

evidence in support of its application.

### 5. Violation of the First Law of Thermodynamics

In the calculation of the mass flow of the flame, the Applicant equated the coefficient of heat transfer of turbulent flow inside a pipe with the coefficient of heat transfer by natural convection. CD .97 at I-8 and I-9. As a portion of this calculation, Applicant also established that the temperature gradient outside the hypothetical pipe is  $T_{\text{plume}} - T_{\text{ambient}}$ <sup>15</sup>. It will be shown that Applicant's calculation violates the first law of thermodynamics.

The first law of thermodynamics requires that "at steady state, the energy flux out of a flame must equal the energy flux that is entering the environment (Dr. Pinto, Tr. at 96 and 97)." In Applicant's flame scenario this means that the energy flux from the hot gases of the flame through the wall of a hypothetical pipe must equal the energy flux absorbed by the environment on the outside of the pipe. This can be expressed mathematically using equation 6-21 of Peters at 138, which describes the heat flow from one fluid to another through a solid retaining wall as follows:

$$h_1 * A_{\text{inside\_wall}} * (T_{\text{flame}} - T_{\text{inside\_wall}}) = h_2 * A_{\text{out\_side\_wall}} * (T_{\text{outside\_wall}} - T_{\text{ambient}})$$

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"Applicant does not distinguish between the temperature of the plume and the temperature of the flame. When Applicant presents equation 11, dt is defined as the temperature difference between the plume and ambient air ("F), however in the discussion immediately following equation 11, 'dt' is defined to be the difference between the fire temperature and the ambient temperature; the flame temperature of 2108 °K was used as the fire temperature or the plume temperature. CD .97 at I-9.

where:  $h_1$  and  $h_2$  = film coefficients of heat transfer,  
 $A_{\text{inside\_wall}}$  = the inside area of the pipe wall,  
 $(T_{\text{flame}} - T_{\text{inside\_wall}})$  = difference between the flame temperature and the inside wall temperature,  
 $A_{\text{out\_side\_wall}}$  = the outside area of the pipe wall, and  
 $(T_{\text{outside\_wall}} - T_{\text{ambient}})$  = difference between the outside of the pipe wall temperature and the ambient temperature.

In Applicant's scenario

$h_1$  =  $h_{\text{turbulent}}$  or the coefficient of heat transfer from a turbulent fluid inside a pipe to the inside surface of the pipe wall, and  
 $h_2$  =  $(h_{\text{n\_cv}} + h_r)$  or the sum of  $h_{\text{n\_cv}}$ , the coefficient of heat transfer by natural convection, and  $h_r$ , the coefficient of radiant heat transfer from the outside wall of the pipe<sup>16</sup>.

No details are provided by Applicant regarding the nature of the thermal boundary layer (hypothetical pipe wall), and so it is assumed that the wall is very thin and therefore  $A_{\text{inside\_wall}}$  and  $A_{\text{out\_side\_wall}}$  are equal.<sup>17</sup> Thus the equation becomes:

$$h_{\text{turbulent}} * (T_{\text{flame}} - T_{\text{inside\_wall}}) = (h_{\text{n\_cv}} + h_r) * (T_{\text{outside\_wall}} - T_{\text{ambient}})$$

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<sup>16</sup>The Board takes administrative notice of "Heat Transfer" by J. P. Holman, Third Edition, McGraw Hill, New York, 1972. at 289.

The total heat transfer is then the sum of the convection and radiation, etc.

"If a **solid** wall is assumed, there is no reason or justification for a **thick** wall. In fact, a thick wall would be a poor assumption.

Now applicant has ignored the radiant component of heat transfer and has claimed that  $h_{\text{turbulent}} = h_{\text{cv}}$ . It then follows that the heat balance equation requires  $(T_{\text{flame}} - T_{\text{inside\_wall}})$  equal  $(T_{\text{outside\_wall}} - T_{\text{ambient}})$ . This is a physically ridiculous condition and therefore is a violation of the first law of thermodynamics. Furthermore, it implies complete insulation of the flame, which is inconsistent with the original assumption of steady state.

The violation of the first law of thermodynamics is yet another error which raises very serious doubts regarding the competency and credibility of the Applicant's evidence in support of its application.

#### 6. Inconsistency in Selection of Values for the Coefficient of Convective Heat Transfer

Applicant has used a convection heat transfer coefficient in the calculation of heat losses from the flame of  $89,776 \text{ J/hr-m}^2\text{-}^\circ\text{K}$  (CD .97, Attachment 1 to Appendix I) which is equivalent to  $4.39 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ . This convection heat transfer coefficient value was taken from a paper titled "A New Theory for a Rotary-Kiln Heat Exchanger"<sup>18</sup>. *Id.* No foundation was found in CD .97 regarding why this value for a convection heat transfer coefficient, applicable to air forced through a kiln, would be appropriate for use in the calculation of the flame temperature of an open fire where air moves by natural convection.

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<sup>18</sup>M. Imber and V. Paschkis, International Journal of Heat and Mass Transfer. Vol. 5, pp. 623635. Pergamon Press 1962. Printed in Great Britain.

The fact that Applicant selected a parameter value from an unrelated study without any justification also raises very serious doubts regarding the competency and credibility of the Applicant's evidence in support of its application.

The principle that a mathematical description of one fire should have a set of values for all parameters in the calculation which simultaneously satisfies all equations in the calculation, would require the use of the same heat transfer coefficient for the flame temperature calculation and the flame residence time calculation. Again, there is only one fire and in each calculation gas flow will be by natural convection. Yet, in the flame residence time calculation, Applicant calculated a value for "h" of 0.79 Btu/hr-ft<sup>2</sup>-°F using equation 11 and then used this value of "h" in calculation of mass flow rate. CD .97 at I-9.

This is yet another example of Applicant's disregard for the necessity of consistency in parameter values which raises very serious doubts regarding the competency and credibility of the Applicant's evidence in support of its application.

#### 7. Destruction and Removal Efficiency

The calculation of the destruction and removal efficiency ("DRE") is a two step process starting with the calculation of "k", a constant for the rate of the combustion reaction. Using the "k" value and the residence time, DRE is calculated. CD .97 at I-10 and I-11.

Using the following equation, values of “k” were calculated by Applicant for every component of a typical hazardous waste fuel and presented at CD .97, Table 1.1-1 at I-12:

$$k = A \cdot \exp\{-E_a / (R \cdot T_{\text{flame}})\}$$

where: values for “A” and “ $E_a$ ” are given in Table 1.1-1 on Page I-12 of CD .97,

R is the gas constant, and  $T_{\text{flame}} = 2108 \text{ }^\circ\text{K}$ , Id.

However, when Board staff attempted to verify the calculation of the “k” values using Applicant’s supplied parameters and equation, the “k” values of Table 1.1-1 were not obtained. For example, Board staff obtained a “k” for acetone of 422 instead of the Applicant’s reported value of 0.7384. Likewise, all other “k” values obtained by the Board staff **were considerably greater** than the value reported by Applicant.

When Board staff are unable to obtain Applicant’s output values using Applicant’s input data and equations, serious doubts are again raised regarding the competency and credibility of the Applicant’s evidence in support of its application.

Board staff then worked Applicant’s equation backwards to determine the flame temperature used to arrive at Applicant’s “k” values. The temperature was found to be 1000 °K and not 2108 °K,<sup>19</sup> as indicated by Applicant.

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<sup>19</sup>On page I-8 Applicant states “The resulting flame temperature for the waste fuel fire was assumed to be 2108 °K (1,835 °C, 3,335 °F).” On pages I-9 and I-10, Applicant uses 2108 °K when calculating flame height and mass flow as a part of the residence time calculations. Id.

Proceeding to verify the DRE calculation, the following is used:

$$\text{DRE} = 1 - \exp(-k*t)$$

where: "k" (1/sec) is the first order rate constant

"t" is the residence time (sec). CD .97 at I-11.

Applicant's estimate of "t" was a dwell time of 3.8 seconds, based upon a flame height of 64 meters and a mass flow of 1,980 lb/hr-ft<sup>2</sup>. CD. 97 at I-g-10. When Applicant's dwell time of 3.8 seconds and flame temperature of 2108 °K is used in the calculation of the "k" values, Board staff observed that the DRE for every component of a typical hazardous waste fuel is 1, which is a prediction of total destruction. However, using the "k" values of Applicant's Table 1.1-1 and the dwell time of 3.8 seconds, Applicant's DRE is obtained.

The Board notes that Applicant has selected a flame temperature of 1000 °K for the calculation of "k" values, while continuing to use 2108 °K in the calculation of flame height and mass flow used to calculate dwell time. This practice contradicts the fundamental concept of consistency, in that a fire described by one set of parameters must simultaneously satisfy other equations regarding said fire. In this case, inconsistency in flame temperature values is yet another error which raises very serious doubts regarding the competency and credibility of the Applicant's evidence in support of its application.

8. Inconsistency Between the Total Evaporation Rate and the Burn Rate

Applicant's reference Ndubizu at 234 states:

fuel is assumed to evaporate from the **surface** at the liquid boiling point

and

as the fuel vapor rises, it entrains the surrounding air and burns.

Also in equation 4 of Ndubizu at 235, the rate of heat released by burning is a function of the evaporation rate. These statements imply that the evaporation rate *must at least equal the* burn rate, as material must move from the pool as a vapor before it enters the **fire**<sup>20</sup>. Thus, as a

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<sup>20</sup>In considering the relationship between the evaporation rate and the burn rate, the heat and mass balance equations of Applicant were compared with those of Applicant's reference Ndubizu. In each case their equations have a term for the heat of combustion produced by the fire. Applicant writes the heat of combustion as follows:

$$H_c = (\text{mass flow of fuel}) * (\text{average heat value, (HHV)}) \text{ CD .97 at I-6.}$$

Ndubizu at 235 writes the heat of combustion as:

$$H_c = b * (\text{fuel evaporation rate}) * (\text{heat content of fuel})$$

where: "b" is the combustion efficiency

Now if the **two** equations for  $H_c$  are equated it follows that:

$$(\text{mass flow of fuel}) = b * (\text{fuel evaporation rate})$$

and if efficiency equals 1 or 100 %, then mass flow of fuel must equal the fuel evaporation rate. Likewise, if the combustion efficiency "b" is as low as 0.64 or **64%**, which was a likely efficiency for fires greater than 100 cm in diameter according to the Applicant's reference, Ndubizu at 240, then the evaporation rate must be about 1.5 times the burn rate. These observations show that in both Ndubizu's and Applicant's models of the fire, the evaporation rate *must at least equal* the burn rate.

verification of consistency of mass flow in Applicant's estimates of air emissions from a fire, the total evaporation rate was calculated and compared to Applicant's bum rate.

While CD .97, Table 1.1-3, does not present evaporation'rate values prior to combustion in grams per second, the rate may be calculated for each constituent of a typical hazardous waste fuel by dividing the emission rates of Table 1.1-3 by the appropriate value of  $(1 - DRE)^{21}$ . When this was completed for each component of a typical hazardous waste fuel and the evaporation rates were summed, it was observed that the total evaporation rate prior to combustion was approximately 236 grams per second. It was then noted that the bum rate was 9,970 grams per second (CD .97 at I-3), and that the total evaporation rate was only about 1/40th of the bum rate, suggesting that Applicant has underestimated air emissions by at least a factor of 40.

CD .97 Table I. 1-3, sets forth the amount of chemical evaporated in a 3.1 hour fire scenario.

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<sup>21</sup>In CD .97 at I-11 through I-13, Applicant states that emission rates are first calculated by the Stiver and Mackay equation and then multiplied by  $(100 - DRE)/100$  to account for the portion of emissions which are destroyed by combustion. In order to avoid confusion, it is important to note that **DRE** in the above correction factor is written as a percentage while DRE in Table I. 1-1 is expressed as a fraction of 1. Therefore if DRE is expressed as a percentage then

$$\text{Emissions to air} = \text{Total emissions} * (100 - DRE)/100, \text{ and}$$

If DRE is taken from Table I. 1-1 or Table I. 1-3 of CD .97 and used in decimal form **then**

$$\text{Emission to air} = \text{Total emission} * (1-DRE).$$

It then follows that if a value for emission to air is read from Table I. 1-3 and this is divided by  $(1-DRE)$  where the decimal form of DRE is read from Table I. 1-3, this calculation would yield the total emission of that component of hazardous waste fuel which was calculated by Applicant using the Stiver and Mackay equation.