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Assessment of off-normal emissions from hazardous waste incinerators
Part 1. Assessment of off-normal emission frequency and duration

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Abstract

This is the first of two papers which report the results of a study of off-normal emissions from operation of a liquid injection hazardous waste incinerator. Reported in this paper are the results of off-normal emission frequency and duration assessment using probabilistic methods. The emissions from the incinerator are grouped into three categories: principal organic hazardous constituents (POHCs), particulates, and acid gases. The Integrated Reliability and Risk Analysis System (IRRAS) software is used for fault tree quantification and uncertainty analysis. The mean off-normal emission frequencies of each category are assessed as 0.24, 0.15 and 0.85 times per year for POHCs, particulates and acid gases respectively, and off-normal durations are modeled as log-normally distributed. The results of off-normal emission intensity and total off-normal emissions are reported in the second paper.

1. Introduction

A big challenge facing modern society today is how to dispose of the large amount of hazardous wastes that are produced every year. As living standards increase, the quantity of wastes also increases; however, the ability of the land, water and air to absorb the wastes is not unlimited. The past hazardous waste disposal practice, frequently by open dumping or uncontrolled burning, has poisoned many rivers, darkened skies and made wastelands. In recent years, incineration has received more and more attention as a viable solution to many hazardous waste problems. Incineration is attractive because it has several merits, which the existing disposal techniques such as landfilling, ocean dumping, and deep-well injection do not have.

In order to protect human health and the environment, hazardous waste incinerators have been regulated since the passage of the Resource Conservation and Recovery Act of 1976 (RCRA). The technical standards for hazardous waste incinerators are listed in the Code of Federal Regulation (CFR)

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under 40 CFR 264.343. These performance standards require that incineration facilities must show that they can attain the following three performance levels:
(1) They must achieve a destruction and removal efficiency (DRE) of 99.99% (four nines) for each principal organic hazardous constituent (POHC) in the waste feed. For certain types of wastes like PCBs, 99.9999% (six nines) of DRE is required. DRE is defined as:

$$DRE=\frac{(W_{\text{in}}-W_{\text{out}})}{W_{\text{in}}}\times 100 \tag{1}$$

where W_{in} is the mass feed rate of the POHC in waste stream fed to the incinerator, and W_{out} is the mass emission rate of the POHC in the stack prior to release to the atmosphere.
(2) They must either achieve a 99% HCl removal efficiency or emit less than 1.8 kg/h of HCl, whichever is smaller.
(3) They must not emit particulate matter in excess of 180 mg/standard m^3 corrected to 7% oxygen in the stack gas. The measured particulate matter concentration is multiplied by the following correction factor (CF) to obtain the corrected particulate matter emissions:

$$CF=14/(21-Y) \tag{2}$$

where Y is the measured oxygen concentration (in percentage) in the stack gas on a dry basis.

There are several problems associated with compliance with the requirements. First of all, although very expensive trial burns, costing between $50,000 to $500,000 and taking about 30 to 60 days before the final results are known, are usually conducted once a year or once every two years to assure that an incinerator can meet government regulations, the current technology does not make it possible either technically or economically to monitor these performance standards continuously. The trial burns only reveal information on how well the incinerator was operating during the trial burn. It is not known how incinerator performance might fluctuate with future changes in operating conditions or feed characteristics. Furthermore, trial burns do not provide the instantaneous information about incinerator performance, which could enable the operator to take action to prevent a deterioration in this respect. Therefore, there is a possibility that the performance standards are not being met on a continuing basis. As a U.S. EPA official pointed out, "We found evidence that performance standards are not being met in some cases, but we don't know the frequency" [1], and Oppelt [2] noted, that "uncertainty and distrust may exist regarding the reliability of thermal destruction systems in day-to-day operation after a permit is approved and when regulators are not present. Little is known quantitatively about the impact of normal process upsets or failure modes upon emissions. This is often a concern of the public in hearings on permit actions". Currently, both performance indicators, like carbon monoxide (CO) and total unburned hydrocarbons (TUHC), and surrogates, like various freons and sulfur hexafluoride (SF_6), are used to assure the performance of hazardous waste incinerators. However, the effectiveness of both approaches is still a debated issue within the technical community.

Another problem is that the products of incomplete combustion (PICs) resulting from hazardous waste incineration are not regulated. It has been found that some PICs are more toxic than the original POHCs, such as dioxins and furans which have been found in some stack emissions. It is possible that an incinerator meets all of the federal performance standards, but releases a fair amount of PICs.

Up to now, some risk assessment work for hazardous waste incineration has been done. The source term used in those risk assessments has been based on the limited measurements made during trial burning tests under steady operation conditions at other existing incinerators, or emission rates corresponding to the federal regulations mentioned previously. Emissions resulting from off-design conditions are usually not considered; as Kelly [3] indicated, one of the assumptions used was that "emission rates are constant and continuous for a facility running under normal operation conditions... . The probabilities of accidents occurring or the emission resulting from non-routine events are not considered ... . These are important conditions which must be considered in producing a comprehensive assessment of all risks posed by such a facility."

From the above discussion, it is clear that there is a need to study the reliability of incineration systems and the emissions associated with incinerator off-normal or upset conditions. Many researchers have realized the importance of such studies. Dellinger et al. [4] pointed out that "Excursions, or fault modes, are probably the controlling phenomena for incineration efficiency", and "Laboratory studies have shown that relatively small excursions from ideality for these parameters can easily drop measured flame destruction efficiency from greater than 99.99% to 90% or even less than 90% (three orders of magnitude)... . The key to understand the significance of upset conditions is that only a very small fraction of total volume of the waste needs to experience these less optimum conditions to result in significant deviations from the targeted destruction efficiency."

The project entails the development and application of a probabilistic methodology for prediction of the frequency, quantity and kind of emissions from hazardous waste incinerators due to system transients, malfunctioning, or failures, as well as for identification of the major contributors to system upsets. This paper only reports the results of off-normal emission frequency assessment; off-normal emission intensities and total off-normal emissions will be reported in the second paper of the series.

2. Methodology

The basic methodology used in the study for off-normal emission frequency assessment is the fault tree technique, which has been widely applied in nuclear engineering, aerospace engineering and other industries. Fault tree analysis is a systematic procedure used to identify the various combinations and sequences of component failures and human errors that lead to system failure. A system fault tree is a graphical representation of a logic model that depicts the component failure modes and other faults that can, through AND and OR combination logic, produce system failure. It can be readily converted to a probabilistic model of the system – a model to which individual component failure probabilities can be assigned and combined to obtain system failure probabilities. The result of fault tree quantification is of real interest to system analysts since it can provide both the system failure probability and the dominant contributors to system failure (More details on the method can be found in [5–7]).

There are hundreds or even thousands of types of pollutants emitted from an incinerator stack. Obviously, it is impractical and impossible to trace each of the pollutants. To make this study manageable, the emissions from the incinerator are grouped into three categories: principal organic hazardous constituents (POHCs), particulates, and acid gases. The pollutants within each category are assumed to have similar formation and release mechanisms. Since the mechanism of PIC formation and release is still not well understood, it is not included in this study for the time being.

The system failure referred to in this study is off-normal emission from the incinerator. Off-normal emissions are defined herein as those events in which incinerator emissions do not meet the federal regulations. As mentioned in Section 1, the current federal regulations require 99.99% of destruction and removal efficiency (DRE) for each POHC (for some POHCs, 99.9999% of DRE required); particulate emission not more than 180 mg/m^3 corrected to 7% oxygen in the stack gas; and HCl emission not more than 1.8 kg/h or 99% HCl removal efficiency.

The general approaches to off-normal emission frequency assessment are summarized in the following:

(1) collect and study incinerator design and operation information;
(2) identify the major failure modes;
(3) develop fault trees for each emission category;
(4) collect failure data;
(5) quantify fault trees and analyze uncertainties.

The majority of hazardous wastes generated by industry are liquid. Since hazardous liquid wastes are prohibited from land disposal by federal laws, incineration has become a very important option for hazardous liquid waste disposal. In fact, the liquid injection type incinerator is the most commonly used incinerator for hazardous waste disposal in the United States now. Because of this reason, a liquid injection incinerator was chosen for this particular study.

3. Off-normal emission frequency assessment

3.1 Facility description

Figure 1 is a simplified diagram of the liquid injection incinerator under study; namely, the incinerator includes the following major components:

(1) waste burner system and auxiliary system;
(2) air supply system;
(3) combustion chamber;
(4) heat recovery system (boiler);
(5) air pollution control device system (including a quench/absorber and a two-stage ionizing wet scrubber).

Organic compounds are destroyed in the combustion chamber under the high temperature environment. Liquid wastes are fed and atomized into the combustion chamber through the burner nozzle. Having a large surface area, the atomized droplets vaporize quickly, forming a highly combustible mix of waste fumes and combustion air, which ignites and is combusted as it proceeds through the combustion chamber.

The flue gases exiting from the combustion chamber go through a boiler to produce steam for generating electricity so that some energy can be recovered. The function of the quench/absorber following the boiler is to reduce the temperature of the flue gases and to remove some of the acid gases and particles.

This incinerator is designed for handling wastes that contain heavy metals and have high ash and chlorine contents so that a two-stage ionizing wet scrubber (IWS) system is chosen. The IWS system is particularly good for fine particle removal, according to many experts. Caustic solution is added to the scrubbing liquid for acid gas removal. The major portion of particles and acid gases is removed in the IWS system.

The flue gas exits the ionizing wet scrubber to the induced draft fan (ID fan) which pulls a negative pressure on the entire incinerator system. The treated flue gas then exits to the atmosphere through the vent stack.

The incinerator system is equipped with automatic controls and instrumen-

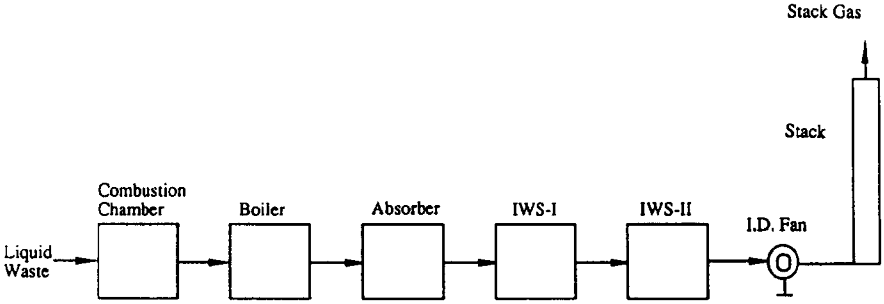

Fig. 1. Simplified diagram of the liquid injection incinerator.

tation to ensure safe operation. The details of the incinerator can be found in [8].

3.2 Failure modes considered

The present study focuses on the combustion chamber and the air pollution control devices as the most likely contributors to the system failures. Only the emissions from the stack are considered, i.e., emissions from transporting, storing and handling are not included in the analysis although they could be important for a more complete study.

The fault tree technique is used for assessing the off-normal emission frequency. The first step for fault tree development is to identify the failure modes that can cause off-normal emissions for each category. The failure modes considered in the study are summarized below:

3.2.1 POHC failure modes

Destruction of POHCs is the primary objective of incineration. In this study, no credit is given to air pollution control devices for POHC removal since the primary function of the air pollution control devices is not POHC removal, and also there is no strong evidence to show that the air pollution control devices can very effectively remove POHCs in flue gas.

Thermodynamic theory indicates that the level of organic destruction depends on the excess air level and the three T's: temperature, turbulence and residence time in combustion chamber. Because it is difficult to define the degree of turbulence, it is not considered explicitly. Atomization is included in the analysis since experimental results have shown that atomization has a direct impact on destruction efficiency [9]. Not only low excess air, which causes low destruction efficiency, is considered, but also high excess air is included, since high excess air can cause low destruction efficiency as well, according to [10] and [11]. In summary, low temperature, poor atomization, low excess air and high excess air are the failure modes that are considered for off-normal POHC emissions in the analysis.

3.2.2 Particulate failure modes

Particulates are removed by the IWS system. The two major mechanisms for particulate removal in the IWS system are electrostatic force attraction (image force attraction) and inertial impaction. When the charging voltage at the ionizing section is too low, the effect of the image force attraction will be decreased. On the other hand, if the flow rate of the scrubbing liquid going through the packing materials is too low, the effect of inertial impaction will be decreased also. Besides, the particulate removal efficiency is dependent upon the particle size distribution. The smaller the particle, the lower the removal efficiency is. According to reference [12], when the combustion temperature is very high, which is desirable for organic compound destruction, the high temperature would shift the particle size distribution to the smaller end and more heavy metals would be vaporized and then condensed into fine particles. In other words, increasing combustion temperature would increase heavy metal emissions, which have been identified as the major contributors to the inhalation risks. Since the combustion process does not destroy metals, excessively high heavy metal content in feed may also cause high metal emissions. So this factor, low charging voltage, low scrubbing liquid flow rate, high combustion temperature and high metal content in feed are considered for off-normal particulate emissions.

3.2.3 Acid gas failure modes

Acid gases are removed by the principles of mass transfer whereby acid gaseous molecules from the air stream are transferred to the scrubbing liquid. Transfer is achieved by a combination of chemical reaction and diffusion, and physical absorption. By adding caustic solution (NaOH) into the scrubbing liquid, acid compounds are neutralized when flue gases go through the IWS system. The possible causes of off-normal acid gas emissions should include improper supply of caustic solution (i.e., improper pH value in the scrubbing liquid), low scrubbing liquid flow rate, and possible excessively high acid content in feed (exceeding the IWS system's capacity for acid gas removal).

3.3 Fault tree quantification

Fault trees are developed to the component failure level, e.g., failure of sensors, valves, etc., for each emission category, based on the information available. Because of page limitations, it is not feasible to present the full fault tree here, but it can be found in reference [13].

Strictly speaking, the failure data for fault tree quantification should be obtained from the past collection of hazardous waste incinerator operation. However, a literature review indicates clearly that there is a lack of failure data for hazardous waste incinerators or similar systems, since incineration is relatively new, and almost no reliability data, either plant-specific data or generic data, has been collected for incineration systems. As a result, the failure data in this analysis are taken from several generic data sources [14–17], including data from nuclear engineering and petrochemical engineering. This approach is based on the similarity of functions provided by, and service conditions experienced by, those components in various process applications. It should be mentioned that some data are not directly available. Input from incinerator operators, designers and other experts, as well as engineering judgement, are used in obtaining the required data.

To quantify the off-normal emission probability per year, the number of hours of operation per year should be determined since most of the basic data are given in the form of failures per hour. For liquid injection incinerators, many existing plants have about 90% of operation per year; therefore, a 90%

availability ($365 \times 0.90 \times 24 = 7880$ hours operation per year) is used. Some components are maintained regularly. To compute the failure probabilities of those components with regular maintenance, the maintenance interval is assumed according to the information available. After maintenance, a component is assumed to be renewed.

A number of studies have shown that in complex man-machine systems, human error has often been the overriding contribution to actual or potential system failures. The hazardous waste incinerator is not an exception to this general finding. In this study, some human errors are included although not in a complete fashion. The primary reason is due to the fact that the state-of-the-art in human reliability analysis is still in an early stage of development. Human error may still be the most difficult one to quantify because of the variability of human performance. The major types of human errors included in this analysis are mistakes in setting values, maintenance errors for some components, inspection errors for waste composition, and operator mistakes.

The software, Integrated Reliability and Risk Assessment System (IRRAS), version 1, developed by Idaho National Engineering Laboratory and sponsored by U.S. Nuclear Regulatory Commission [18], is used for the fault tree analysis. This program is capable of generating minimum cut sets, and performing point estimate and uncertainty analysis. Since it is a mouse-driven program, it is very user-friendly.

The probabilities of off-normal emissions per year for each emission category can be obtained by using the IRRAS program. As mentioned earlier, the objective in this paper is to assess the off-normal emission frequency of the incinerator. The frequency can be found from knowledge of the probability per year. If the frequency is assumed to be constant, the off-normal emission probability per year is obtained from:

$$p = 1 - e^{-\lambda t} \tag{3}$$

where p is off-normal emission probability per year; λ the off-normal emission frequency; and t the operation time (one year).

Equation (3) can be rewritten as:

$$\lambda = -\frac{1}{t} \ln(1-p) \tag{4}$$

The off-normal emission frequencies based on eqn. (4) are summarized in Table 1. It is interesting to note that Sloane and Sherbine [19] and many other safety studies, including the comprehensive nuclear power plant safety study WASH-1400 [20], treated the probability per year as the frequency, which is true only when the probability p in eqn. (4) is very small.

The minimum cut sets generated by the IRRAS program make it very easy to identify the major contributors to a top event (the complete minimum cut sets can be found in [13]). For instance, oxygen analyser drifting, thermocouples

TABLE 1

Summary of off-normal emission frequency (times/year)

Category	f_5	$\bar{f}$	f_{95}
POHC	0.10	0.24	0.61
Particle	0.09	0.15	0.24
Acid	0.37	0.85	2.64

drifting, pH analyser drifting, etc., are among the major contributors to off-normal emissions. It is found that most of the important minimum cut sets contain only one basic event. This is because the probability of the minimum cut sets which contain two or more basic events is small and those minimum cut sets can not be the major contributors. Another reason is due partly to the fact that many design features of the incineration facility are not redundant.

Minimum cut sets provide very important information that can be used to improve the performance of incinerator operation. Resources should be used for the major contributors to off-normal emissions first so that the maximum improvement can be achieved with the lowest expense. For example, the current design uses only one automatic pH analyser to monitor the pH value for acid gas emission control. The minimum cut sets for acid gas emission indicate that pH analyser failure is primarily responsible for off-normal acid gas emission. Therefore, more attention should be paid to the inspection and maintenance of the pH analyser. Also, redundancy or other methods (such as using an additional, different method for acid gas emission monitoring) could be used to change the current design to increase the reliability of acid gas emission monitoring.

3.4 Uncertainty analysis

Uncertainty analysis is an integral part of any probabilistic risk assessment (PRA) studies. There are uncertainties in every step of a PRA, and they are inherent and not avoidable. The uncertainties that arise in PRA can be classified as parameter uncertainty (arising from the need to estimate parameter values from incomplete or biased data), model uncertainty (due to inadequacies in the various models used in the analysis), and completeness uncertainties (related to the inability of analysts to evaluate exhaustively all contributions to the undesired events). To date, most PRAs have given attention to parameter uncertainties because parameter uncertainties can be treated straighforwardly using the Bayesian or other approaches. A quantitative treatment to model uncertainties or completeness uncertainties is still in its infancy. In the present study, only parameter uncertainties are treated thoroughly.

Parameter uncertainty analysis is conducted using the IRRAS program. The top event uncertainty is calculated using a Monte Carlo simulation method in the program through uncertainty propagation. To use the IRRAS program for parameter uncertainty analysis, two parameters for each basic event in a fault tree are required: mean value and error factor (*EF*) of the failure rate. All of the failure rates are assumed to be lognormally distributed. There are two major reasons that a lognormal distribution is assumed. First of all, many failure data may vary by several orders of magnitude. A lognormal distribution may be the best distribution to handle this kind of situation; also it has been widely used in nuclear engineering safety studies. The second reason is that, currently, IRRAS version 1 has only the log-normal distribution option for uncertainty analysis. The error factor which is needed for uncertainty analysis is determined by:

$$EF=\sqrt{\lambda_u/\lambda_l} \tag{5}$$

where λ_u is the upper limit failure rate in the data source, and is regarded as the 95th percentile; λ_l is the lower limit failure rate in the data source, and is regarded as the 5th percentile. For example, from IEEE Std-500, p. 551, one can find $\lambda_u = 8.4$, and $\lambda_l = 0.86$ failures per 10^6 hours for a pressure transmitter; then the error factor for the pressure transmitter is

$$EF=\sqrt{8.4/0.68}=3.5$$

Engineering judgement or expert opinion is used when information for *EF* is not available. Table 2 is an example of the uncertainty analysis results for off-normal POHC emission probability. Table 1 summarizes the results of off-normal emission frequency for the three emission categories.

The uncertainty analysis using the IRRAS program can not only give the bounds of a distribution, but also provide the whole probability distribution of a top event of interest, as shown in Table 2. The off-normal emission frequency presented in Table 1 only gives the total off-normal emission frequency for each emission category. For the purpose of estimating off-normal emissions, it is necessary to know the frequency of the events occurring that lead to the failure modes identified previously, since different failure modes and scenarios may have different emission intensity and duration. For this reason, the cumulative probability distribution of unnoticed low combustion temperature, unnoticed low excess air, etc., are calculated using the IRRAS program, and an example is presented in Table 3. The reason that only the unnoticed scenarios are considered is because drifting type failures may not be detected for a relatively long period of time. By contrast, for gross type failures (noticed failures), such as loss of I.D. fan, automatic shutdown of the feed system will occur or the operator can terminate the waste feed almost immediately. The residence time of liquid waste which has already entered the combustion chamber is only on the order of seconds. Hence, the off-normal emissions due to gross type failures should be small.

TABLE 2

Uncertainty analysis[a] of off-normal POHC emission probability

Distribution quantile level (%)	95% Confidence interval on quantile level (% ±)	Quantile value	95% Confidence interval on quantile	
			Lower bound	Upper bound
0.5	0.5	6.0557E-2	4.8376E-2	6.7215E-2
1.0	0.7	6.7984E-2	5.9775E-2	7.3817E-2
2.5	1.0	7.7803E-2	7.3228E-2	8.0149E-2
5.0	1.4	8.4645E-2	8.0745E-2	8.6880E-2
10.0	1.9	9.4845E-2	8.9907E-2	9.9754E-2
20.0	2.5	1.1133E-1	1.0812E-1	1.1490E-1
25.0	2.7	1.1961E-1	1.1487E-1	1.2335E-1
30.0	2.9	1.2760E-1	1.2262E-1	1.3141E-1
40.0	3.1	1.4500E-1	1.3891E-1	1.4951E-1
50.0	3.1	1.6114E-1	1.5476E-1	1.6940E-1
60.0	3.1	1.8164E-1	1.7833E-1	1.8942E-1
70.0	2.9	2.1116E-1	2.0283E-1	2.2092E-1
75.0	2.7	2.2861E-1	2.1932E-1	2.3873E-1
80.0	2.5	2.5202E-1	2.3811E-1	2.6970E-1
90.0	1.9	3.2688E-1	3.0442E-1	3.4408E-1
95.0	1.4	4.2289E-1	3.7863E-1	4.6109E-1

[a] A Monte Carlo procedure for determining the distribution and simulation limits was used.
Parameters used:
Random seed = 3571
Sample size = 1000
Number of events = 222
Number of cut sets = 335
Point estimate value = 1.9547E-1
5th Percentile value = 8.4645E-2
Median value = 1.6114E-1
Mean value = 1.9518E-1
95th Percentile value = 4.2289E-1
Minimum sample value = 4.8376E-2
Maximum sample value = 1.2360E+0
Standard deviation = 1.2518E-1
Coefficient of skewness = 3.3420E+0
Coefficient of kurtosis = 2.1447E+1

TABLE 3

Cumulative probability distribution of unnoticed low temperature

Quantile level	0.05	0.30	0.50	0.70	0.95
Quantile value	0.015	0.025	0.032	0.041	0.086

4. Off-normal duration modeling

To assess total off-normal emissions, one has to know how long a fault status may last, once it occurs. Obviously, for a given failure mode, off-normal durations depend on many factors, and may vary from plant to plant, from scenario to scenario. Since there are too many events and their combinations (minimum cutsets) that may lead to a given failure mode, it is not feasible to treat off-normal duration on an event by event basis. Instead, off-normal duration is modeled as lognormally distributed for each failure mode to cover the large variation of off-normal durations. The parameters of off-normal duration distributions for each failure mode are determined as follows:

4.1 POHC category

4.1.1 Unnoticed low temperature

For the temperature drifting case, it is assumed that only temperature calibration could find the fault situations. According to this assumption, the off-normal emission duration is determined by the frequency of the temperature calibration. It should be mentioned that, based on this assumption, the effect of CO monitoring has not been given credit. The reasons are: (1) The effectiveness of CO monitoring is still a debated issue within the technical community [11], and [21]. In other words, it is still not clear whether or how the CO level is correlated with DRE level. (2) The CO level for waste shutdown varies greatly from plant to plant (values ranging from 100 ppm to 2800 ppm have been used). Again, this raises a question concerning the effectiveness of CO monitoring. Calibration frequency for temperature measurement varies from plant to plant, ranging from once every day to once every month. A mean value of 7 days and an error factor of 5 are assumed, because bi-weekly calibration is used in a few facilities. Using these assumptions, the distribution of the off-normal duration D due to temperature drifting is:

$$D = \Lambda(\mu = 4.465, \sigma = 0.9784)$$

where $\Lambda(\mu,\sigma)$ represents a lognormal distribution with parameters μ and σ.

4.1.2 Unnoticed low excess air

In the fault tree development for low excess air, it has been assumed that low excess air is always accompanied by high CO concentration. Therefore, unnoticed low excess air operation requires that low excess air and CO monitor "drifting" occur at the same time. In this situation, the off-normal duration is very much determined by the length of unnoticed high CO concentration, which includes CO analyser drifting and other scenarios that make high CO concentration go unnoticed. This is because excess air is not a waste feed shutdown parameter for the liquid injection incinerator; the operator would pay less attention to it, as indicated by an operator in an interview. In some cases, even if the operator has noticed a low excess air situation, as long as the CO level has not reached the shutdown value, he might not take any action. In fact, many incinerator operators like to keep a low excess air as possible to save fuel and power. A good example is the incinerator that is often running at 1.5% of the excess air, which is not very common for hazardous waste incinerator operation. On the other hand, CO is a waste shutdown parameter, and any unreasonable CO concentration will force the operator to take corrective action or to cut off waste feed. Hence, it is reasonable to assume that the duration of low excess air is determined by the duration of unnoticed high CO concentration. A high CO level may not be detected due to: (1) CO analyser drifting; (2) a large amount of air leaking into the system between the combustor and the stack. The incidence of CO analyser drifting has been found for a few facilities. The calibration frequency for CO analyser is about once every two weeks. The duration of air leaking into the system can be short or long, depending on the inspection frequency, the experience of the operator, etc. Considering these factors, it is assumed that the mean of the low excess air operation is one week (168 hours) with an error factor of 10, i.e.:

$$D=\Lambda(\mu=4.144,\sigma=1.40)$$

4.1.3 Unnoticed high excess air

High excess air is neither a waste shutdown parameter nor a warning parameter for the incinerator as long as the flue gas flow rate does not reach the limit. In other words, if it occurs, probably the operator may not care about it too much. According to Staley [11], under high excess air conditions, CO level does not necessarily go up as high as the case for low excess air, and "under high excess air conditions, large volumes of POHCs and PICs can be emitted over long periods of time resulting in a worse air pollution problem than a momentary upset like a flameout". Therefore, it is anticipated that the off-normal duration under high excess air condition would be longer than that of low excess air. The mean of the high excess air duration is assumed to be two weeks, and an error factor of 10. Namely, the parameters of off-normal duration are:

$$D=\Lambda(\mu=4.837,\sigma=1.40)$$

4.1.4 Unnoticed poor atomization

The duration of poor atomization may depend on the cause of poor atomization, i.e., low atomization pressure, nozzle worn or plugged, improper nozzle alignment, or liquid high viscosity, etc. If poor atomization is caused by a nozzle problem, for example, the duration may depend on the frequency of nozzle inspection if no credit is given to CO monitoring as discussed previously. If poor atomization is caused by other reasons, the duration may be different. Because of a lack of actual data, and from the minimum cut set information, it seems that it is more likely that poor atomization is caused by nozzle problems; the duration between nozzle inspections will be assumed as the mean duration of poor atomization. Nozzle inspection frequency ranges from every work shift (every 8 hours) to weekly, but daily inspection is quite common. Therefore, the mean duration is assumed to be 1 day. Since the variation of inspection frequency and uncertainty are large, an error factor of 10 is also assumed. The parameters of the off-normal duration are:

$$D=\Lambda(\mu=2.198,\sigma=1.40)$$

4.2 Particulate category

4.2.1 Unnoticed low charging voltage in IWS

The off-normal duration for unnoticed low charging voltage operation will very much depend on the frequency of voltmeter calibration if the low voltage is caused by voltmeter drifting. Since the voltmeter is a relatively reliable instrument, monthly or longer calibration is likely. The operating experience on IWS was very limited. Therefore, the mean duration of the unnoticed low voltage operation is assumed to be 1 month with an error factor of 10. The parameters of the duration can be obtained as:

$$D=\Lambda(\mu=5.599,\sigma=1.40)$$

4.2.2 Unnoticed low scrubbing liquid flow rate

The actual data of off-normal duration for this type failure is not available. The instrument calibration frequency, which is about once a month in some plant, is used as the mean duration. The error factor is assumed to be 5. The parameters of the duration are:

$$D=\Lambda(\mu=6.101,\sigma=0.9784)$$

4.2.3 Unnoticed high temperature

Since higher temperature is good for POHC destruction, as long as it has not reached the upper limit, probably the operator might not take action immediately even if a higher temperature is noticed. For this reason, the duration for high temperature operation could be longer than that of low temperature operation. Therefore, a mean of two weeks (14 days) with an error factor of 5 are used. The distribution of the duration is:

$$D=\Lambda(\mu=5.338,\sigma=0.9784)$$

4.3 Acid gas category

4.3.1 Unnoticed low pH in scrubbing liquid

The unnoticed low pH in the scrubbing liquid can only be detected by calibration of the pH analyser. Since the automatic pH analyser is not yet reliable, weekly calibration has been used in one facility. It is assumed that the mean duration of the unnoticed low pH in the scrubbing liquid is one week and the maximum duration (95th percentile) is two weeks to account for possible human errors in calibration. Therefore, the distribution of the off-normal duration can be found as:

$$D=\Lambda(\mu=5.00,\sigma=0.496)$$

4.3.2 Unnoticed low scrubbing liquid flow rate

In the previous section, the duration of distribution of the unnoticed low scrubbing flow rate has been determined as:

$$D=\Lambda(\mu=6.101,\sigma=0.9784)$$

5. Conclusions

From the present study, it can be concluded that, for modern incinerators, designed and operated according to the assumptions of this study, the off-normal emission frequency due to equipment or instrument malfunction or human errors is about once a year, and drifting type failures of measuring devices play an important role in off-normal emissions for liquid injection incinerators.

It should be emphasized that the results should be interpreted with caution. The occurrence of off-normal or upset emissions would not necessarily cause significant risk to the surrounding populations. The consequences of such an emission may depend on the intensity of off-normal emissions and the type of wastes that are incinerated, besides the off-normal duration. The results for off-normal emission intensities and total off-normal emissions will be reported in the second paper of this series [22].

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