning is not like an incinerator where one can adjust the air input levels, waste feed rate, and temperatures. Knowing that CO and TC6max are sometimes correlated with dioxin may be of interest, but it is fundamentally of less practical importance than the finding that PVC level in the waste is the strongest predictor of dioxin output. By definition, uncontrolled combustion cannot be controlled. However, the types of waste materials burned are controllable.

These new conclusions drawn from the most comprehensive open burning emissions experiments to date have important policy implications. They suggest that reducing PVC content of wastes may be the only practical way to reduce dioxin emissions from open burning, short of stopping the burning altogether. Many classes of open burning are not amenable to outright stopping. For instance, structure fires are rarely intentional. Many regions where open burning is common do not have economical access to alternative waste management methods. Open burning is common in rural areas of the US and in many areas of developing countries[18, 21]. Intentional or accidental landfill fires are another form of open burning. Again, in developing countries, there is often no practical or economical way to eliminate landfill fires in the near term. Even in areas where economics and convenience is not a major barrier to reducing open burning, such as rural US, habit and custom are major barriers. The US EPA estimates that 40% of rural residents in the US burn their trash. Politically, the US government has been reluctant to regulate open burning and has delegated this responsibility to states or local governments. Most states have yet to pass legislation to halt open burning and local governments in rural areas are even less likely to regulate open burning.

Until authorities around the world can provide better methods of waste management and get their populaces to use them, the best way to reduce dioxins from open burning may be reduction in PVC burning. Most of PVC in waste is packaging or low-value disposable items. Virtually all of these PVC uses have currently available cost-effective substitutes. Regulating sales of PVC products is potentially a practical and cost-effective way of reducing dioxin emissions worldwide.

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