# Dioxin and Furan Emissions From Landfill Gas-Fired Combustion Units

## 98-RP105A.03

**Frank R. Caponi, Ed Wheless & David Frediani**

County Sanitation Districts of Los Angeles County, 1955 Workman Mill Rd. Whittier, CA 90607

## ABSTRACT

The 1990 Federal Clean Air Act Amendments require the development of maximum achievable control technology standards (MACT) for sources of hazardous air pollutants, including landfill gas-fired combustion sources. The Industrial Combustion Coordinated Rulemaking (ICCR) Federal Advisory Committee is a group of stakeholders from the public and private sector whose charge is to develop recommendations for a unified set of federal toxic air emissions regulations. Specifically, the group will establish MACT standards for industrial-commercial-institutional combustion sources. The ICCR proceedings have given rise to considerable interest in potential dioxin and furan emissions from landfill gas-fired combustion units. In order to establish the potential of dioxin and furan emissions from this group of combustion sources, a world-wide literature search was conducted. A total of 22 references were evaluated. The references covered a wide range of test programs, testing methodologies and combustion equipment type. The most abundant data was for landfill gas-fired flares (shrouded and afterburners) and I.C. engines. Because of limitations in obtaining actual test reports with complete lab data and QA/QC results, and a lack of knowledge as to the exact types of waste received at the European landfills, the test data from these sources, for the purposes of this paper, are considered qualitative. The conclusion reached from review of the test data is that there is a potential for dioxin and furan emissions from landfill gas-fired combustion units, but at very low levels for well operated systems.

## INTRODUCTION

Emissions of chlorinated dibenzo-p-dioxins (dioxins) and chlorinated dibenzofurans (furans) from the combustion of municipal solid waste (MSW) have been recognized and intensely studied world-wide over the past 20 years. While many regulatory efforts have been undertaken, further interest in integrated MSW management approaches has led in recent years to studying and quantifying potential dioxin and furan emissions from landfill gas-fired combustion units.

As a general regulatory framework, the 1990 Federal Clean Air Act Amendments (FCAA) contain a list of 189 hazardous air pollutants (HAPs) which the U.S. Environmental Protection Agency (EPA) must study, identify sources of, and determine the need for regulations. Dioxins and furans are identified as HAPs on this list. Source regulations of HAPs in the form of Maximum Achievable Control Technology Standards (MACT) have been and continue to be promulgated for a specific list of source categories. Once the MACT standards are in place, the EPA is charged with assessing the need for further standards that may be required to provide an ample margin of safety to protect public health.

The development of MACT standards has proven to be an major undertaking for the EPA. In order to more efficiently address the number of sources requiring regulatory review, the EPA in

1997 set out to develop a coordinated rulemaking for industrial-commercial-institutional (ICI) combustion sources. This led to the formation of the Industrial Combustion Coordinated Rulemaking (ICCR) Federal Advisory Committee whose charge is to develop recommendations for a unified set of Federal toxic air emissions regulations. The committee may also address some criteria pollutants under New Source Performance Standards. Stakeholders include environmental groups, regulated industries, local governments, federal agencies and state/local regulatory agencies. Potential regulation of toxic emissions from landfill-gas fired combustion units will be considered in the ICCR process. The ICCR Committee can recommend that these combustion units be more appropriately addressed in the Landfill MACT, scheduled for the year 2000.

The ICCR proceedings have given rise to a considerable interest in the potential dioxin and furan emissions from landfill gas-fired combustion. This is especially interesting considering that this category of combustion equipment is air pollution control for methane and toxics emissions. Unfortunately, discussion of dioxins/furans tends to be emotionally charged which tends to blur the important technical issues that need to be addressed. Of most importance is data to establish what potential this source category has to generate emissions of dioxins and furans, and at what level. Once that has been established, then a meaningful dialogue can begin as to the need for regulations. The purpose of this paper is to review and report the world-wide source test data available on the emissions of dioxins and furans from landfill gas-fired combustion units. The units include flares, boilers and internal combustion (I.C.) engines. The paper will also review the methods used to source test these combustion units as well as existing regulations for dioxin and furan emissions relative to the concerns of this review. The results presented, although very comprehensive, are by no means complete; our search for data still continues. Conclusions reached from this review are the opinions of the authors and do not represent the opinions of any committees or agencies.

## WORLD-WIDE LITERATURE REVIEW

In May 1997, EPA completed the document *Locating and Estimating Air Emissions From Sources of Dioxins and Furans.*[1] The EPA estimates that approximately 67 percent of solid waste generated in the United States is disposed in landfills, representing in 1990, 130 million tons annually. The same reference identified only one test report of a landfill gas-fired flare that presents dioxin and furan emissions results. The general lack of data for this source category prevented EPA from estimating national emissions of dioxins and furans. Other publications world-wide have also attempted to estimate national emissions of dioxins and furans from all potential sources, including landfill gas combustion.[2,3,4] Each of these reports have concluded that the contribution of landfill gas combustion to the total inventory of dioxin and furan emissions is minor. While these reports have provided estimates, examination of their references reveal sparse data sources.

This lack of data prompted review of literature reporting emissions of dioxins and furans from landfill gas-fired combustion units. A literature search in the United States quickly revealed that the bulk of data lie in California. As for Canada, Environment Canada was contacted for available information. European references were obtained through a general literature search and through a consultant in Germany commissioned by the authors to obtain all available source test data.

Our efforts have resulted in a wealth of data; unfortunately, much of the data should be viewed as qualitative. Except for the California facilities, none of the data is accompanied by detailed test reports showing QA/QC procedures. Furthermore, except for one German study, little information is given about the types of waste received at the landfills under study. Most of the German reports required some English translation. In fact, one German report is so extensive in its data that the authors commissioned a full English translation. The Canadian data, while very complete in reporting, is qualified within its own reports as qualitative because of the nature of the testing procedures (this is discussed later in this paper). Furthermore, there is a lack of information in these reports as to the nature of the solid waste disposed in the landfills. While it is assumed that the waste is primarily a municipal solid waste (MSW), the level of hazardous constituents contained in each landfill is unknown. Therefore, the data is appropriate for estimating the potential of landfill gas-fired combustion units to generate dioxin and furan emissions, but is not appropriate for developing regulations. We believe a qualitative assessment of this nature can help regulators and the regulated communities determine if further assessment, or perhaps source testing, is warranted.

## DIOXIN AND FURAN SOURCE TEST PROCEDURES

In recent years, the measurement of dioxins and furans has been standardized in Europe, Canada and in the United States. Experienced test teams utilizing the standardized methods in conjunction with qualified laboratories will generate acceptable test data. Some reports cited in this document have not reported if the sampling and analytical methods followed the standardized test procedures. Additionally, some researchers question the adequacy of some of the standardized methods. Provided here is a review and comparison of the existing test procedures and, where appropriate, a note of concerns of procedures documented in the literature.

Prior to the standardization of the test methods, a modified EPA Method 5 (MM5) sampling train was used for dioxin and furan emissions sampling. This sampling train includes all of the components of a Method 5 sampling train with the addition of a water-cooled condenser (added to condition the sample prior to entering the resin cartridge), followed by a XAD-2® resin cartridge (the resin is designed to adsorb a broad range of volatile organic species) between the heated filter and first impinger. A variation of the MM5 sampling train, the Source Assessment Sampling System (SASS), may be used where higher sampling volumes and multi-component sampling is necessary.[1]

More recently, EPA Reference Method 23 was instituted.[5] EPA Reference Method 23 is identical to the MM5 sampling system with few exceptions and is the sampling system of choice in the United States for waste incinerators subject to federal dioxin and furan emissions regulations. A second dioxin and furan emissions sampling system is used in the United States, California Air Resources Board (CARB) Method 428.[6] It is similar to the EPA Reference Method 23 sampling train with the exception of the impinger solution - either ethylene glycol or water may be used and recovery solvents vary. The Canadian method is similar to both these methods.[7]

In other parts of the world, Europe and Germany, in particular, dioxin and furan emissions sampling methods vary from those used in the United States. Several studies have been conducted using various European and German test procedures against EPA Reference Method 23. The results, at times, show good correlation.

European Test Method EN 1948 consists of three parts.[8] The first part, or test procedure, includes the use of a filter/condenser between a probe and bank of impingers. The second test procedure uses dilution as the mechanism of collection. The third test procedure incorporates the use of a cooled probe to condense the collected sample.

The filter/condenser procedure (EN 1948-1) consists of the same components as EPA Reference Method 23 with a slight difference. In EN 1948-1, the filter holder temperature is regulated in addition to the oven temperature to achieve a filter casing temperature at least 50°F above the dew point. It has been suggested that the potential for significant dioxin and furan formation in the filter box of EPA Reference Method 23 is possible without temperature control.[9] Preliminary test results at a wet cement kiln support this theory.[9] In addition, the use of an adsorbent is optional. In EN 1948-2, the dilution method, the sample is rapidly cooled in a mixing channel using dried, filtered air. If necessary, the dilution air can be cooled. After dilution, a filter collects the particulate dioxins and furans contained in the sample. In addition, an adsorbent located downstream of the filter collects any gaseous dioxins and furans. Different variations of the third EN 1948 test procedure are possible. A typical sampling system consists of a water-cooled probe, a condensate flask, impingers and/or adsorbent, and filter. In this system, the sample is cooled in the probe with the resultant condensate collected in the condensate flask.

All three European PCDD/PCDF test methods were employed at an incineration plant. The results indicated that all three test methods were comparable in the range of 0.05 ng International Toxic Equivalent (I-TEQ)/$m^3$ to 0.16 I-TEQ/$m^3$, within the expected range of uncertainty.[8]

In addition to the three European test methods, three German dioxin and furan emissions sampling methods exist, the VDI Guidelines.[10,11,12] VDI Method 3499/1 is a dilution method similar to corresponding European test method EN 1948-2. VDI Method 3499/2 consists of an up-front filter, cooler and corresponding condensate trap, condenser for further sample conditioning, and resin cartridge. VDI Method 3499/3, on the other hand, includes a cooled probe and condensate flask and a series of ethoxyethanol impingers. A comparative study was conducted at a waste incinerator using EPA Reference Method 23, VDI 3499/2, and VDI 3499/3. The study demonstrated excellent agreement between EPA Reference Method 23 and VDI 3499/2, and reasonably good agreement between all three methods for the corresponding dioxin and furan loadings and site specifics.[13]

The adequacy of EPA Method 23 for compliance determinations with recently developed MACT standards (specifically the Municipal Waste Combustor MACT) has been questioned.[14] At issue is the Reference Method Quantification Limits which have been found to be well in excess of the current MACT standards. For dioxins and furans, this value lies between 0.22 and 0.47 ng I-TEQ/$dsm^3$ @7% $O_2$. This issue should be explored as part of any upcoming MACT development process.

## REGULATORY LIMITS IMPACTING DIOXIN AND FURAN EMISSIONS

As concerns over dioxin and furan emissions have developed, primarily with regard to waste combustion, many regulatory limits have been established world-wide. In the context of this paper, it would be helpful to review some of these limits so that test data presented here can be compared against a benchmark. This provides a useful perspective of the data.

- New Source Performance Standards (NSPS) and Emission Guidelines (EG) for new and existing large Municipal Waste Combustion Units were finalized by the U.S. EPA in 1997.[15]

The limits here are set for total dioxin and furan emissions at 13 and 30 ng/dscm @ 7% $O_2$ for new and existing large Municipal Waste Combustion Units, respectively. EPA estimates that these levels correspond to toxic equivalent values (I-TEQ) of 0.1 to 0.3 and 0.3 to 0.8 ng/dscm for new and existing units, respectively.

- New Source Performance Standards and Emission Guidelines for new and existing Hospital/Medical/Infectious Waste Incinerators, respectively, were finalized by the U.S. EPA in 1997.[16] A limit is set for dioxin and furan emissions at 2.3 ng I-TEQ/dscm @ 7% $O_2$ for existing small, medium and large units, as well as for new small units. A limit for medium and large new units is set at 0.6 ng I-TEQ/dscm @ 7% $O_2$.
- U.S. EPA proposed a Hazardous Waste Combustor MACT Standard in April 1996.[17] The proposed dioxin and furan emissions standard for both new and existing combustors is 0.2 ng I-TEQ/dscm @ 7% $O_2$.
- A Dioxin and Furan limit for waste incineration plants in Germany are set forth in the 17$^{th}$ BlmSchV.[18] The limit is set at 0.1 ng I-TEQ/$Nm^3$ @ 11% $O_2$.
- Guidelines have been established in Canada for waste incineration at 0.5 ng I-TEQ/$m^3$ @ 11% $O_2$.[19] Environment Canada will likely revise this limit to 0.1 ng I-TEQ/$Nm^3$ in 1998.[20]
- New guidelines for the control of dioxin and furan emissions in municipal waste management were developed by the Japanese Government in January 1997.[21] For full-continuous-feed incineration, the guidelines recommend levels of 0.1 and 0.5 ng I-TEQ for new and existing units, respectively.

The most stringent of the standards presented is 0.1 ng I-TEQ/$Nm^3$ @ 11% $O_2$. This will be used as the standard at which the results presented in this paper will be compared.

## REPORTING OF DATA

All data reported here are in International Toxic Equivalents (I-TEQ) (corrected to 11% $O_2$ ), as established in 1989 through a joint international effort.[22] It is important to note that most of the studies cited in this review report dioxin and furan emissions as I-TEQs only. We therefore, do not know how non-detected species are handled. For example, in summing of the individual 2,3,7,8 substituted congeners, non-detected congeners can be treated as having a zero value, a value equal to the detection limit or a value equal to one-half the detection limit. The Canadian data, reported by Environment Canada, treats non-detected values as zero in their I-TEQ calculation. The County Sanitation Districts of Los Angeles County report dioxin and furan congeners not detected at the full detection limit.[37]. There are several reports for which no 2,3,7,8 substituted congeners are detected.[38-44] For these, the I-TEQ is also calculated at the full detection limit. It should be noted that two of these references reported some detection of the octa-dioxin homologue group.[38,39] Since octa-dioxin is considered non-toxic in California, and all other 2,3,7,8 substituted congeners were not detected, these references are considered here to contain no detections.

All graphical presentations of data are individual test data points from the test reports; repeat runs are not averaged. Some European test studies report emission data from kilns. To the authors knowledge, this type of combustion unit is not used in the United States for landfill gas incineration; therefore, the results are not reported.

This paper reports data for a wide variety of combustion devices that fall into the following general categories: 1) candle flares; 2) shrouded or enclosed flares; 3) shrouded flares used as afterburners for engine exhaust; 4) I.C. Engines; 5) landfill gas-fired turbines; and 6) landfill gas-fired boilers (boilers). A brief description of each follows:

*Candle Flares*: These are the simplest of flares akin to an open-flame Bunsen burner.

*Shrouded or Enclosed Flares*: This type of flare can come in different configurations depending upon the manufacturer or designer. What is common to all units is combustion of landfill gas at high temperature and residence time in an enclosed insulated environment. In the United States, shrouded flares consist mainly of an insulated cylindrical shroud in heights from 16 to 60 feet. Towards the base of this shroud is a burner assembly where landfill gas ignition takes place. Both primary and secondary combustion air are typically introduced through natural draft into the burner assembly. The method by which air is introduced into the burner assembly varies depending upon the designer. Combustion air is typically regulated by dampers to maintain a minimum stack discharge temperature. In Germany, several different designations are used for this type of combustion. First, is what the Germans describe as a "muffle" furnace. This is an enclosed chamber that affords a detention time for combustion and allows for post heat recovery. Other types of flares designated as normal-temperature and high-temperature are used. These are variations of the shrouded or enclosed flares. One reference reported here explores the impact of flare temperature on dioxin and furan emissions.[28]

*Internal Combustion I.C. Engine*: I.C. engines are use quite extensively for the management of landfill gas. It is estimated that 89 facilities currently operate over 300 I.C. engines in the United States.[23] I.C. engines are reported to be the most common energy recovery device in Germany.[24] Units in Germany, where reported, are MWM and MAN, all less than 1 MW. The engine reported in Canada is a Caterpillar, also less than 1 MW.

*Flares used as Engine Afterburners*: Many of the I.C. engines operated in Germany use high temperature flares as afterburners allowing the engines to operate at optimum combustion and efficiency which may result in higher emission levels. The afterburners reduce these potentially higher emission levels.

*Landfill Gas-Fired Turbine*: There are 24 landfills in the United States operating gas turbines; the literature contains data on two turbines fired by landfill gas, world-wide. The German facility is simple-cycle Kawasaki/MWM at 386 kW.[26] The second unit is located at an English facility; no information is provided on the type or make of unit.[34]

*Landfill Gas-Fired Boilers*: The literature contains data on four landfill gas-fired boiler facilities. Three of the facilities (multiple units) located in California are high temperature/pressure type feeding a steam turbine ranging in size from 9 to 50 MW.[38,39,40] Each facility uses state-of-the-art low $NO_x$ burners with flue gas recirculation for additional $NO_x$ control. Specific information is not available for the fourth unit in Germany.[26]

## RESULTS

A total of 22 references were evaluated for information related to dioxin and furan emissions.[24-45] Three were discovered to be presentations of the same data found in two other reports (Reference 27/29 and 25 present the same data as 28 and 24, respectively). Another report contains data for total dioxin and furan emissions, but not speciated data, so that I-TEQ could not be calculated.[45]

This report was not included in the database. An effort was made to report all other test data contained in the reports.

Data was divided into four groupings depending upon the number of data points; detected vs. non-detected data; and confidence in data or test methods.

**Combustion units with greater than three tests, and detected data**

The most abundant test data found in the literature search are for landfill gas-fired flares (shrouded and afterburners) and I.C. engines. Provided in Table 1 is a summary of emissions test and dioxin and furan test methods for combustion equipment with greater than three tests, and detected values. The report reference numbers and landfill codes presented in this table are used to support identification of the test data points in Figures 1 through 3. Table 2 provides an overview of the number of units/facilities and test data for combustion equipment with greater than three test, and detected data. Included in this table are descriptive statistics (range, mean and standard deviation) of the test data. It should be noted that statistics assume a normal distribution of the data; the test data is log normally distributed. Figures 1 through 3 show each test, for the respective combustion equipment, in relation to the comparative standard of 0.1 ng I-TEQ/$Nm^3$.

Shown in Figures 1 and 2, but not part of the descriptive statistics presented in Table 2, are the dioxin and furan emissions data for a flare and engine measured at 6,602 and 46,434 pg I-TEQ/$Nm^3$, respectively. There is no technical reason provided by the authors for these very high values (e.g., upsets or equipment breakdown). Based upon a second set of measurements which show very low concentrations, similar to all the other data collected in this study, the report concludes that these data points are “implausible”.[24] On this basis, these data points are treated as outliers in the review to follow.

*Flares (Shrouded)*: Of the 35 dioxin and furan emissions test data, two exceed the 0.1 comparative standard. The remaining data are all below this level, with 33 of the 35 below 28 pg I-TEQ/$Nm^3$.

As discussed, the first set of measurements from the flare reported in Reference No. 24, designated as test series No. 1, Landfill A, in Figure 1, had very high values. The second set of measurements resulted in low levels of dioxins and furans. The remaining measurements reported in this study show consistently low levels of dioxins and furans. All the flares in this study except for the units located at Landfill F are considered high temperature flares operating up to 1,200°C. The flare at Landfill F operated at 800 to 950°C, and the flare at Landfill A, where the high levels in the first measurement series were detected, was also operating in this temperature range; the flare was operated well above 1,000°C during the second set of measurements. The authors did not draw any correlation between the flare temperature and the high dioxin and furan levels. It should also be noted that this reference does not report where the temperature measurement was taken in the flare shroud.

The data series from Reference No. 28, shown in Figure 1, results from a study to examine the impact of flare combustion temperature on emissions. The flares located at Landfill D, in test No. 1, were operated at 1,000°C (note: this reference also does not specify where in the flare shroud the temperature measurement was taken). Dioxin and furan emissions in this test reached 156 pg I-TEQ/$Nm^3$. In a second set of measurements, the flare combustion temperature was adjusted to 1,200°C, which lowered the concentration of dioxins and furans considerably. The flare located at Landfill B was operated at 900 to 1,000°C, yet dioxin and furan concentrations were measure in the exhaust at very low levels. The flare located at Landfill C in this test series was operated at a combustion temperature of 1,200°C which also resulted in very low levels of dioxins and furans.

The flare test from Environment Canada (Reference No. 35) resulted in very low levels of dioxins and furans. Environment Canada deemed these results, in the test report, as "qualitative" because the testing was performed at a single point in the stack (a full traverse is required by the sampling methodology), and field blanks, also required, were not taken. The purpose of the test program was to screen for the presence of dioxins and furans, and if found, a magnitude estimate of the levels. Based upon this information, the agency would decide if further studies were needed.

Duplicate flare tests for dioxins and furans were conducted at the County Sanitation Districts of Los Angeles County's Palos Verdes Landfill (Reference No. 37). This site is an inactive hazardous waste/MSW landfill that ceased operation in 1980. The levels measured in this test are below the comparative standard.

*I.C. Engines*: Of the 36 dioxin and furan emissions test, one data point exceeded the comparative standard. This was part of the test series (Reference No. 24) that has been discussed previously. The remaining test measured dioxins and furans at levels below 74 pg I-TEQ/$Nm^3$, with 29 of the 36 data points below 30 pg I-TEQ/$Nm^3$. Except for the first three data points from the first test series, all levels in this test series were very low.

The remaining data from the other test series are variable, but generally low.

*Flare (Afterburner)*: The flare units that operated as afterburners for I.C. engine exhaust all generated very low levels of dioxins and furans; with a mean value of 3.10 pg I-TEQ/$Nm^3$. The six reported data points result from three duplicate tests, all from the same test series (Reference No. 28).

**Combustion units with three or less tests, and detected data**

Presented in Table 3 are the dioxin and furan emission data for combustion units with three or less tests, and detected 2,3,7,8 substituted congeners. In this category are two flares (candle), one boiler and 2 turbines. In general, it is difficult to draw conclusions on these few data points. The high concentration of dioxins and furans measured for the candle flare is from a test study where it is not clear if the testing methodologies followed a standard method.[23] Furthermore, sampling emissions from a candle flare, which has an open flame, is difficult; no standard methods exist for this type of test. The second test of a candle flare was performed by Environment Canada.[36] As discussed, the test program was designed to produce qualitative results.

The two turbine tests produced dramatically different data. One would expect that the turbines, if generating dioxin and furan emission at all, would produce low-level emissions. The values of the first test, 7.5 and 9.3 pg I-TEQ/$Nm^3$, support this notion.[26] The single data point generated in the second test program seems implausible based upon the very low CO reading during the test of 7.3 ppm, which indicates complete combustion was taking place.[34] This reference does not describe the test methodology but references other reports for the test methods; therefore, these methods were not reviewed. Furthermore, an examination of the dioxin and furan emissions results from other test units also reported in this study shows that the test protocol achieved only very high detection limits (greater than 400 pg I-TEQ/$Nm^3$). This gives an indication of possible problems with the testing.

**Combustion units for which no dioxin and furan emissions are detected**

Table 4 contains test data for combustion units found in the literature review where no dioxin and furan emissions are detected. In this category are three boilers and two I.C. engines. The three boilers are operated by the County Sanitation Districts of Los Angeles County, and are considered state-of-the-art for this type of application.[38,39,40] The lowest detection limit achieved in these tests were 22 pg I-TEQ/Nm$^3$. It should be noted that these test reports contain complete data on QA/QC procedures as well as all calculation and raw data sheets, and as such, should be considered as data suitable for supporting regulatory decisions.

Dioxin and furan emissions could not be detected at two facilities operating landfill gas-fired I.C. engines.[24] The detection limits reported for both facilities are less than 1 pg I-TEQ/Nm$^3$.

Not included in the database are four reports of testing conducted by the California Air Resources Board at four landfill combustion units; one each of a flare (shrouded), boiler, turbine and I.C. engine.[41,42,43,44] Part of the goal of this series of tests was to further test method development, with a goal to standardize a dioxin and furan test method. No dioxin and furan emissions were detected in any of these tests, however, the detection limits of all the tests were extremely high.

**Manufacturers flare (shrouded) emissions data**

The literature search found two dioxin and furan emissions test reports for flares (shrouded) that are manufactured by German firms.[30,31] The data is not included in the main database because no details were offered as to the test parameters or methodologies; however, the result are in general agreement with the data shown in Figure 1.

## CONCLUSIONS

In all, 22 references were reviewed for dioxin and furan emissions data from the combustion of landfill gas. Several major reports were part of this reference series covering many types of landfill gas-fired combustion units. The most abundant test data were for flares (shrouded and afterburners) and I.C. engines. Lesser amounts of test data were found for landfill gas-fired candle flares, boilers and turbines. The majority of the test data were from Europe, primarily Germany. Because of limitations in obtaining actual test reports complete with lab data and QA/QC results, and a lack of knowledge as to the exact types of waste received at most of the European landfills, the test data from these sources, for the purposes of this paper, are considered qualitative. This in no way indicates that the data is not “good” data. To the contrary, much of the studies uncovered in the literature search appear to be very comprehensive. Many of these studies were commissioned by the German Federal Government or individual states within Germany.

The purpose of this paper was to provide a review of the available data on dioxin and furan emissions from landfill gas-fired combustion systems. Except for some outliers, the data indicates a potential for dioxin and furan emissions from landfill gas-fired combustion units, but at very low levels, below the most stringent standards for dioxin and furan emissions (standards for waste incineration). Two reports provide conclusions that should be noted here (note: quotes to follow are translations).

- A study commissioned by the German Environment Office concluded, “*The results show that PCDD/F (I-TEQ)(dioxins and furans), if detected at all, lie in the range of traces, while the concentrations found in flue gas ranged from 0.06 to 75.3 pg I-TEQ/Nm$^3$ with the majority of values clearly below the limit of the 17$^{th}$ BlmSchv of 100 pg I-TEQ/Nm$^3$.*[26]

- A study commissioned by the Bavarian Agency for Environmental Protection concluded,*"No concentrations of dioxin worth mentioning could be found in the exhaust gas of flares and recovery plants. All measured concentrations lay clearly below the actual emission limit for incineration plants of the $17^{th}$ BlmSchv of 100 pg I-TEQ/$Nm^3$"*.[24]
- The same study concludes, "*On the basis of the values that were found, a determination of dioxins and furans for the flares and utilization plants does not seem necessary. If the adjustments of the facilities are optimized on the basis of CO measurements, no relevant concentrations of dioxins and furans should be anticipated*." Also, with regard to toxicological relevance, it is concluded, "*In view of the expected dilutions, the toxicological relevance of dioxins and furans has to be ruled out.*"

Other researchers have also come to these general conclusions.[46,47]

The conclusions of these reports are important, not only because the data was so extensive and covered a wide variety of combustion sources, but because these reports help shape German policy on the treatment of landfill gas-fired combustion systems.

Although not explored in this paper, it is recommended that further work examining how accurate data is when detected down to the single digit, or fraction of a pg. This is the concentration at which much of the data is reported in this review. Analytical techniques can measure dioxins and furans down to the fentogram range, but do real world conditions allow these very low concentrations to be achieved?

In summary, the available test data on dioxin and furan emissions from landfill gas-fired combustion units indicates that the potential exists for emissions of these compounds, but for well operated combustion systems, dioxin and furan emissions are at very low levels.

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## TABLES

**Table 1**. Summary of emissions test and dioxin and furan test methods for combustion equipment with greater than three test, and detected values.

| Reference No. | Combustion Equipment Type | Landfill Code | Test Methods |
|---|---|---|---|
| 24 | Flare (shroud) | A, B, D, E, F | VDI-3499/3 |
| 28 | Flare (shroud) | B, C, D | VDI-3499/? |
| 35 | Flare (shroud) | None | Canadian |
| 37 | Flare (shroud) | None | CARB-428 |
| 26 | I.C. Engine | 1, 2, 3, 6, 7 | VDI-3499/2 |
| 24 | I.C. Engine | A, B, D, F | VDI-3499/3 |
| 32 | I.C. Engine | None | VDI-3499/2 |
| 28 | I.C. Engine | A, B, D, E | VDI-3499/? |
| 33 | I.C. Engine | None | Not Specified |
| 35 | I.C. Engine | None | Canadian |
| 28 | Flare (afterburner) | B, D | VDI-3499? |

**Table 2**. Dioxin/furan emissions summary for combustion equipment with greater than three tests, and detected values (concentration in pg I-TEQ/Nm$^3$ @ 11% $O_2$).

| Combustion Equipment | No. of Units/Facilities | No. of Tests | Concentration Range (Mean - Std Dev.) |
|---|---|---|---|
| Flare (shrouded) | 11 | 35 | 0.22 to 156<br>(13.6 – 33.0) |
| I.C. Engine | 16 | 36 | 0.04 to 318<br>(19.6 – 54.5) |
| Flare (afterburner) | 3 | 6 | 0.28 to 6.67<br>(3.10 – 2.44) |

**Table 3.** Dioxin/furan emissions summary for combustion equipment with three or less tests, and detected values (concentrations in pg I-TEQ/Nm$^3$ @ 11% $O_2$).

| Combustion Equipment | No. of Units/Facilities | Concentrations[Ref] (test methods) |
|---|---|---|
| Flare (candle) | 2 | 155[33], 1.86[36]<br>(not specified, Canadian) |
| Boiler | 1 | 0.04[26]<br>(VDI-3499/2) |
| Turbine | 2 | 7.5 & 9.3[26], 1830[34]<br>(VDI-3499/2, not specified) |

**Table 4.** Dioxin/furan emissions summary for combustion equipment with test containing no detections (detection levels in pg I-TEQ/Nm$^3$ @ 11 % $O_2$).

| Combustion Equipment | No. of Units/Facilities | No. of Tests | Avg. Detection Levels[Ref] (test methods) |
|---|---|---|---|
| Boiler | 3 | 8 | <51[38], <25[39], < 27[40]<br>(CARB-428, CARB-428, Mod. Meth. 5) |
| I.C. Engine | 2 | 6 | <1 & <1[24]<br>(VDI-3499/3) |

## FIGURES

**Figure 1.** Flare (shrouded) dioxin and furan emissions (tests with detections).

**Figure 2.** I.C. engine dioxin and furan emissions (tests with detections).

**Figure 3.** Flare (afterburner) dioxin and furan emissions (tests with detections).