AN IMPROVED MODEL FOR THE PREDICTION OF RADIANT HEAT FROM FIREBALLS

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ABSTRACT

This paper presents an integrated model for predicting the radiant heat effects of fireballs created by near-instantaneous releases of superheated flammable liquids. Films and videos of fireballs show that a fireball grows quickly in size, rises into the air after some time delay, then dissipates when the available fuel is consumed. Most of the published fireball radiation models ignore this behavior and simply assume the diameter, location, and surface emissive power of the fireball are constant over the full duration of the event. In contrast, the model described in this paper provides a more realistic representation of the true behavior of fireballs by employing equations that account for fireball growth, lift-off, and changing radiative characteristics. Thermodynamic changes that occur during the release of superheated liquids are incorporated into the model, making it suitable for predicting the radiant heat effects of fireballs formed as a result of cold catastrophic failures of pressure vessels, as well as fireballs created by BLEVE incidents. Predictions of the time-varying radiant heat flux incident upon targets located outside the fireball are shown to agree well with results from moderate-scale experiments.

INTRODUCTION

The sudden release of superheated flammable liquid from a storage tank or process vessel is the beginning of a complex event that often ends in the formation of a short-lived fireball. The event starts with a major failure of the container. Because the pressure in the container is greater than atmospheric pressure, much of the liquid is quickly expelled into the atmosphere. In response to this rapid drop in pressure, a portion of the liquid flashes to vapor nearly instantaneously. This vapor expands rapidly, shattering some of the remaining liquid into small drops, thereby creating a turbulent aerosol cloud consisting of vapor, liquid drops, and air. The aerosol cloud quickly increases in size, entraining more air as it grows.

Ignition of this aerosol cloud results in a fireball that exists until the vapor and liquid fuel within the cloud are consumed. The fireball can emit a large amount of radiant energy during its brief life, and is capable of causing injuries and damage over an area several times greater than the size of the fireball. Therefore, when conducting a hazards or risk analysis of process vessels or storage tanks that contain superheated flammable liquids, it is important to be able to accurately model the radiant heat effects of fireballs. Most fireball radiation models ignore the dynamic nature of fireballs and simply treat them as static events. This simplification often causes such models to overpredict the extent of potentially damaging or injurious radiant heat hazard zones. The fireball model introduced in this paper provides better predictions of hazard zones by treating fireballs as dynamic events.

THE BASICS OF FIRE RADIATION

All fires emit thermal radiation. When modeling thermal radiation from fires involving flammable liquids and gases, the flame is typically represented as a simple geometric shape (cone, tilted cylinder, etc.) that emits radiation from its surface. The following equation is then used to calculate the intensity of the thermal radiation at any specific "target" location outside the flame.

$$= q_i = q_s \cdot F \cdot \tau \qquad \text{(Equation 1)}$$

where: q_i = radiant heat flux incident upon the target due to radiant heat emitted by the fireball, kW/m^2 (Btu/(hr·ft^2))
q_s = average radiant heat flux emitted from the "surface" of the fireball, kW/m^2 (Btu/(hr·ft^2))
F = view factor from the target to the fireball, dimensionless
τ = atmospheric transmittance, dimensionless

The seriousness of injuries and extent of damage that can be caused by thermal radiation from a fire depend on the intensity of the incident radiation, q_i, and the duration of exposure to that level of heat flux. Since fireballs exist for only a few seconds, the duration of exposure is commonly set equal to the duration of the fireball.

Methods for predicting the thermal radiation consequences of fireballs typically include elements or models to define or calculate the following factors.

- Surface emissive power of the fireball
- Geometric view factor
- Atmospheric transmittance
- Fireball duration

Input parameters for these models will either be calculated by submodels or be based on assumptions. For example, the following parameters are required for input to most geometric view factor models.

- Fireball shape (assumed)
- Fireball size (calculated)
- Mass of fuel involved in the fireball (required by fireball size equation)
- Location of the fireball relative to the target (assumed)
- Orientation of the target relative to the fireball (assumed)

CURRENT MODELS

A fireball is a dynamic phenomenon. Typically, a fireball begins its life as a small ball of fire located near grade. Over the next few seconds, the fireball grows in size, soon reaching its maximum diameter. The fireball becomes buoyant and lifts off the ground as the heat of the fire vaporizes liquid droplets and increases the bulk temperature of the remaining mixture of vapor, air, and reaction products. As it rises, the limited fuel supply is consumed and the fireball ceases to exist.

In spite of this dynamic behavior, most fireball radiation models currently in use treat the fireball as a static event in which the fireball has a constant size, emits radiant heat at a constant rate, and is located at a fixed position relative to grade. This type of model generally consists of eight primary elements or submodels.

Fireball Shape

Nearly all fireball models treat the fireball as a sphere. Videos and other observations of accidental and experimental fireballs indicate that most fireballs can be reasonably described as being spherical over most of their duration.

Fireball Diameter

Static models typically assume the fireball reaches its maximum diameter instantaneously and maintains that size for the full duration of the fireball. Nearly all of the static models calculate the fireball diameter by using an equation of the following form, which relates maximum fireball diameter to the mass of fuel involved in the fireball.

$$= D = k \cdot M^{n} \qquad \text{(Equation 2)}$$

where D = maximum fireball diameter, m
M = mass of fuel involved, kg
k and n = constants

In published models, the constant ranges from 2.97 to 6.48. The most common value of the exponent n is 1/3, although some models use slightly lower values. The following form of the equation, which was developed by Roberts [1981/82], is widely used.

$$D = 5.8 \cdot M^{1/3} \qquad \text{(Equation 3)}$$

Fireball Duration

The equation for fireball duration normally has the following form, which relates the duration or lifetime of the fireball to the mass of fuel involved in the fireball.

$$t_d = k \cdot M^{n} \qquad \text{(Equation 4)}$$

where: t_d = fireball duration, seconds

In published models, values of the constants k and n range from 0.23 to 2.61, and from 0.0966 to 0.333, respectively. The TNO [1983] version of this equation is as follows.

$$t_d = 0.825 \cdot M^{0.26} \qquad \text{(Equation 5)}$$

The Health and Safety Executive of the United Kingdom developed the following set of two equations for duration [Clay, et al., 1988]. These equations are widely used. The change in exponent from 1/3 to 1/6 is said to reflect a change in behavior of a fireball as the mass of fuel increases [IChemE, 1989].

$$= t_d = 0.45 \cdot M^{1/3} \qquad \text{if } M < 37{,}000 \text{ kg} \qquad \text{(Equation 6a)}$$

$$= t_d = 2.60 \cdot M^{1/6} \qquad \text{if } M > 37{,}000 \text{ kg} \qquad \text{(Equation 6b)}$$

Mass of Fuel Involved

The mass of fuel involved in the fireball is an integral part of the equations for fireball diameter and duration. This mass can be the same as the mass contained within the vessel prior to its rupture, but it can also be less than that amount—particularly if the amount of superheat is small.

Various authors have proposed different relationships between the mass released and the mass involved in the fireball. Crocker and Napier [1988] proposed the following guidelines.

> Mass involved equals mass released if adiabatic flash exceeds 50%. Otherwise, mass involved equals twice the adiabatic flash.

Based on the work of Hasegawa and Sato [1977], Roberts [1981/82] proposed the following rules.

> Mass involved equals mass released if adiabatic flash exceeds 35%; and zero if adiabatic flash equals zero. Linear interpolation is suggested between these two limits.

The CCPS book, *Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs* [CCPS, 1994], suggests the following variation of Roberts' rules.

> Mass involved equals mass released if adiabatic flash exceeds 1/3. Otherwise, mass involved equals three times the adiabatic flash.

This variation provides the most conservative results since the mass of fuel it puts in the fireball always equals or exceeds the amount calculated by either of the other two methods.

Surface Emissive Power

Equations for calculating the surface emissive power (SEP) typically relate the SEP to the pressure in the vessel at the time it bursts. Two methods are in common use. Roberts [1981/82] developed the following equation, which predicts the fraction of the total available heat energy that is radiated by the fireball.

$$= f = 0.27 \cdot P^{0.32} \qquad \text{(Equation 7)}$$

where: f = fraction of heat radiated, dimensionless
P = burst pressure, MPa

Once the fraction of heat radiated has been calculated, the following equation is used to calculate the surface emissive power of the fireball.

$$=q_s = \frac{f \cdot M \cdot H_c}{\pi \cdot D^2 \cdot t_d} \qquad \text{(Equation 8)}$$

where: H_c = heat of combustion of the fuel, kJ/kg
$M \cdot H_c$ = total amount of heat energy available, kJ
$\pi \cdot D^2$ = surface area of the spherical fireball, m^2

At first glance, this equation appears to indicate that the surface emissive power, q_s, is proportional to the mass of fuel involved in the fireball. However, if the fireball duration and diameter are both proportional to the cube root of the mass of fuel involved, the SEP predicted by this method is independent of the mass of fuel. Conversely, if either the diameter or duration is not proportional to $M^{1/3}$, then the SEP prediction will be affected by changes in the mass.

The other common method uses a single equation developed by Moorhouse and Pritchard [1982]. As shown below, it provides a direct relationship between surface emissive power and the pressure at which the vessel burst—for pressures no greater than 2 MPa (~300 psi).

$$q_s = 2.35 \cdot P^{0.39} \qquad \text{(Equation 9)}$$

Location of Fireball

Most of the static fireball models assume the fireball is tangent to grade, but some use a higher location. For example, the TNO model [TNO, 1983] places the center of the fireball at 1.5 radii above grade.

View Factor

The view factor (F in Equation 1) is based on the geometric relationship between the spherical fireball and a flat target located outside the fireball. In some static models, the vector that is normal to the surface of the target points directly at the center of the spherical fireball, as illustrated in Figure 1a. (This orientation results in the maximum possible values for the view factor.) The following equation is used to calculate view factors for this orientation.

$$F = \frac{R^2}{h^2} \qquad \text{(Equation 10)}$$

where: R = radius of the fireball, m
h = distance from target to center of fireball, m

In other static models, the target is assumed to have a vertical orientation. Thus, the vector that is normal to the surface of the target will be horizontal. If the fireball is tangent to grade and the target is located at grade, the normal vector will be tangent to the fireball, as illustrated in Figure 1b. The following equation is used to calculate view factors for this orientation.

$$F = \frac{R^2 \cdot \sqrt{h^2 - R^2}}{h^3} \qquad \text{(Equation 11)}$$

For otherwise identical situations, this difference in orientation of the target results in a difference in the predicted values of the view factor F. This can lead to a considerable difference in predicted values of incident heat flux, q_i, when the target is close to the fireball.

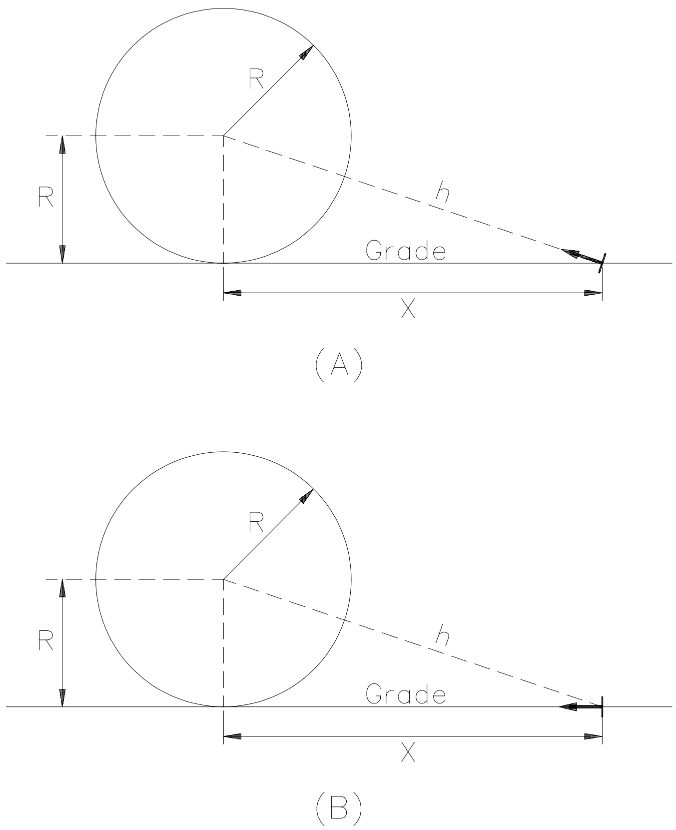

Figure 1
Examples of Target Orientation Relative to Fireball

<u>Atmospheric Transmittance</u>

Water vapor and carbon dioxide in the atmosphere will absorb some thermal radiation as it passes through the air between the fireball and the target. Several methods have been put forward for calculating this effect. They range in complexity from the use of a constant value (e.g., 0.75) for transmissivity, to equations in which transmissivity is a function of absolute humidity, carbon dioxide concentration in air, and path length (e.g., [Wayne, 1991]).

AN EXAMPLE OF A STATIC MODEL

In 1989, The Institution of Chemical Engineers published its *Thermal Radiation Monograph* [IChemE, 1989], in which it recommended the use of a static model consisting of the following elements.

(1) The fireball has a spherical shape, and it reaches its maximum size instantaneously.

(2) $D = 5.8 \cdot M^{1/3}$ (Equation 3)

(3) $= t_d = 0.45 \cdot M^{1/3}$ if M < 37,000 kg (Equation 6a)

$t_d = 2.60 \cdot M^{1/6}$ if M > 37,000 kg (Equation 6b)

(4) Recommends setting the mass of fuel involved in the fireball equal to the mass of fuel released.

(5) $q_s = 2.35 \cdot P^{0.39}$ (Equation 9)

(6) The fireball is tangent to grade.

(7) The view factor formula is not specified.

(8) The atmospheric transmittance formula is not specified.

Predictions of incident radiant heat flux from this type of model will resemble a square wave, as illustrated in Figure 2, which is based on the following assumptions.

- Fuel = butane
- M = 2,000 kg
- P = 1.51 MPa
- The absolute humidity is zero (i.e., τ =1.0).
- The horizontal distance between the target and the ruptured vessel is 50 m.
- The target is located at grade and the vector normal to the surface of the target points directly at the center of the fireball.

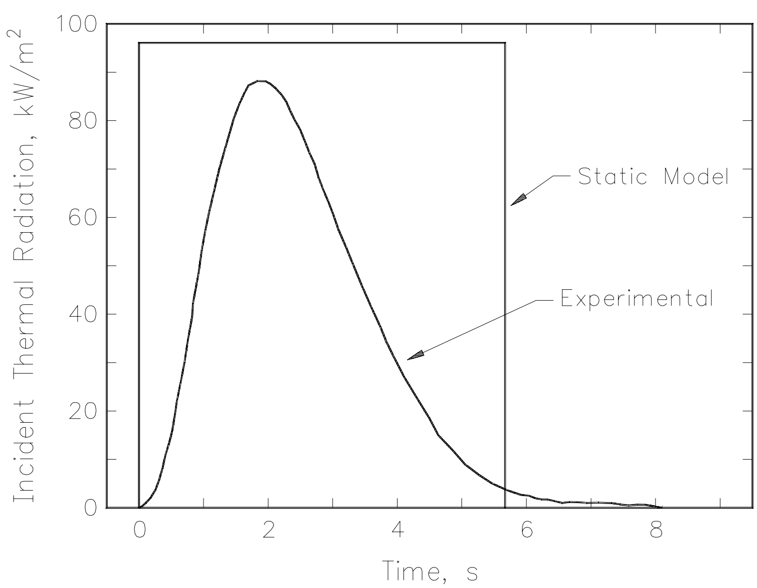

Figure 2
Comparison of Incident Thermal Flux History;
Static Model Prediction versus Experimental Data
from Johnson, Pritchard, and Wickens [1990]

In contrast, Figure 2 also presents the time-varying incident radiant heat flux data from an actual fireball experiment conducted by British Gas [Johnson, Pritchard, and Wickens, 1990]. Like the scenario modeled above, this experiment released 2,000 kg of butane at a pressure of 1.51 MPa, and the horizontal distance between the target (a heat flux radiometer) and the ruptured vessel was 50 m. The radiometer was located 1.1 m above grade, and the flat sensing element was tilted 30° upward from vertical. Thus, the vector normal to the sensing element was inclined 30° upward from horizontal and intersected the vertical line that passed through the center of the test vessel.

THE DYNAMIC MODEL

Dynamic fireball models attempt to model the time-varying behavior of fireballs in order to more accurately predict the thermal radiation consequences of actual fireballs. Like static models, dynamic models are based on certain assumptions (e.g., a sphere is a reasonably accurate representation of a fireball) and several empirical formulas. Unlike static models, a good dynamic model should account for time-varying phenomena that have been observed during planned and unplanned fireball incidents.

The dynamic fireball model developed by the authors is described below.

Fireball Shape

The fireball is assumed to be spherical in shape. Although no fireball will be perfectly spherical, the appropriateness of the assumption of a spherical shape is borne out by observations of still photographs and videos of actual fireballs.

Mass of Fuel Involved

Equating the mass of fuel involved in the fireball to the mass of fuel released is overly conservative for any fireball created by a release of liquid that is only slightly superheated. Instead, the guidelines proposed by the CCPS [1994] are used.

> Mass involved equals mass released if adiabatic flash exceeds 1/3. Otherwise, the mass involved equals three times the adiabatic flash (calculated at the vessel burst pressure).

These guidelines should provide reasonably conservative results, without being unduly pessimistic.

Fireball Duration

TNO proposed the following relationship between fireball duration and the mass of fuel involved in the fireball [TNO, 1983].

$$t_d = 0.825 \cdot M^{0.26} \quad \text{(Equation 5)}$$

The dynamic model uses the following relationship, which is a slight variation of the TNO equation.

$$t_d = 0.9 \cdot M^{0.25} \quad \text{(Equation 12)}$$

Figure 3 compares these two equations and Equations 6a and 6b from Clay, et al. [1988]. Durations predicted by Equation 12 are nearly identical to those of TNO until the mass exceeds 10,000 kg, and are slightly shorter than predicted by TNO when the mass exceeds 10,000 kg. Compared to the duration predictions of Equations 6a and 6b, durations predicted by Equation 12 are slightly longer for masses less than 5,000 kg or more than 300,000 kg.

The surface emissive power section of the static model presented a brief discussion of the relationship between mass of fuel involved in the fireball and the SEP. According to that discussion, if Equations 7 and 8 are used to calculate the SEP, and the fireball duration and diameter are both proportional to the cube root of the mass of fuel involved, the predicted SEP is independent of the mass of fuel. Thus, if Equation 3 is used to calculate the maximum diameter and Equation 6a is used for duration, the SEP is independent of the mass of fuel. However, if Equation 6b is used to calculate the duration of fireballs involving more than 37,000 kg of fuel, the SEP suddenly becomes dependent on the mass of fuel. This change in behavior of the SEP when the mass of fuel reaches 37,000 kg is highly unlikely. Therefore, we have chosen to use Equation 12 for calculating fireball duration. (Additional discussions related to our choice of Equation 12 are presented in the following sections on fireball diameter and surface emissive power.)

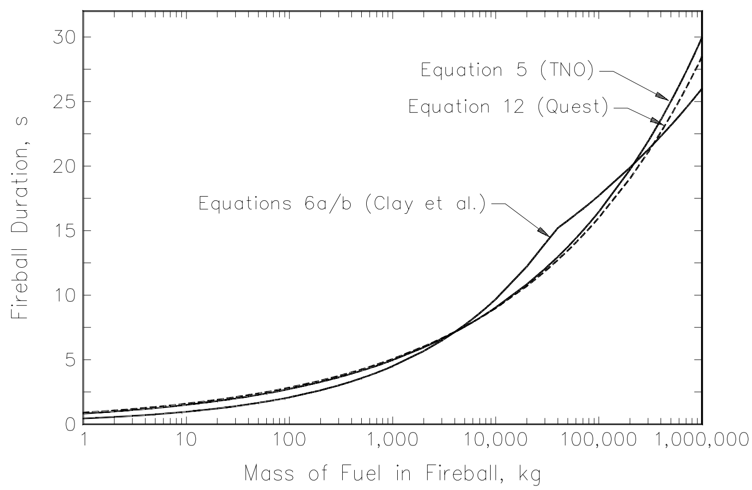

Figure 3
Comparison of Fireball Duration Predictions

Fireball Diameter and Location

During the early portion of a fireball's existence, the dynamic model treats the fireball as a sphere that increases in diameter with time, remaining tangent to grade as it grows. At the end of the growth phase, the fireball has reached its maximum diameter (which is predicted by Equation 3) and begins to rise into the air.

$$D = 5.8 \cdot M^{1/3} \qquad \text{(Equation 3)}$$

The fireball is assumed to achieve its maximum diameter at the end of the first third of its duration. This is also the time at which lift-off is assumed to occur (i.e., $t_{lo} = t_d / 3$)

These assumptions are based on:

- experimental data from Hasegawa and Sato [1978] and Maillette and Birk [1995], which indicate that peak radiation output occurs at the end of the first third of the fireball's duration;

- the work of Roberts [1981/82], who noted that peak radiation output occurs when the fireball has grown to its maximum diameter; and
- experimental data from Hasegawa and Sato [1977] and Hardee and Lee [1973], which show the fireball begins to rise into the air once it has reached its maximum diameter.

Hardee and Lee [1973] conducted experiments in which they ignited premixed quantities of gaseous propane and air. According to those experiments, the diameter of the fireball was proportional to the cube root of time, until the diameter reached its maximum. Moorhouse and Pritchard [1982] reviewed other experiments and reached the same conclusion. To check this hypothesis, we conducted a frame-by-frame analysis of three BLEVE fireballs from the NFPA video, "BLEVE Update." The three accidents involved propane tanks ranging in size from a portable cylinder to a railcar. The results of this analysis are presented in Figure 4. In each of these incidents, the growth rate of the fireball was roughly proportional to the cube root of time. In addition, the time at which the fireball reached its maximum size and the time at which it lifted off were approximately equal.

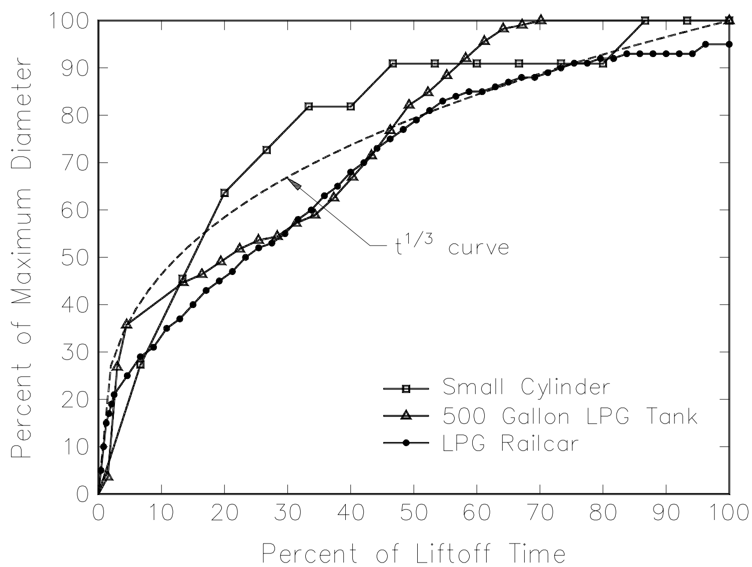

Figure 4
Dimensionless Fireball Growth Rate Measurements
(Based on the NFPA Video, "BLEVE Update")

Hardee, Lee, and Benedick [1978] suggested an equation of the following form for calculating the diameter of a fireball during its growth period.

$$D(t) = C \cdot M^{5/18} \cdot t^{1/3} \qquad \text{(Equation 13)}$$

where: $D(t)$ = fireball diameter at time t, m
C = proportionality factor

Since the fireball reaches its maximum diameter at t_{lo}, Equation 13 can be "solved" by substituting the maximum diameter $5.8 \cdot M^{1/3}$ for $D(t)$, and $t_{lo} \cdot (0.3 \cdot M^{1/4})$ for t. This results in the following equation for calculating the fireball diameter during its growth phase.

$$D(t) = 8.664 \cdot M^{1/4} \cdot t^{1/3} \qquad \text{for } t \le t_{lo} \qquad \text{(Equation 14)}$$

Once the fireball diameter has reached its maximum value and the fireball has begun to rise, the diameter remains constant until the fireball completely dissipates at t_d.

Shield [1994] observed that the fireball ceased to exist once the center of the fireball rose to a height of three times the maximum radius. He also observed that the velocity of a rising fireball was approximately constant [Shield, 1993]. Thus, the center of the fireball moves upward at a constant rate from its pre-lift-off position (one maximum radius above grade) to three times that elevation in the last two-thirds of the fireball's existence. With this correlation established, the location of the fireball at any given time can be determined.

Surface Emissive Power

The SEP is based on Equation 7 [Roberts, 1981/82], which predicts the fraction of the total available heat energy that is emitted as radiation.

$$f = 0.27 \cdot P^{0.32} \qquad \text{(Equation 7)}$$

Once the fraction of heat radiated has been calculated, the following variation of Equation 8 is used to calculate the surface emissive power.

$$q_s = \frac{f \cdot M \cdot H_c}{0.8888 \cdot \pi \cdot D^2 \cdot t_d} \qquad \text{(Equation 15)}$$

where: $0.8888 \cdot \pi \cdot D^2$ = time-averaged surface area of the fireball, m^2

Substituting $5.8 \cdot M^{1/3}$ for D and $0.9 \cdot M^{1/4}$ for t_d results in the following equation.

$$q_s = 0.0133 \cdot f \cdot H_c \cdot M^{1/12} \qquad \text{(Equation 16)}$$

This equation increases the surface emissive power as the mass of fuel involved in the fireball increases. This trend is supported by experimental data, such as that compiled in Table 6.3 of the CCPS [1994] reference. However, fire research indicates that the SEP will not exceed some upper limit, regardless of the mass or pressure involved. Limits ranging from 300 kW/m^2 [Moorhouse and Pritchard, 1982] to 450 kW/m^2 [Roberts, 1981/82] have been proposed. Based on the British Gas experiments [Johnson, Pritchard, and Wickens, 1990], we believe 400 kW/m^2 is a realistic upper limit for SEP. Hence, the dynamic model uses the SEP calculated by Equation 16, or 400 kW/m^2, whichever is smaller.

The resulting SEP is applied to the fireball during its growth period. Experimental data from Hasegawa and Sato [1977] and Maillette and Birk [1995] show that SEP decreases once the fireball has reached its maximum diameter. The dynamic fireball model accounts for this behavior by linearly decreasing the SEP from its maximum value to zero over the last two-thirds of the fireball's duration.

View Factor

Any of the view factor equations for a sphere radiating to a point outside the sphere can be used with this model. The preferable equation would vary with the situation to be modeled and the desires of the modeler. For general purpose use, the dynamic model places the target at grade, with the vector normal to the surface of the target passing through the center of the fireball. Equation 10 is then used to calculate the view factor. As the fireball rises, the target is continually rotated such that the vector normal to the surface of the target continues to pass through the center of the fireball at all times. This is a conservative assumption since it assures that, at any given time, the calculated view factor will be the maximum possible for a point target located a given distance from the fireball.

Atmospheric Transmittance

The equations from Wayne [1991] are used to calculate atmospheric transmittance. They account for the absorption of thermal radiation by water vapor and carbon dioxide in the atmosphere, and predict an increase in absorption as absolute humidity and path length increase.

The model sets the path length equal to the distance between the target and the nearest point of the fireball surface. (This is a conservative assumption since thermal radiation from all other points on the surface of the fireball would need to travel a greater path length.) Because the location of the fireball is constantly changing, the path length between the target and the sphere also changes with time.

MODEL VALIDATION

Several of the equations used in the dynamic fireball model are empirical relationships based on data from small – to medium - scale experiments, which ensures reasonably good agreement between model predictions and experimental data for variables such as maximum fireball diameter. Comparisons of experimental data and model predictions of incident heat flux as a function of time are more meaningful and of greater interest. However, very few reports on small- or medium-scale fireball experiments contain the level of detail required to make such comparisons, and no such data are available for large-scale (e.g., railcar) experiments.

One of the most complete sources of test data for medium-scale fireball tests is a report by Johnson, Pritchard, and Wickens [1990]. It contains data from a series of five well-instrumented fireball experiments in which superheated liquids were released nearly instantaneously from ruptured pressure vessels. Four of the tests involved commercial grade butane (>90% *n*-butane), in quantities of 1,000 and 2,000 kg; the other involved 2,000 kg of commercial grade propane. Electric immersion heaters were used to heat the lading in each test, simulating the effects an external fire would have on the temperature and pressure within the vessel. A linearshaped charge was used to initiate catastrophic failure of the vessel.

Each test was filmed with regular- and high-speed film cameras, and videotaped. Several wide-angle radiometers were used to measure incident heat fluxes at distances of 50 to 250 m from the test vessel, and a single narrow-angle radiometer was used to measure the fireball SEP.

The report on these tests [Johnson, Pritchard, and Wickens, 1990] includes a plot of radiant heat flux versus time for each radiometer for each test. Figure 5 presents radiant heat flux data from one of the radiometers used in Test No. 1, along with predictions from the IChemE static model and from our dynamic model. (For the purpose of this comparison, the target in the static model was located at grade, at the same distance as the radiometer, and tilted such that the vector normal to the surface of the target passed through the center of the fireball. The target in the dynamic model was located at the same distance and elevation as the radiometer, and inclined at the same angle. For both models, the equations from Wayne [1991] were used to calculate the atmospheric transmittance.) The flux versus time curve predicted by the dynamic model follows the general shape of the experimental curve, with only a small overprediction of the maximum incident heat flux and a slight offset in time. In contrast, the prediction from the static model bears little relationship to the test data.

The thermal damage or injury potential of a fireball is related to the incident heat flux and the duration of the fireball. One way of expressing the combination of intensity and time is to use dosage (i.e., absorbed energy), which is equivalent to the area under the radiant heat flux versus time curve. The report by Johnson, Pritchard, and Wickens [1990] reports a dosage for each wide-angle radiometer for each test. Figure 6 is a plot of the dosage data from Tests 2-5 versus the dosages predicted by the IChemE static model. (For the purpose of this comparison, the targets were located at grade, at the same distances as the radiometers, and were tilted such that the vector normal to the surface of each target passed through the center of the fireball. Atmospheric transmittance was calculated using the method proposed by Wayne [1991].) As shown in Figure 6, the static model overpredicts dosages, with the amount of overprediction being greatest at high dosages, i.e., at points closest to the fireball. (Although there are thirty-one data points, only twenty-five points are included in Figure 6. Six of the thirty-one predicted dosages exceeded 350 kJ/m^2, which put them outside the boundaries of Figure 6.)

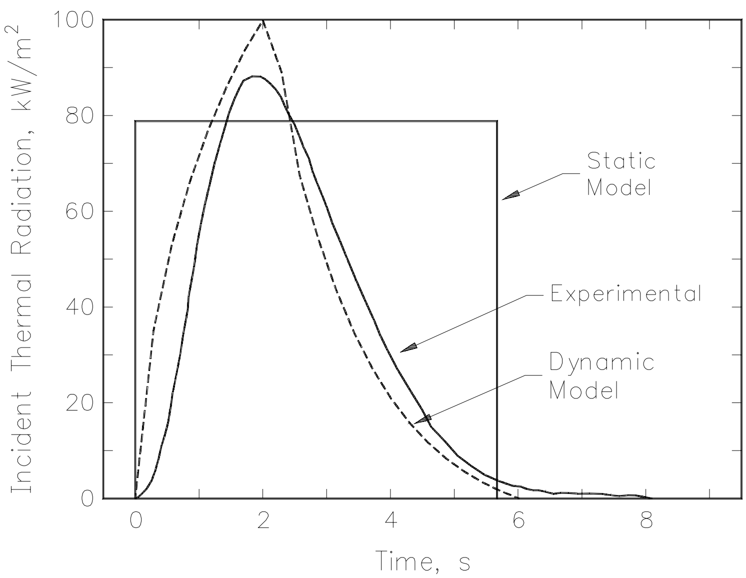

Figure 5
Comparison of Experimental and Predicted Incident Thermal Flux Histories

Figure 7 is a plot of the same dosage data versus predictions from the dynamic fireball model (with the target being moved and tilted such that it replicated the distances, elevations, and angles of inclination of the radiometers in the tests). A comparison of Figures 6 and 7 illustrates the degree of improvement provided by the dynamic fireball model.

Thus, in comparison to static fireball models, the dynamic model provides more realistic estimates of the extent of potentially damaging or injurious radiant heat hazard zones produced by fireballs, which makes it preferable to static models when conducting a hazards or risk analysis.

NOMENCLATURE

C	= proportionality factor
D	= maximum fireball diameter, m
$D(t)$	= fireball diameter at time t, m
f	= fraction of heat radiated, dimensionless
F	= geometric view factor, dimensionless
h	= distance from target to center of fireball, m
H_c	= heat of combustion of the fuel, kJ/kg
k	= constant
M	= mass of fuel involved, kg
n	= constant
P	= burst pressure, MPa
q_i	= incident heat flux on the target, kW/m^2
q_s	= surface emissive power of the flame, kW/m^2
R	= radius of the fireball, m
t	= elapsed time, seconds
t_d	= fireball duration, seconds
t_{lo}	= lift-off time, seconds
τ	= atmospheric transmittance, dimensionless

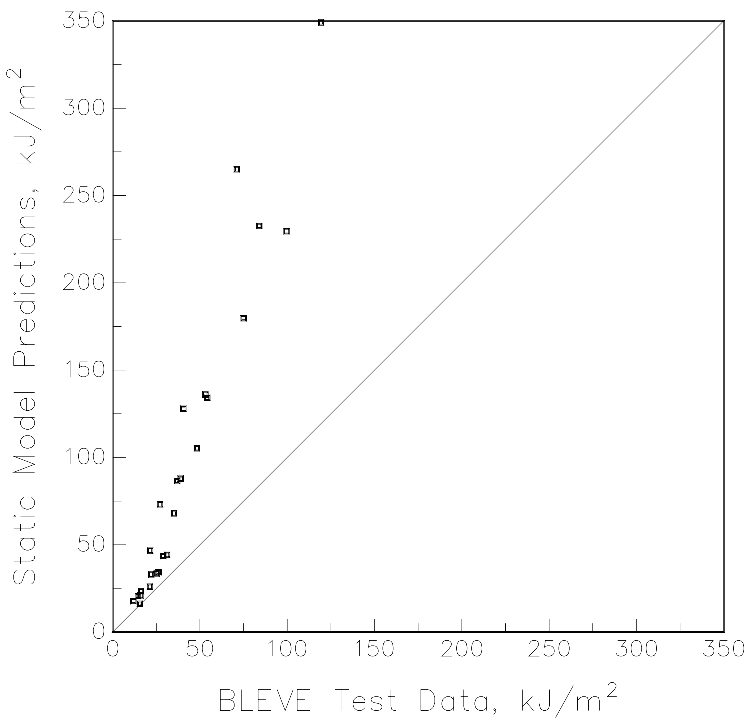

Figure 6
Absorbed Energy Predictions from the Static Model versus Experimental Data from Johnson, Pritchard, and Wickens [1990]

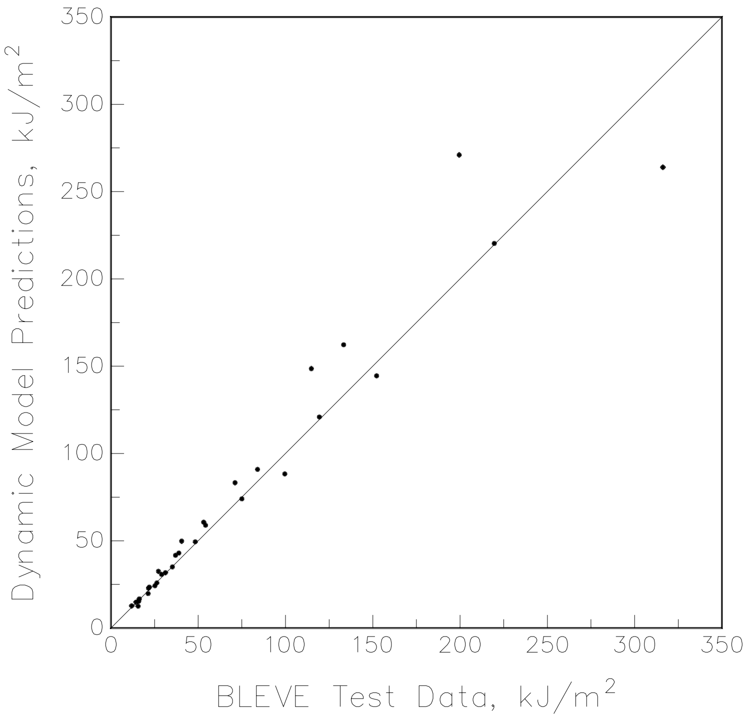

Figure 7
Absorbed Energy Predictions from the Dynamic Model versus Experimental Data from Johnson, Pritchard, and Wickens [1990]

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