Technical documentation and software quality assurance for project Eagle-ALOHA

A project to add fire and
explosive capability to ALOHA®

FEBRUARY 2006

This report summarizes the technical details and quality assurance methods for the addition to the NOAA/EPA air dispersion model (Areal Locations of Hazardous Atmospheres (ALOHA), of capabilities to estimate risk from simple fire and explosion hazards involving hazardous chemicals. It is a supplement to existing ALOHA documentation that describe the toxic atmosphere risk modeling of the earlier version.

Mention of a commercial company or product does not constitute an endorsement of that company or product.

Office of Response and Restoration
National Oceanic and Atmospheric Administration (NOAA)

Environmental Protection Agency (EPA)

Pipelines and Hazardous Materials Safety Administration
Department of Transportation

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Purpose:

Project Eagle-ALOHA modifies the existing model, Areal Locations of Hazardous Atmospheres (ALOHA) version 5, to include estimation of fire and explosive hazards related to accidental spills of flammable chemicals under certain scenarios. Following the philosophy of ALOHA, the new version reflects a compromise between complexity of the model and ease of use. Only information easily available to the first responder is required and output is designed to provide a conservative and simple graphic estimate. The additional scenarios are:

- pool fire
- BLEVE (boiling liquid expanding vapor explosion)
- flare (jet fire)
- flammable or explosive vapor cloud

Staffing:

CAMEO/ALOHA Program	Mark Miller, Carl Childs
Project co-managers	Jerry Muhasky, Bill Lehr
Software development	Jon Reinsch, Gennady Kachook
Algorithm development	Debra Simecek-Beatty, Robert Jones

Questions and bug reports:

software and interface	Jerry.Muhasky@noaa,gov
algorithms	Bill.Lehr@noaa.gov
model access	Mark.W.Miller@noaa.gov

Project Team Credentials:

Jerry Muhasky has a Ph. D. in Mathematics and has more than ten years experience in design of large environmental software programs. Dr. Muhasky is the lead programmer for ALOHA version 5. Bill Lehr has a Ph. D. in Physics and has over twenty years experience in software model development in the environmental field. Dr. Lehr was lead scientist for the source strength component of ALOHA, version 5. Jon Reinsch is an experienced software developer and was lead programmer for the NOAA/EPA RMPCOMP project. Gennady Kachook is an experienced programmer and has worked on several environmental modeling programs. Debra Simecek-Beatty is an environmental modeling specialist and has worked on several large modeling projects. Dr. Robert Jones has a Ph. D. in Chemistry and has been lead researcher on many ALOHA updates.

External Review Team:

James Belke	Environmental Protection Agency
Don Ermak	Lawrence Livermore National Laboratory

Martin Goodrich	Baker Engineering and Risk Consultants
Greg Jackson	University of Maryland
Tom Spicer	University of Arkansas
Doug Walton	National Institute of Science and Technology
Kin Wong	Department of Transportation

Special Training Requirements/Certification:

There are no special additional requirements or certification required to use the new fire and explosion option scenarios in ALOHA. However, certain terminology peculiar to these specific scenarios will be different from those involving the toxic gas model runs. It is recommended that anyone new to fire and explosives forecasting review the user documentation and become familiar with the example problems. In particular, hazards now include overpressure and thermal radiation risk, as opposed to toxic chemical concentrations.

Data Sources:

Eagle-ALOHA uses the existing ALOHA/CAMEO chemical data sources with the exception of information on fuel reactivity. For a small set of chemicals, ALOHA uses values for fuel reactivity referenced in Appendix C of John L. Woodward, Estimating the Flammable Mass of a Vapor Cloud, published by American Institute of Chemical Engineers, 1998. For all other flammable chemicals, ALOHA assigns medium reactivity.

TECHNICAL DOCUMENTATION

Program structure:

Generally, the project only allows the new scenarios for that subset of existing ALOHA chemicals that are classified by the National Fire Protection Association's Fire Protection Guide to Hazardous Materials as a category 3 or 4 flammable hazard. This includes flammable gases and liquids with a flash point below 100 °F. The model will allow the user to select combustible liquids (category 1 and 2 flammable hazard) but may, for low-temperature scenarios, provide a warning to the user that the chemical may not burn at the user-specified temperature.

Figure 1 shows the possible scenarios for a chemical release from a tank, pool, or pipeline with an ignition source present at the beginning of the release. For a delayed ignition, there may be time for a flammable cloud to develop, thereby creating the potential for a flashfire or explosion. For a pool release, there is also the potential for a flashback causing a subsequent pool fire. This is not modeled in this project.

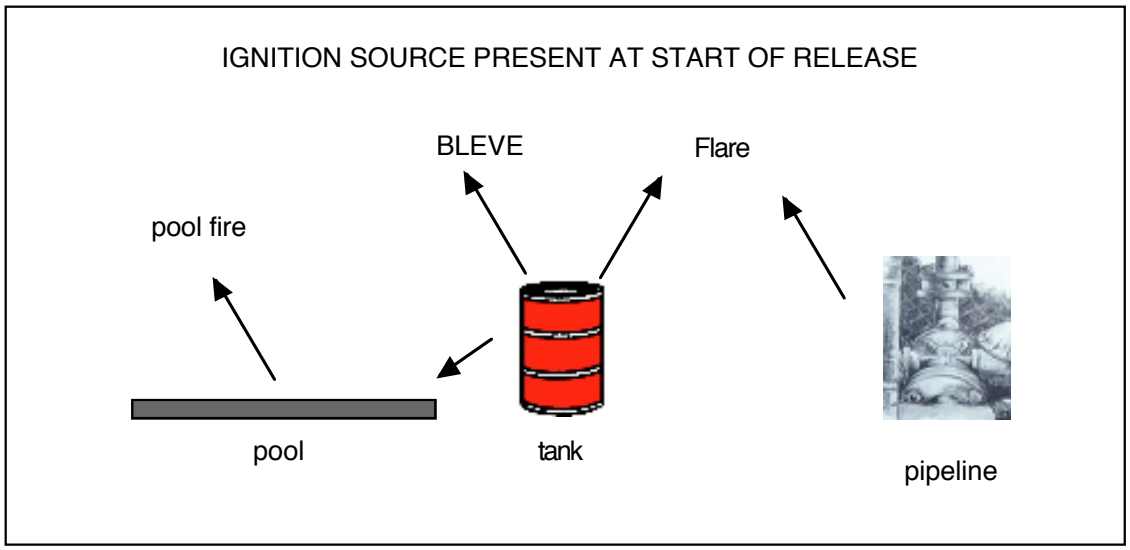

Figure 1. Possible scenarios when fire is present

ALOHA does not model liquid spills from pipelines. Spills of liquids from unpressurized tanks are assumed to form circular pools around the tank. These pools will spread until a minimum thickness or a maximum area (e.g., a spill into a diked pond) is reached. Pressurized tanks may produce a two-phase flow from the tank rupture. Some of the chemical may go into the air while some product spills onto the ground forming a pool fire. The fraction of chemical that contributes to the alternative scenarios will vary depending upon the chemical and release conditions.

Individual Scenario Documentation

BLEVE

Summary
Model calculates thermal radiation from BLEVE fireball, using standard formulas for fireball diameter and burn duration, a constant surface emissive power, atmospheric dampening, and a spherical view factor.

MODEL ASSUMPTIONS:

• Complete failure of the tank while engulfed in fire
• Up to three times the fraction flashed contributes to flashfire
• Overpressure hazard and fragment hazard are noted but not calculated
• Liftoff of fireball is neglected

MODEL INPUTS

• amount and type of chemical
• tank failure pressure or temperature

• radiation levels of concern (LOC)

MODEL DESCRIPTION

Figure 2 shows the flow diagram for the module. The model assumes complete tank failure while the tank is surrounded by fire. This is a common situation for a BLEVE occurrence. A limit of 5000 metric tones is employed as the maximum amount of chemical that will be modeled. This limit is of the order of the largest historical single BLEVE incident.

The model calculates only the thermal radiation hazard. The overpressure wave and any fragment hazard are not calculated although warning messages are provided. The reasons why they are not calculated are several. First, estimates of release energy by standard methods can only be given to an order of magnitude. Second, the main hazard posed by BLEVE of a flammable liquid is the radiation from the resulting fireball (AICHE Guidelines, 1994). Third, estimates of shrapnel mass, velocity, and number are apt to contain high uncertainties and are currently not estimated in the existing ALOHA code. Although non-flammable pressurized liquid containers can BLEVE, the model will not calculate effects from these scenarios, since overpressure and fragmentation effects are not calculated

Depending upon the chemical and the tank pressure and temperature at failure, not all of the product will flash and participate in the fireball. The fraction, f, that flashes is given by

$$f = \frac{C_p\left(T - T_b\right)}{H_v}$$

where T is the chemical temperature at tank failure, T_b is the ambient boiling point, C_p is the specific heat capacity at constant pressure, and H_v is the latent heat of vaporization. If the fraction is more than one third, then the entire tank contents participate in the fireball. If it is less than one third, then following Hasegawa and Sato (1977), three times the amount flashed is used in the fireball calculation. The amount not contributing to the fireball is used for a pool fire scenario.

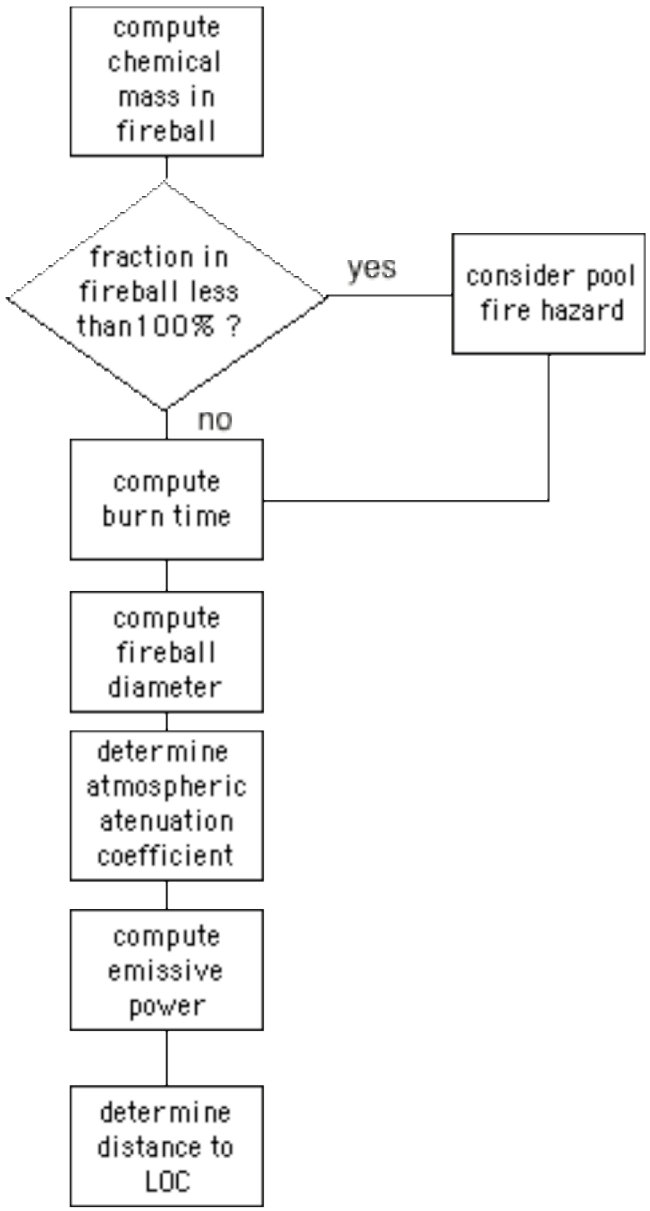

Figure 2. BLEVE flow diagram

The model uses an average of empirical formulas to estimate the maximum diameter of the fireball from the fractional mass participating in the fireball. (see table).

$$D_{\max}(meters) = 5.8 mass^{1/3}(kg)$$

reference	mass exponent(diameter)	mass exponent (time)	max. diam.(m) for 10,000 kg release
Lihou and Maund	0.320	0.320	74
Duiser	1/3	1/6	117
Fay and Lewis	1/3	1/6	135
Hasegawa and Sato	0.277	0.097	67
Roberts	1/3	1/3	125
Williamson & Mann	1/3	1/6	127
Moorhouse & Pritchard	0.327	0.327	108
Pieterson	0.325	0.26	129
TNO	0.325	0.26	129
Martinsen & Marx	1/3	0.25	124

Table 1: Reported empirical mass exponents for diameter and burn time formulas. Note that formulas were developed using different chemicals and definition of mass so results may not be directly comparable

The time of the burn uses a slight modification of the TNO formula (based upon averages obtained from reported literature values [TNO, 1992])

$$t_{burn}(\text{sec}) = 0.9 mass^{1/4}(kg)$$

The TNO formula assumes that the fireball forms directly above the vessel and grows in size according to

$$D(meters) = 8.66 \cdot mass^{1/4}(kg) \cdot t^{1/3}(\text{sec}) \qquad t \le \frac{1}{3} t_{burn}$$

reaching its maximum size at 1/3 of the burn time. Dynamic models of the fireball would then have the ball lift off the ground, with the center of the ball eventually reaching 3 times the radius of the fireball (alternative formulas base liftoff time as a function of mass) The ALOHA model, however, does not model the liftoff since keeping the fireball on the ground yields a more conservative answer. Also the radiation hazard footprint is based upon the maximum fireball diameter.

Experiments show that the surface emissive power, E, depends upon fireball size, the actual distribution of flame temperatures, partial pressure of combustion products and other factors. One common method is to estimate emissive power using the vessel burst pressure, but this is not determined based upon the limited information asked the ALOHA user. Experiments by British Gas give average surface-emissive powers between 320-370 kW/m2 for hydrocarbon fuels. AICHE suggests that 350 kW/m2 is a reasonable emissive power for such fuels, using experimental results for butane and propane. ALOHA adjusts this value by multiplying 350 by the ratio of the heat of combustion of the chemical divided by the heat of combustion of propane.

Experimental fireballs show a reduction in peak radiation during the last two-thirds of the burn. ALOHA adopts the more conservative approach by keeping radiation levels fixed at a constant level during this time period.

Thermal radiation transmitted from the fireball can be reduced considerably due to absorption and scattering from the atmosphere. According to Lees (2001), there are many different ways to calculate the atmospheric transmissivity coefficient, τ. For simplicity, three transmissivity formulas were considered that only require data already available in ALOHA, specifically, the relative humidity. The first two formulas selected from Lees follow

$\tau = 1.382 - 0.135\log_{10}(\rho_w x)$ TNO (1979) Yellow Book
$\tau = 2.02(\rho_w x)^{-0.09}$ TNO revised

In ALOHA, the atmospheric water vapor pressure in Pascals is computed by

$$\rho_w = 99.89\frac{R_H}{100}\exp\left(21.66 - \frac{5431.3}{T_a}\right)$$

where T_a is the ambient air temperature and R_H is the relative humidity (Thibodeaux, 1979).

Comparison values generated from the above formulas for a range of ambient temperatures and relative humidities indicated the two TNO methods agree very well over a wide range of conditions and distances. We then compared the TNO methods with Wayne (1991) empirical formulas:

$$\tau = 1.006 - 0.01171\left[\log_{10} X(H_2 0)\right] - 0.02368\left[\log_{10} X(H_2 0)\right]^2 - 0.03188\left[\log_{10} X(CO_2)\right]$$
$$+0.001164\left[\log_{10} X(CO_2)\right]^2$$

with

$$X(C0_2) = L\frac{273}{T}$$
$$X(H_2 0) = R_H L S_{mm}\left(\frac{288.651}{T}\right)$$

where L is the path length, R_H is the fractional relative humidity, S_{mm} is the saturated vapor pressure of water temperature T, T is the atmospheric temperature, $X(C0_2)$ is a function representing the amount of carbon dioxide in the path and $X(H_2 0)$ is a corresponding function for water vapor.

Both TNO methods show good agreement with Wayne's method for most conditions and distances, but there is disagreement for the higher ambient temperatures (40 C) and high relative humidity cases. Limiting the Wayne's values to a minimum of 0.46 brings this method closer to the TNO methods for the high ambient temperature and humidity cases. The differences between the three approaches for calculating atmospheric transmissivity were not considered significant. For consistency, the TNO (1979 Yellow Book) method is used because the formulas also appear in Cook (1991), used elsewhere in the flare scenario..

The view factor, F, is defined as the ratio of the incident radiation received by a surface to the emissive power from the emitting surface per unit area. ALOHA uses a spherical view factor for the fireball.

$$F = \frac{xr^2}{\left(x^2 + r^2\right)^{3/2}} \qquad x > r$$

where r is the radius of the fireball.

The incident radiation, q, received at the object a distance x away is

$$q = E \cdot F \cdot \tau$$

The damage from the heat radiation is properly measured as a dosage; heat radiation received over time. However, ALOHA plots concentration for toxicity for toxic gas clouds. Hence, to be consistent with regard to the various hazards, levels of concern for burn hazard are expressed in terms of incident radiation level. However, it should be noted by the user that burn times for fireballs are short. The actual amount of thermal radiation dosage received may be higher for a pool fire of lower peak radiation intensity.

OUTPUT

Module returns heat radiation hazard threat zone for each LOC. Threat zone must not be smaller than the fireball itself.

Major References

Center for Chemical Process Safety (1994) Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVES, American Institute of Chemical Engineers, New York.

K. Hasegawa and K. Sato (1977) Study on the fireball following steam explosion of n-pentane. *Second International Symposium on Loss Prevention and Safety Promotion in the Process Industry*, pp 297-304, Heidelberg.

F. Lees (2001) Loss Prevention in the Process Industries, Butterworth-Heinemann, Boston.

TNO, Committee for the Prevention of Disasters (1992) Methods for the calculation of physical effects, 2nd edition, Netherlands.

L.G. Thibodeaux, (1979) Chemodynamics: Environmental Movement of Chemicals in Air, Water, and Soil, John Wiley and Sons.

F.D. Wayne (1991) An economical formula for calculating atmospheric infrared transmissivities, *J. of Loss Prevention* 4:186.

POOL FIRE

Summary:
Model calculates thermal radiation from a spreading or fixed pool. Flame is represented by solid tilted cylinder. Length of cylinder is determined from pool diameter using Thomas equation. Average emissive power is estimated from the heat of combustion and burn regression rate.

MODEL ASSUMPTIONS

• Burn regression rate is constant
• Pure chemicals burn clean (little smoke production)
• Flames are optically thick
• Circular pool

MODEL INPUTS

•wind speed
•radiation levels of concern (LOC)
•pool area (stand-alone)
•initial pool thickness (stand-alone)

MODEL DESCRIPTION

Figure three shows the pool fire flow diagram. Flammable and volatile liquid spilling from a container can produce large pool fires. This is particularly true for cryogenic liquids that will rapidly boil an as they spread. The major threat from such fires is thermal radiation hazard, which can produce damage directly, or cause secondary fires. Key factors in modeling pool fires are such things as spread rate of the pool, burn rate, smoke fraction, geometry of the flame and thermal emission rate.

The user has two options; either (1) a stand-alone puddle where the user inputs the volume and area of the puddle or (2) a spreading puddle based upon a leak from a tank. The leak rate from the tank will vary over time and is calculated using the standard ALOHA algorithms. In both cases, the pool is assumed to be circular, uniformly thick, and on a level surface.

For the stand-alone case, the pool maintains a constant surface area and burns with a constant regression rate until the chemical is completely consumed. The burn regression rate is calculated from ratios of the heats of combustion and vaporization. A study done for the Bureau of Mines determined that liquid fuel burn rate may be correlated to

$$\dot{h}_o = 1.27 \cdot 10^{-6} \frac{\Delta H_c}{\Delta H_v}$$

where $\dot{h}_o$ is the burn regression rate in m/sec and $\Delta H_{c,v}$ are the net heats of combustion and vaporization in J/kg. A similar correlation for mass burn rate is

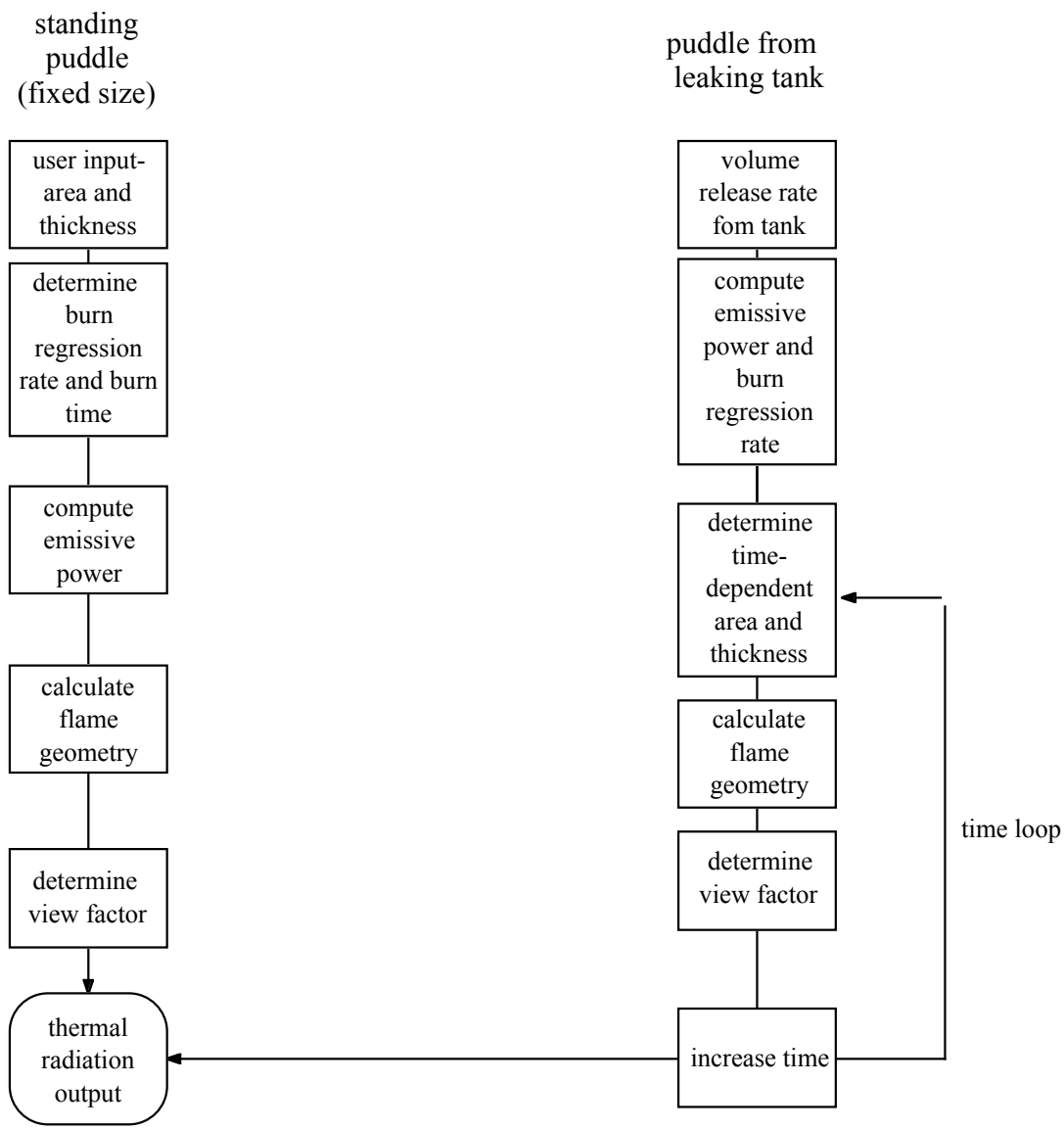

Figure 3. Pool fire flow diagram

$$\dot{m} = 0.001 \cdot \frac{\Delta H_c}{\Delta H_v + C_p\left(T_b - T\right)}$$

where $\dot{m}$ is the mass burning rate (kg/m2-sec), C_p is the specific heat capacity (J/kg K), T_b is the ambient boiling temperature (K) and T is the initial pool temperature.

According to experimental results, this latter correlation works better for a wider range of fuels, including liquefied gases such as LNG or LPG. Therefore, it is the correlation used by the program. Mixtures of chemicals are more problematic since the mole fraction of the components changes over time, affecting heat estimates. The current version of ALOHA does not estimate this for mixtures. Burning rates for liquids on water, particularly cryogenic liquids, are probably greater, and more variable, than burning on land but are not modeled in the program.

The burn time of the pool fire is determined by

$$\tau = \frac{\rho h_0 A}{\dot{m}}$$

where τ is the time, h_0 is the initial spill depth, A is the pool area and ρ is the chemical liquid density. The liquid density is assumed constant throughout the burn and is determined by the present methods used in ALOHA.

Pools caused by leaking tanks are handled similarly to the existing ALOHA methods except that evaporation is replaced by burning as the removal mechanism from the surface of the pool. Increase of the pool area is based upon Fay gravity-inertial spreading. This means that the radius of the pool, r, grows according to

$$\frac{dr}{dt} = \frac{1}{r}\sqrt{\frac{2g\dot{V}_0 t}{\pi}}$$

where $\dot{V}_o$ is the time-dependent volume leak rate from the tank. The 2 under the radical comes from Briscoe and Shaw's effort to account for inertia of the spreading liquid. ALOHA has the puddle cease spreading when the thickness reaches 0.5 cm on land. ALOHA does not model burning on water.

ALOHA limits the maximum diameter of any potential pool fire to 200 m. The simple pool fire model is probably not applicable to very large pool fires since such factors as pool breakup and oxygen supply are not calculated. The model stops pool spreading either when the ALOHA thickness or diameter limit is met.

The flame of the pool fire is assumed to be an optically dense cylinder. The average emissive power per unit area, E, of the cylinder surface is estimated using the approach of Moorhouse and Pritchard (1982)

$$E = \frac{f_{rad}\Delta H_c \dot{m}}{\left(1 + 4\frac{H}{d}\right)}$$

Here, $\frac{H}{d}$ is the ratio of the flame height to the diameter of the pool. The fraction of heat radiated, f_{rad}, depends upon the chemical. Mudan (1984) reports that the fraction of heat

radiated by pool fires varies from 0.15 to 0.6. Roberts (1981) suggests a default factor of 0.3 that is used by the model.

The flame geometry is that of a tilted cylinder which intersects a plane parallel to the ground in a circle. The flame length (see Figure 4), h, is estimated by a modification of the Thomas formula for flame length. Let u^* be a non-dimensional wind velocity defined as

$$u^* = u \cdot \left(\frac{\rho_a}{g \cdot \dot{m} \cdot d} \right)^{1/3}$$

Then the flame length is given by

$$h = d \cdot 55 \cdot \left(\frac{\dot{m}}{\rho_a \cdot \sqrt{g \cdot d}} \right)^{0.67} \cdot \left(u^* \right)^{-0.21}$$

Here, ρ_a is the air density.

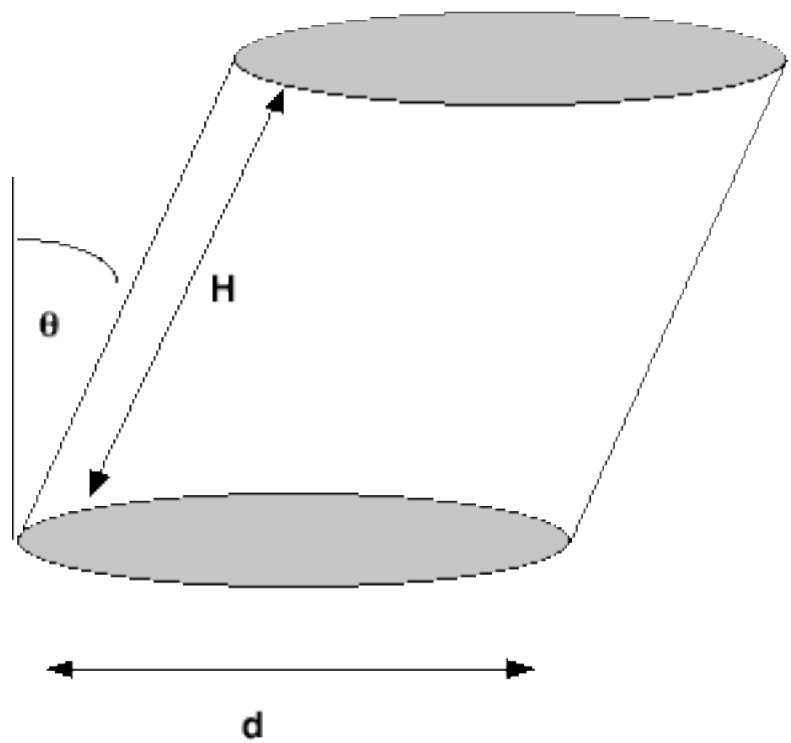

Figure 4. Flame geometry

The angle of tilt is given by (based on formulas from the American Gas Association)

$$\cos\theta = 1 \;\; if \;\; u^* < 1$$
$$= \frac{1}{\sqrt{u^*}} \;\; otherwise$$

The incident radiation intensity, q, received at the object a distance x away is

$$q = E \cdot F \cdot \tau$$

where:

E is the emissive power,
F is the view factor defined as the ratio of the incident radiation received by a surface to the emissive power from the emitting surface, and
τ is the attenuation by the atmosphere (see BLEVE scenario discussion).

The damage from the heat radiation is properly measured as a dosage; heat radiation received over time. However, ALOHA plots concentration for toxicity for toxic gas clouds. Hence, to be consistent with regard to the various hazards, levels of concern for burn hazard are expressed in terms of incident radiation level.

The view factor F is defined by Sparrow and Cess, equation 4-14:

$$dF_{A_j - dA_i} = \frac{dA_i}{A_j} \int_{A_j} \frac{\cos\beta_i \cos\beta_j dA_j}{\pi r^2}$$

where:
A_j is the area of the radiating surface,

dA_i is the receiving element,

β_i is the angle between the normal to the receiving element and the line between the element and the radiating surface,
β_j is the angle between the normal to the radiating surface at a point and the line between that point and the receiving element,
r is the distance between the point on the radiating surface and the receiving element.

For a radiating surface of area A_i and a receiving element of area dA_j, we can let
q' = incident radiation intensity per unit area, and
E' = emissive power per unit area,
so

$$q' = \frac{q}{dA_i} = \frac{E \cdot F \cdot \tau}{dA_i} = \frac{E' \cdot A_j \cdot F \cdot \tau}{dA_i} = E' \cdot \left(\frac{A_j}{dA_i} \cdot F \right) \cdot \tau \, .$$

Thus it is actually $\int_{A_j} \frac{\cos\beta_i \cos\beta_j dA_j}{\pi r^2}$ that we need to calculate.

We calculate this integral numerically by dividing the flame surface into 1000 tiles (40 radial divisions x 25 axial divisions). The value of the integrand is calculated at the center of each tile[1], and those values are added to produce an estimate of the integral. This process is carried out for three orthogonal orientations of the receiving surface, producing view factors f_1, f_2, and f_3. The maximum view factor (over all orientations of the receiving surface) is then calculated as:
$f = \sqrt{f_1^2 + f_2^2 + f_3^2}$. (For a true view factor, the integral omits portions of the radiating surface where $\cos\beta_j$ <0. But since f_1, f_2, and f_3 are used to calculate the maximum view factor, portions where $\cos\beta_j$ <0 are not excluded.)

OUTPUT

Module returns heat radiation hazard threat zone for each LOC. Threat zone must not be smaller than the pool fire itself.

Major references

F. Lees (1996) Loss Prevention in the Process Industries, 2nd edition, Butterworth-Heinemann, Boston.

K. Mudan (1984) Thermal radiation hazards from hydrocarbon pool fires. *Progress in Energy Combustion Science* 10:59-80.

J. Moorhouse and M. Pritchard (1982) Thermal radiation hazards from large pool fires and fireballs, *Industrial Chem. E. Symposium Series.*

A.F. Roberts (1981) Thermal radiation hazards from releases of LPG from pressurized storage, *Fire Safety Journal* 4:197.

E. M. Sparrow and R. D. Cess (1978) Radiation Heat Transfer, Hemisphere Pub. Corp., New York.

P.H Thomas (1963) The size of flames from natural fires, *9th International Combustion Symposium, Combustion Institute*, Pittsburgh, PA, pp 844-859.

VAPOR CLOUD SCENARIOS

Summary:
Program considers flashfire risk as 0.6 of the LEL. Explosive model uses Baker-Strehlow-Tang method to estimate overpressure. Two cases are considered, hard ignition, which assumes an initial detonation, and soft ignition, which assumes a deflagration. The mass of the vapor cloud between the UEL and 0.9 LEL is assumed to participate in the explosion with 20% efficiency for deflagration and 100% for detonation. Explosion is considered to be unconfined with varying levels of congestion.

[1] For tiles at the base of the flame surface, the point used is on the ground, not the tile center. This permits greater accuracy when calculating view factors for observers near the surface.

MODEL ASSUMPTIONS

- Gas dispersion module provides reasonable estimate of gas concentration
- Explosion overpressure waves are hemispherical
- Gas ignition is at ground level
- Congestion level is uniform throughout vapor cloud
- Flashfire hazard footprint corresponds to 0.6 LEL
- Explosive mass fraction between UEL and 0.9 LEL concentrations
- Explosion efficiency factor is 20%-100%
- Detonation flame speed is 5.2 Mach

MODEL INPUT

- vapor cloud concentrations (from other ALOHA modules)
- overpressure levels of concern
- level of congestion
- ignition time (optional)
- choice of hard or soft ignition

MODEL DESCRIPTION

Figure 5 shows the module flow diagram. If there is no immediate ignition of the released gases, a flammable vapor cloud may spread from the source point. This cloud may present a flashfire hazard or, less likely, an explosive hazard, until the gas disperses sufficiently. ALOHA uses either a Gaussian plume or a heavy gas model (DEGADIS) to compute the gas concentration over time and space. See the ALOHA technical documentation for the details.

In the case of a flashfire, a flame front is propagated by molecular-diffusive transport or turbulent mixing from the ignition source. Radiation from flashfires can be estimated by formulas similar to those used to compute radiation hazards from pool fires except that the view factor used is a flat, vertical radiator rather than a cylinder. Typically, however, the radiation generated is highly transient and standard methods give too high an answer because the flame will probably not burn as a closed front. Therefore, the model uses the approach of EPA/CEPP (RMP) and assumes that the risk footprint from radiation hazard is equivalent to a fraction of the lower flammability or explosive limit footprint (ground level concentration contour) for the cloud. Based upon recommendations of the project external review team, the choice was made to use 60% of the lower flammability limit as the level of concern in defining this risk footprint. This value reflects the fact that the concentration calculation in ALOHA involves some time averaging. Therefore, there is the possibility that a location with an average concentration below the LEL may have a fluctuating concentration that sometimes exceeds the LEL.

In calculating the explosive risk, ALOHA calculates the mass of the released gas that is between the upper and 90% of the lower flammability limit (between UEL and 0.9 LEL). Gas concentrations above the upper limit are presumed to be too rich and those below the lower limit too lean to participate in the explosion. This calculated mass is

time-varying, depending directly upon the gas release source rate and the vapor cloud dispersion.

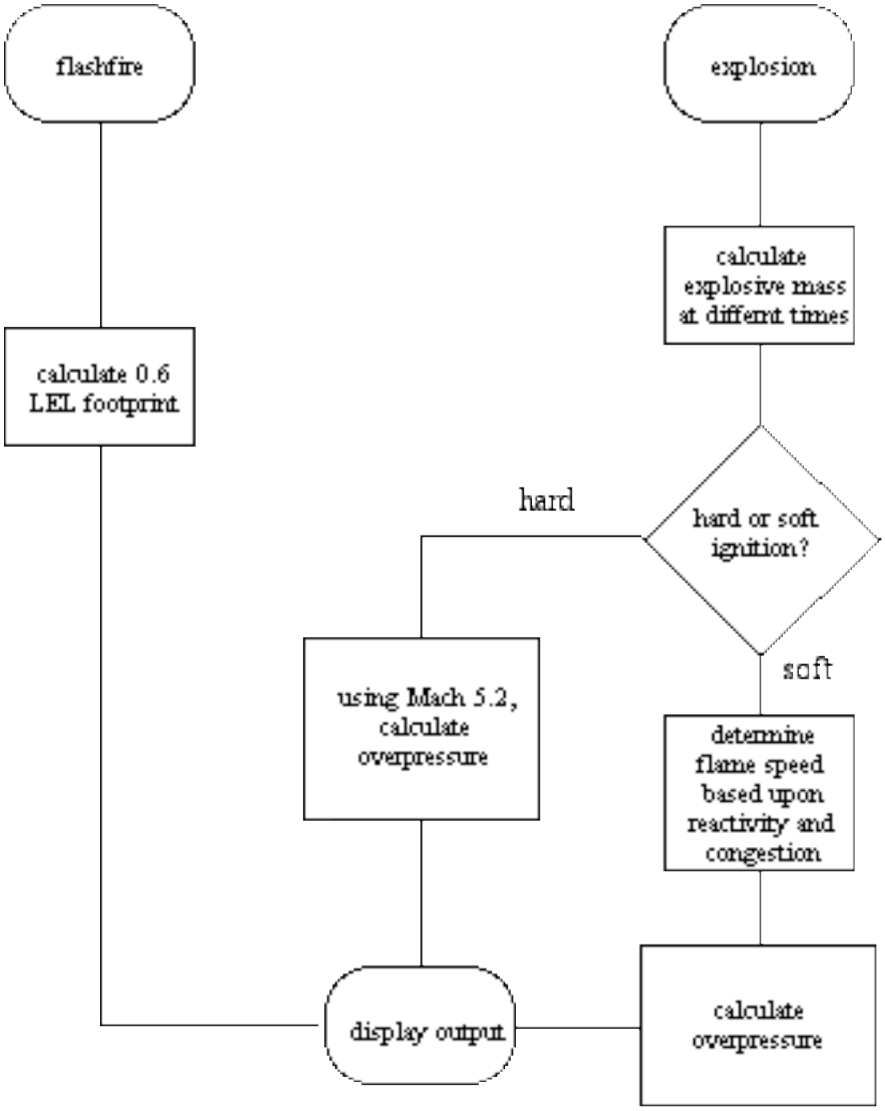

Figure 5. Vapor cloud scenario flowchart

The center of an explosion can be different than the center of the chemical release. ALOHA uses the time dependent ground level center-of-mass of the cloud as the explosion ignition point. It does this in two ways. If the user sets the ignition delay time, i.e. the time between the start of the gas release and the start of the explosion, then ALOHA uses the center-of mass at this time to determine the explosion center. If the user does not specify the ignition delay time, then ALOHA determines a summary footprint, based upon maximum overpressures from explosions at different locations, representing the center-of-mass at different times. This is similar to the non-temporal summary footprint that ALOHA displays for toxicity levels. The maximum time used in calculating

this summary footprint is less than the time when the centerline concentration of 0.9 LEL last reaches the farthest distance from the gas release source point.

ALOHA separates the explosive scenario into two cases. The first case assumes that the initiation of the explosion involves such a high energy that a detonation (reaction front exceeds sonic velocity) begins immediately. This is called a 'hard ignition' in the model. An example would be ignition by high-energy condensed matter explosive. Direct initiation of detonation requires large amounts of energy. The Center for Chemical Process Safety (1994) estimates that direct initiation of detonation requires an energy of approximately one million Joules. A much more likely explosion case is deflagration (reaction front less than sonic velocity), where initiation can occur at less than one Joule. The low energy initiation case is referred to in the model as 'soft ignition'. Under special confinement and congestion circumstances, a deflagration may transition to a detonation.

Following the Center for Chemical Process Safety (CCPS) guidelines, the model estimates the energy participating in the explosion as

$$E = ref \cdot e_f \cdot H_c \cdot Mass$$

where ref is a ground reflection factor. The model uses a value of 2 for ref, assuming a cloud that is contact with the ground. Elevated clouds would have a smaller reflection factor. The efficiency factor e_f is set to 20%, the high end of the range (5%-20%) mentioned by CCPS, since the philosophy of the program is to provide a conservative estimate. However, others (Woodward, 1998) suggest an even higher maximum efficiency rate, as high as 75% for highly reactive materials. $Mass$ refers to the flammable mass calculated as described earlier. Based upon the recommendation of our expert review panel, the project team uses 100% efficiency for the detonation scenario.

The model uses the Baker-Strehlow-Tang (Tang and Baker, 1999) approach to model predicted overpressures. This vapor cloud explosion prediction methodology uses non-dimensional, empirically derived blast curves to predict blast load. The basic principle of this method for explosion modeling is similar to another widely used approach, the multi-energy method. Both methods assume that within the vapor cloud there are areas of congestion where, during deflagration, flames accelerate. After exiting these areas, the flame front decelerates. In general, overpressure will be larger in deflagrations where the fractional congestion volume blockage is larger but the average obstacle size is smaller and the flame path length is a maximum. In a real incident it is possible to have different areas with varying levels of confinement and obstacle density, resulting in a series of different sub-explosions. ALOHA does not offer this option. The vapor cloud is assumed to be unconfined and congestion throughout the flammable cloud region is taken to be uniform. The user therefore needs to use the model with discretion, realizing that an actual explosion might be quite different than the model predictions.

The user is allowed to directly assign high (congested) or low (uncongested) congestion level. As guidance, Baker et al. (1994) defines congestion levels in terms area blockage ratio (ABR), i.e. the area blocked by obstacles divided by the total area. Areas with ABR less than 10% and having widely spaced obstacles is considered low congestion. Those with ABR greater than 40 % with fairly close obstacles are defined as high congestion.

A second parameter for the Baker-Strehlow-Tang (BST) approach is the reactivity of the released gas. Reactivity ratings used by Zeeuwen and Wiekema (1978) classify reactivity based upon chemical laminar burning velocity. Low reactivity has velocities less than 45 cm/sec. High reactivity applies to those chemicals with burn velocities greater than 75 cm/sec and anything in between is labeled medium reactivity. Most of the flammable chemicals in ALOHA do not have reactivity values. As a default (reactivity not known), the model uses medium reactivity.

Based upon values for congestion and reactivity, BST estimates turbulent flame speed in Mach number. The model uses recent Mach values (Pierorazio et al, 2005) that are higher than those found in earlier publications. These newer values are based upon larger scale experiments and are claimed to better represent results typical of an industrial plant incident. Note, in certain cases, the tables predict that there will be a deflagration to detonation transition (DDT). Based upon a recommendation from the external review team, the model uses the same Mach number as in the hard ignition detonation scenario.

reactivity\congestion	low	medium	high
high	0.36	DDT	DDT
medium	0.11	0.44	0.5
low	0.026	0.23	0.34

Table 2 : Revised Baker-Strehlow-Tang flame speeds (Mach number)

The Baker-Strehlow-Tang-model uses a set of empirically determined graphs of normalized overpressure versus normalized distance with a different graph for different flame speeds. The model does a curve fit to these graphs, using a function of the form

$$y = D \;\; if \;\; x < x_0$$
$$else \;\; y = A \cdot B^{1/x} x^C$$

where A, B, C, D, and x_0 are constants. The table gives values of these constants for various flame Mach numbers

constants\Mach	0.2	0.35	0.7	5.2
A	0.0335	0.1041	0.3764	0.2932
B	0.8359	0.8642	0.7439	1.399
C	-1.1192	-1.0568	-1.2728	-1.1591
D	0.065	0.22	0.65	20
x_0	0.35	0.32	0.3	0.16

Table 3 : Curve fit constants for various Mach numbers for use in the BST method

The normalized distance, x, is defined as

$$x = r \cdot \sqrt[3]{\frac{E}{P_{atm}}}$$

where E is the participating energy calculated earlier. P_{atm} is the atmospheric pressure and r is the actual distance away from the center of the explosion. The normalized overpressure y is given by

$$y = \frac{\Delta P}{P_{atm}}$$

where ΔP is the maximum overpressure.

If the hard ignition option is selected by the user, a detonation situation is presumed from the beginning and the BST curve for Mach 5.2 is used to estimate the overpressure.

OUTPUT

For the flashfire, the level of concern footprint is the 0.6 LEL contour. For the overpressure case, three levels of over-pressure are plotted. While these can be changed by the user, the defaults are 1.0, 3.5, and 8 psi. These relate, respectively, to overturning objects and personnel, possible serious personal injury, and serious risk of death from the direct blast.

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FLARE (Jet Fire)

Summary:
Model calculates the size and shape of a flare or jet for gaseous releases from pipelines, tanks and two-phase releases from tanks. Chamberlain (1987) empirical formulas for vertical and inclined burns in a horizontal wind are used to describe the geometry of the flame.

MODEL ASSUMPTIONS

• Gas releases from pipe or tank
• Choked and unchoked flow
• Two-phase flow from tank
• Flame assumed from open pipe rather than flare tip
• Burning gas is assumed to behave similar to a hydrocarbon (methane, propane and ethylene).
• Visible flame described by a frustum of a cone

MODEL INPUTS

• inside diameter of the pipe or orifice (meter)
• average wind speed (meter per second)
• density of air

MODEL DESCRIPTION

Figure 6 shows the flow diagram for the flare. An in-depth description of the model is reported in Chamberlain (1987) and Lee (2001). Chamberlain's model was selected over the alternative point source model since the latter is known to be insufficient within one to two flame lengths for short-term radiation levels although sufficiently accurate in the far field (Chamberlain, 1987). The Chamberlain better mimics the actual size and shape of a flare.

A review of the literature in SFPE (1995) and Lee (2001) identified two versions of the model, Kalghatgi (1983) and Chamberlain (1987), both of which approximated the geometry of a flare as a frustum of a cone. While Kalghatgi's used small burners in a wind tunnel, the main focus of Chamberlain's work was on field trials at onshore oil and gas production installations. Both models used empirically fit equations to describe the flame shape. In fact, Chamberlain uses Kalghatgi (1983) empirical equation to derive the flame length. Because Chamberlain's work was more recent and involved larger scale testing, the Chamberlain model was selected for ALOHA to describe thermal radiation hazards for both flares and jets.

From Chamberlain (1987), the gas velocity of the expanded jet, u_j, is

$$u_j = M_j \sqrt{\frac{\gamma_g R_c T_j}{W_{gk}}}$$

For unchoked flow, the Mach number of the expanded jet, M_j, is calculated

$$M_j = \left[\frac{\left(1 + 2(\gamma_g - 1)F^2\right)^{\frac{1}{2}} - 1}{(\gamma_g - 1)} \right]^{\frac{1}{2}}$$

The effective source diameter, D_s, is

$$D_s = d_o \sqrt{\frac{\rho_j}{\rho_a}}$$

for pure gas. The effective source diameter is the throat diameter of an imagined nozzle from which air at normal ambient density issues at the gas mass flow rate and exit velocity. Here

$$\rho_j = \rho_g \frac{273}{T_j}$$

For choked flow, M_j, is

$$M_j = \sqrt{\frac{\left(\gamma_g + 1\right)\left(\frac{P_c}{P_o}\right)^{\frac{(\gamma_g - 1)}{\gamma_g}} - 2}{\left(\gamma_g + 1\right)}}$$

The jet expands to atmospheric pressure at a plane downstream of the exit hole with the plane acting as a virtual source of diameter, d_j. Then

$$D_s = d_j \sqrt{\frac{\rho_j}{\rho_{air}}}$$

$$d_j = \sqrt{\frac{4\dot{m}}{\pi u_j \rho_j}} = \sqrt{\frac{4\dot{m}}{\pi P_o M_j} \sqrt{\frac{R_c T_j}{\gamma_g W_{gk}}}} = \sqrt{3.6233 \cdot 10^{-5} \frac{\dot{m}}{M_j} \sqrt{\frac{T_j}{\gamma_g W_{gk}}}}$$

where

$$F = 3.6233 \cdot 10^{-5} \frac{\dot{m}}{d_o^2} \sqrt{\frac{T_s}{\gamma_g W_{gk}}}$$

$$P_c = 3.6713 \frac{\dot{m}}{d_o^2} \sqrt{\frac{T_c}{\gamma_g W_{gk}}}$$

$$T_j = \frac{2T_s}{2 + \left(\gamma_g - 1\right) M_j^2}$$

$$T_c = \frac{2T_s}{1 + \gamma_g}$$

These formulas need to be modified slightly for the pipeline flare and two-phase release scenarios. ALOHA assumes that the gas expands adiabatically in the last 200 pipe diameters in the pipeline release. It exits at atmospheric pressure and therefore the effective source diameter, D_s for the choked option reduces to that for the unchoked option given earlier. For two-phase, ALOHA uses a modification of the formula in Cook et al. (1990)

$$D_s = d_j \sqrt{\frac{\sqrt{\rho_j \rho_v}}{\rho_a}}$$

where ρ_v is the pure vapor density. The modification of the Cook formula was necessary to insure that it would reduce to the proper algorithm when the two-phase case reduced to the pure gas scenario.

For a tilted jet, Kalghatgi (1983) showed in laboratory experiments that the flame length reduces as the jet is tilted into the wind. Chamberlain (1987) uses Kalghatgi's empirical fit equation to determine the flame length, LB. Extending from the center of the hole to the flame time, LB, is calculated

$$L_B = 105.4 D_s \left[1 - 6.07 \cdot 10^{-3} \left(\theta_j - 90\right)\right]$$

and the flame length in still air, LBO,

$$L_{Bo} = \frac{L_B}{\left[0.51 \exp\left(-0.4 v\right) + 0.49\right]\left[1 - 6.07 \cdot 10^{-3} \left(\theta_j - 90\right)\right]}$$

$$\xi\left(L_{Bo}\right) = \left[\frac{g}{D_s^2 u_j^2}\right]^{\frac{1}{3}} \cdot L_{Bo}$$

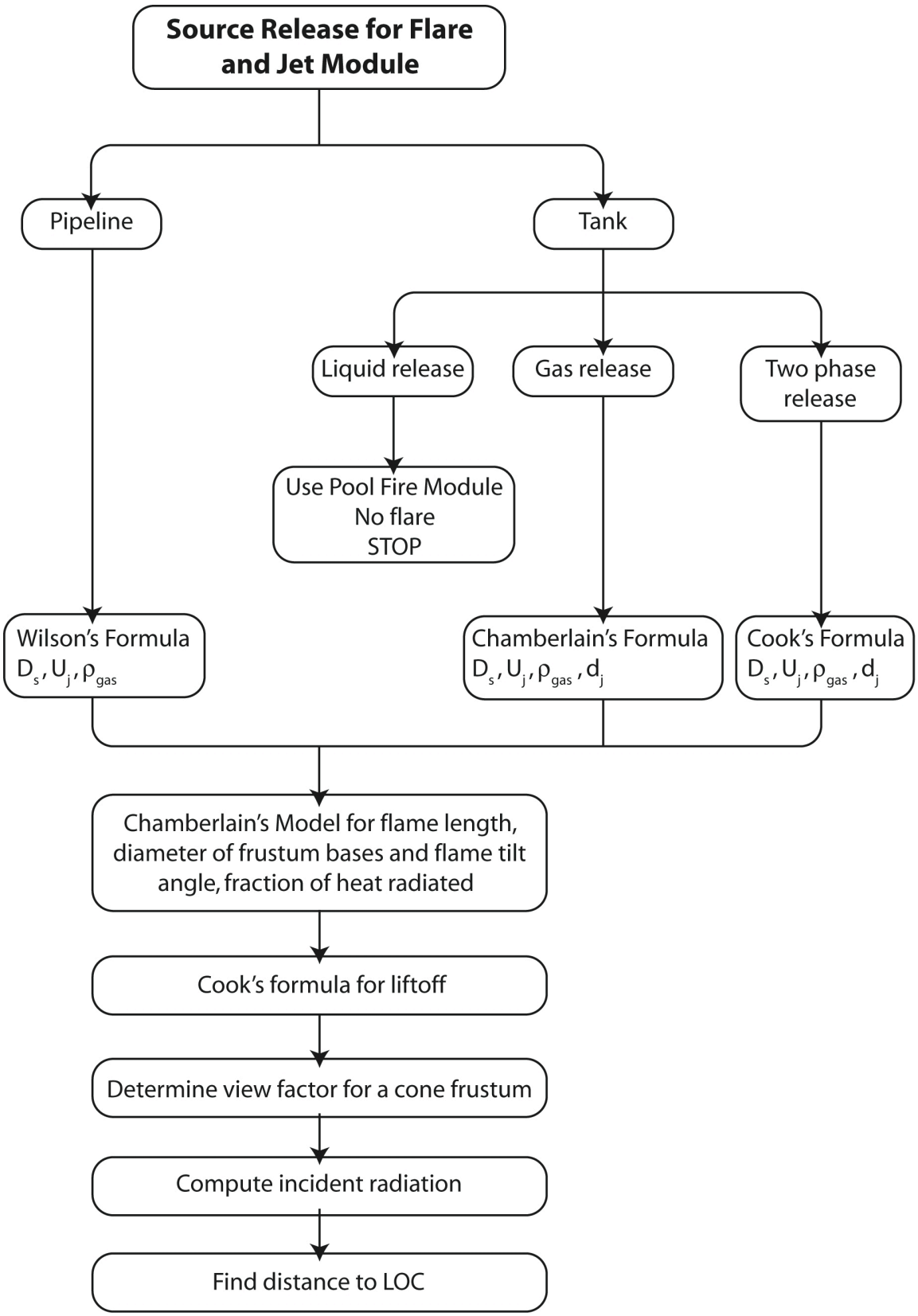
Source Release for Flare and Jet Module
Pipeline
Tank
Liquid release
Gas release
Two phase release
Use Pool Fire Module
No flare
STOP
Wilson's Formula
D_s, U_j, ρ_{gas}
Chamberlain's Formula
$D_s, U_j, \rho_{gas}, d_j$
Cook's Formula
$D_s, U_j, \rho_{gas}, d_j$
Chamberlain's Model for flame length, diameter of frustum bases and flame tilt angle, fraction of heat radiated
Cook's formula for liftoff
Determine view factor for a cone frustum
Compute incident radiation
Find distance to LOC

Figure 6. Flare flow diagram

The angle, α, between the orifice axis and the flame depends on the velocity ratio, $R = \frac{V}{U_j}$

such that if $R \le 0.05$ then

$$\alpha = \frac{8000R + \xi(L_{Bo})(\theta_j - 90)(1 - \exp(-25.6R))}{\xi(L_{Bo})}$$

and if $R > 0.05$

$$\alpha = \frac{\left[1726\sqrt{R - 0.026} + 134\xi(L_{Bo})(\theta_j - 90)(1 - \exp(-25.6R))\right]}{\xi(L_{Bo})}$$

The flame-lift off, b, is the distance along the hole axis from the hole to the point of intersection with the cone axis calculated as:

$$b = L_B \frac{\sin K\alpha}{\sin\alpha}$$

with $K = \frac{(\alpha - \alpha_b)}{\alpha}$. K has been correlated with experimental data with a best fit $K = 0.185e^{-20R} + 0.015$

The frustum length is given by the geometrical relationship between R_L, L_B, α and b

$$R_L = \sqrt{\left(L_B^2 + b^2 \sin^2\alpha\right)} - b\cos\alpha$$

There appears to be a difference in the formula for the width of the frustum base as it appears in Chamberlain's paper when compared to Lees (2001) presentation of Chamberlain's formula. Based on sample calculations, we determined to use the Chamberlain version (Chamberlain p. 303) with the width of the frustum base, W_1, as

$$W_1 = D_s\left[13.5\exp(-6R) + 1.5\right]\left\{1 - \left[1 - \frac{1}{15}\left(\frac{\rho_a}{\rho_j}\right)^{\frac{1}{2}}\right]\exp\left(-70\xi(D_s)^{CR}\right)\right\}$$

with

$$C = 1000\exp(-100R) + 0.8$$

and the Richardson number, $\xi(D_s)$, based on D_s

$$\xi(D_s) = \left(\frac{g}{D_s^2 u_j^2}\right)^{\frac{1}{3}} D_s$$

Chamberlain formula for the width at frustum tip, W_2, is

$$W_2 = L_B\left(0.18\exp(-1.5R) + 0.31\right)\left(1 - 0.47\exp(-25R)\right)$$

The surface area of the flame, A, is calculated as:

$$A = \frac{\pi}{4}\left(W_1^{\,2} + W_2^{\,2}\right) + \frac{\pi}{2}\left(W_1 + W_2\right)\left[R_L^2 + \left(\frac{W_2 - W_1}{2}\right)^2\right]^{\frac{1}{2}}$$

The fraction of the heat, F_s radiated from the flame surface was determined from experimental data and the curve is:

$$F_s = 0.21\exp\left(-0.00323u_j\right) + 0.11$$

The view factor F is defined by Sparrow and Cess, equation 4-14:

$$dF_{A_j - dA_i} = \frac{dA_i}{A_j}\int_{A_j} \frac{\cos\beta_i \cos\beta_j dA_j}{\pi r^2}$$

where:
A_j is the area of the radiating surface,

dA_i is the receiving element,

β_i is the angle between the normal to the receiving element and the line between the element and the radiating surface,
β_j is the angle between the normal to the radiating surface at a point and the line between that point and the receiving element,
r is the distance between the point on the radiating surface and the receiving element.

For a radiating surface of area A_i and a receiving element of area dA_j, we can let
q' = incident radiation intensity per unit area, and
E' = emissive power per unit area,
so

$$q' = \frac{q}{dA_i} = \frac{E \cdot F \cdot \tau}{dA_i} = \frac{E' \cdot A_j \cdot F \cdot \tau}{dA_i} = E' \cdot \left(\frac{A_j}{dA_i} \cdot F \right) \cdot \tau \ .$$

Thus it is actually $\int_{A_j} \frac{\cos\beta_i \cos\beta_j dA_j}{\pi r^2}$ that we need to calculate.

We calculate this integral numerically by dividing the flame surface into 1800 "tiles" (40 radial divisions x 25 axial divisions of the conical surface, plus 400 tiles for each circular "cap"). The value of the integrand is calculated at the center of each tile, and those values are added to produce an estimate of the integral. This process is carried out for three orthogonal orientations of the receiving surface, producing view factors f_1, f_2, and f_3. The maximum view factor (over all orientations of the receiving surface) is then calculated as:

$f = \sqrt{f_1^2 + f_2^2 + f_3^2}$. (For a true view factor, the integral omits portions of the radiating surface where $\cos\beta_j$ <0. But since f_1, f_2, and f_3 are used to calculate the maximum view factor, portions where $\cos\beta_j$ <0 are not excluded.)

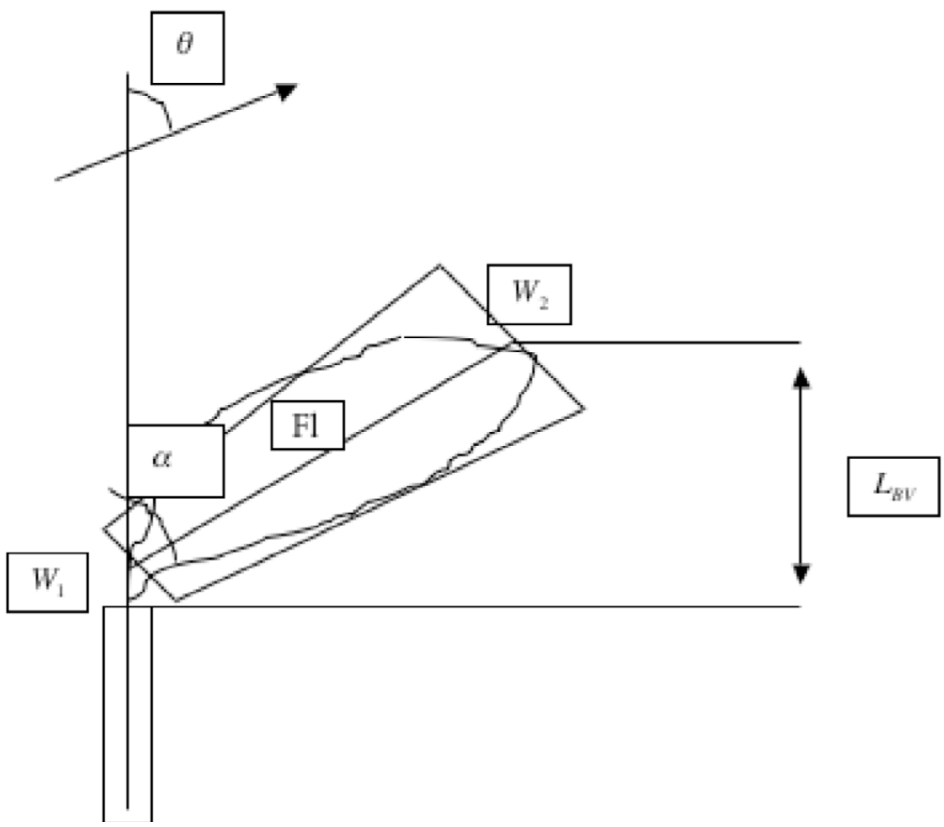

Figure 7. Diagram of the flame and cone frustum. Modified from Kalgahatgi (1983).

From Cook et al (1990), the emissive power of the flame, *E*, is calculated

$$E = \frac{FQ\Delta H_c \cdot 10^{-3}}{A}$$

with

Q = mass discharge ($\frac{kg}{s}$)

ΔH_c = heat of combustion ($\frac{J}{kg}$)

A = surface area of the flame (m^2)

From Chamberlain, the fraction of heat radiated from the flame surface, F, is

$$F = 0.21\exp(-0.00323u_j) + 0.11$$

The atmospheric attenuation coefficient, τ, described earlier is used for jets and flares.

MODEL OUTPUT

The model returns the ground level distance for each of the Levels of Concern (LOC). The flame centroid is the center of the footprint.

NOMENCLATURE

d_o	hole or throat diameter, m
F	fraction of heat radiated from surface of flame
L_B	length of flame measured from tip of flame to center of plane, m
L_{Bo}	L_B in still air, m
M_j	mach number of expanded jet
$\dot{m}$	mass flow rate, $\frac{kg}{s}$
R	velocity ratio, dimensionless
P_c	static pressure at the hole exit plane, $\frac{N}{m^2}$
P_o	atmospheric pressure, $\left(1.013 \cdot 10^5 \frac{N}{m^2}\right)$
T_s	stagnation temperature, gas temperature inside the container, K
u_j	velocity of the gas in the expanded jet, $\frac{m}{s}$
V	wind velocity, $\frac{m}{s}$
W_{gk}	kilogram molecular weight of gas, $\frac{kg}{mol}$

W_1 width of frustum at base, m
W_2 width of frustum tip, m
α angle between burner axis and flame length, degrees
$\xi(L_{Bo})$ Richardson number for length, L_{Bo}
θ_j angle between hole axis and horizontal in the vertical plane, degrees
γ_g ratio of specific heats for gas

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Quality Assurance

The project team used three different procedures to check the model output for accuracy and sensitivity.

(1) Algorithm check versus computer code.

The new algorithms in Project Eagle-ALOHA were coded up in an alternative high-level language (either MATHCAD, MATHEMATICA, or MATLAB). These alternative versions were then compared with the C-code in ALOHA designed to perform the same calculations. The team ran the different software for various scenarios selected to cover a range of input parameters.

BLEVE

Parameters that were varied were mass, humidity, emissive power, fraction flashed and tank temperature. Comparisons were made on burn time, BLEVE diameter and the distance to the 5kQ/sq. m level of concern (LOC). No differences were found, outside of roundoff error, for the alternative language code model or ALOHA for burn time or BLEVE diameter. A slight difference (2%) in the LOC distance predictions was found between two model approaches, traceable to different numerical techniques for root-solving of the equations.

Pool Fire

Parameters that were varied included wind speed and boiling point of the chemical. The latter was varied so as to cover both non-cryogenic and cryogenic liquids. Comparisons were made on the burn duration, flame length, flame tilt angle, and average emissive power. No differences were found, outside of roundoff error, between the alternative language code model and ALOHA. Results were also checked for the burn rate correlation formula against experimentally reported values. A difference of 16% was found for the non-cryogenic case and 32% for the cryogenic case. It should be noted that the selected cryogenic example (butane) had the largest reported variance from the correlation formula. Nevertheless, burn regression rate represents an area of uncertainty in the model.

Flare

Parameters that were varied were tank pressure (assuring both choked and unchoked flow) and wind speed. Comparisons were made on gas exit speed, effective source diameter, flame length and width, and flame tilt. No significant differences were found between ALOHA and the alternative language model.

Vapor Cloud Explosion

Overpressures 100 m downwind and 50 m. perpendicular to the wind for a 1000 kg instantaneous release and immediate ignition were compared for ALOHA and the alternative-coded model. Parameters that were varied were reactivity and level of congestion. Also the separate situation of immediate detonation by hard ignition was considered. Overpressure results in all cases showed no differences to four significant figures.

(2) Comparison against existing models.

ALOHA predictions were compared against existing fire and explosive prediction models. The models used were Automated Resource for Chemical Hazard Incident Evaluation (ARCHIE), produced by Hazmat America for the EPA, Risk Management Program Guidance for Offsite Consequence Analysis (RMP*Comp), produced by for the EPA Chemical Emergency Preparedness and Prevention Office, and the Maritime

Cargoes Hazard Assessment Model (HAM) developed by the University of Maryland for the Office of Naval Intelligence.

It is often difficult to compare models because of different assumptions and required input. None of the comparison models cover each of the four new scenarios incorporated into ALOHA. Certain choices were made in running the other models to best approximate that same scenario in ALOHA but significant differences in the actual input and output remain, causing discrepancies in model prediction unrelated to model algorithms. The following scenarios were run (ALOHA inputs):

BLEVE scenario (1)

chemical	propane
volume	31825 gal (DOT-112J400 railcar for LPG)
tank temperature	20 C (assumed as ambient temp.)
wind speed	5 m/sec
humidity	60%

model	fireball diameter	burn duration	9.5 kW/sq m distance	5 kW/sq m distance
ARCHIE	271 yd	16 sec		
RMP			880 yd *	
HAM			709 yd	1013 yd
ALOHA	249 yd	14 sec	617 yd	850 yd

* RMP radiation level is defined as distance to 2nd degree burn

BLEVE scenario (2)

chemical	O-xylene
volume	31825 gal (DOT-112J400 railcar for LPG)
tank temperature	20 C (assumed as ambient temp.)
wind speed	5 m/sec
humidity	60%

model	fireball diameter	burn duration	9.5 kW/sq m distance	5 kW/sq m distance
ARCHIE	327 yd	18sec		
RMP				
HAM			810 yd	1134 yd
ALOHA	300 yd	16 sec	639 yd	881 yd

pool fire scenario (1)

chemical	acetaldehyde
wind	5 m/sec
pool temperature	20 C (assumed ambient)
pool area	400 sq. m.
humidity	0%

model	flame height	5 kW/sq m distance
ARCHIE	29 yd	72 yd*
RMP		176 yd
ALOHA	20 yd	56 yd

* Defined as injury zone radius

pool fire scenario (2)

chemical	acetaldehyde
wind	5 m/sec
pool temperature	20 C (assumed ambient)
pool area	2000 sq. m.
humidity	0%

model	flame height	5 kW/sq m distance
ARCHIE	51 yd	160 yd*
RMP		528 yd
ALOHA	36 yd	122 yd

flare scenario (1)

chemical	methane
wind	5 m/sec
tank pressure	20 atm
hole diameter	50 cm
humidity	0 %

model	flame length	2 kW/sq m distance
ARCHIE	509 yd	1019 yd *
ALOHA	82 yd	372 yd

* Defined as safe separation distance.

flare scenario (2)

chemical	methane
wind	5 m/sec
tank pressure	20 atm
hole diameter	10 cm
humidity	0 %

model	flame length	2 kW/sq m distance
ARCHIE	102 yd	204 yd *
ALOHA	18 yd	80 yd

vapor cloud scenario (1)

chemical	acetylene
mass	1000 kg
ignition	soft
congestion	medium

model	8 psi distance	3.5 psi distance	1 psi distance
ARCHIE*	52 yd	121 yd	394 yd
RMP			123 yd
HAM**	55 yd	106 yd	406 yd
ALOHA	104 yd	129 yd	167 yd

* Does not relate overpressure levels directly to psi
** Assumes detonation case

vapor cloud scenario (2)

chemical	acetylene
mass	1000 kg
ignition	soft
congestion	medium

model	8 psi distance	3.5 psi distance	1 psi distance
ARCHIE*	28 yd	64 yd	209 yd
RMP			106 yd
HAM**	22 yd	47 yd	174 yd
ALOHA		53 yd	111 yd

(3) Sensitivity to input parameters

It cannot be assumed that emergency responders will have access to completely accurate input values for the fire and explosives scenarios. Therefore, the project team determined which input parameters have the most significant impact on model results. This should help to relate uncertainty in output to uncertainty in input. The method used was relative sensitivity S,

$$S = \frac{\partial y}{\partial x} \cdot \frac{x}{y}$$

where y is the output and x is the input variable. S provides an estimate of the relative change in y if x is changed and other parameters are held constant. It is most useful for functions that are monotonic and approximately linear, which is often the case for ALOHA inputs.

Standard inputs for selected chemicals were run for each fire and explosive scenario and then repeated with a variation in one of the input parameters. The chosen

output was the distance to the default orange level threat zone. The results are listed below:

BLEVE

chemical = propane
tank temperature = 25 C (assumed as ambient)
mass = 2000 kg
humidity = 50%

input parameter	relative sensitivity
humidity	-0.282
mass	0.337

flare

chemical = methane
tank temperature = 25 C
tank pressure = 10 atm
hole size = 10 cm
wind speed = 5 m/sec

input parameter	relative sensitivity
wind speed	0.074
hole size	0.929
pressure	0.414

pool fire

chemical = vinyl acetate
pool diameter = 50 m
wind speed = 5 m/sec

Radiation received showed a highly non-linear response to wind speed with a maximum centered around 5 m/sec. The result for pool diameter was:

input parameter	relative sensitivity
pool diameter	0.85

vapor cloud explosion

chemical = butane
mass = 1000 kg
ground roughness = open country
wind = 5 m/sec
congestion = high

Because of their non-quantitative nature, S could not be calculated for ground roughness or congestion level. However, output was highly dependent upon the choice for these parameters. The results for the others were:

input parameter	relative sensitivity
mass	0.368
wind	-1.373

Peer Review and Usability Testing

Information Quality Act specifications for Project Eagle-ALOHA are provided in appendix A. On December 15, 2004, the United States Office of Management and Budget issued a bulletin regarding peer review before the dissemination of important scientific information. The purpose was to enhance the quality and credibility of such information. Under this bulletin, agencies are granted broad discretion to weigh the benefits and costs of using a particular peer review mechanism for a specific information product. The selection of an appropriate peer review mechanism for scientific information is left to the agency's discretion.

However, the bulletin does not apply to information that was already being addressed by an agency initiated peer review process prior to June 2005. The Eagle-ALOHA project had indeed initiated such a prior peer review process and is therefore exempt from the bulletin. Nevertheless, the project team has instituted a peer review procedure that meets the spirit and intent of the new regulations.

The peer review panel includes members that are all external to the National Oceanic and Atmospheric Administration and who have not actively participated (outside of the specified review and advise procedures listed below) in the project work. Two members were with organizations that provided funding for the project; James Belke of the Environmental Protection Agency and Kin Wong of the Department of Transportation. All the other review team members were with organizations that had no financial interest in the project. Affiliations of the review team were listed earlier. The reviewers were selected based upon their recognized expertise and variety of backgrounds to cover the necessary scientific disciplines. Reviewers were selected from other government agencies, academia, and industry.

The review panel met for two days in February, 2005 to review a prototype of ALOHA with the new fire and explosives scenario. A brief synopsis of the workshop is provided in Appendix B. Note that the comments apply to the prototype only, not necessarily the existing model.

Also in Appendix B are the results of a usability test of the model prototype conducted at the 2005 International Oil Spill Conference. Results from the workshop and the usability tests were used to revise the prototype.

In early January 2006, the final draft version of the model and technical documentation was sent to the external review panel for their examination and evaluation. Listed below are their comments and the team response.

Reviewer's comments (team response in italics)

1. Page 4, BLEVE model description. Limit is set to 5000 metric tons - "order of the single largest historical BLEVE incident." I agree with this approach, and would

add that it is also on the order of the capacity of the largest pressurized flammable storage tanks currently manufactured. The largest I can locate after a quick internet search holds about 3,500 metric tons (located in India). The Mexico City spheres held about 1400 metric tons.

It is always a difficult challenge to determine the proper input restrictions on an emergency response model. The 5000 metric ton limit is larger than any likely BLEVE scenario and therefore should not limit the responder.

2. I recommend adding a note that although non-flammable pressurized liquid containers can BLEVE, the model will not calculate effects from these scenarios, since overpressure and fragmentation effects are not calculated.

Note added in the technical and user documentation.

3. A question on the model's logic for calculating fireball and pool fire fractions: For scenarios where the flash fraction is less than one third of tank contents, did you mean to say that the <u>amount not flashed</u> is used to calculate the pool fire, or that the <u>amount not consumed in the fireball</u> is used in pool fire? Conserving mass would require using the amount not involved in the fireball, but using the non-flashed fraction would be a more conservative approach, which might make sense if the calculated fireball mass itself was thought to be conservative.

The model displays to the user the amount of released chemical that is used to generate the fireball. The remaining chemical is assumed to form a pool fire. This approach conserves mass but neglects possible contributions to the pool fire from rainout and, hence, is not the most conservative answer from a risk viewpoint. It is, however, consistent with existing ALOHA modeling of aerosols.

The description of the BLEVE flow diagram indicates that the model uses an "average of empirical formulas." But it is not clear exactly what is being averaged. Maybe it is a reading comprehension problem on my part. Do you mean that it uses the average of the mass exponents for burn time and diameter? The equation at the top of page 6 indicates an exponent of 1/3. Is this exponent where the average is applied?

The average (mode) applies to the mass exponent used to calculate the maximum diameter.

4. Page 18 – Do I understand correctly that if the user specifies soft ignition, but provides inputs of high reactivity and high congestion or high reactivity and medium congestion (i.e., where DDT is assumed to occur), the model essentially proceeds just as if the user had specified hard ignition?

The model treats detonation caused by hard ignition or detonation caused by reactivity and congestion (resulting in a deflagration to detonation transition) in a similar fashion.

5. Based on my experience, common hydrocarbon fuel spill or pool fires (gasoline, diesel, jet fuel, etc.) represent a significant percentage of unwanted "chemical" fires. These fuels typically produce significant amounts of smoke, which makes the calculation of thermal radiation from these fires difficult. However, I feel that the absence of common fuels means that first responders could not predict the threat from a significant number of actual fires.

The project team agrees that the inability to calculate threats from hydrocarbon mixtures is an important limitation of this version of ALOHA. Presumably the user would select a pure hydrocarbon such as propane or butane as a (usually) conservative substitute.

APPENDIX A - Information Quality Act Details

I. **Name/Title of information product:** Revision of the Areal Locations of Hazardous Atmospheres (ALOHA) to include fire and explosive scenarios (Project Eagle-ALOHA)

II. **NOS Office/Division disseminating information product:** Office of Response and Restoration, Hazardous Materials Response Division

III. **Contact person:** William Lehr (206-526-6310, Bill.Lehr@noaa.gov)

IV. **Document how the following standards for <u>utility</u> are met by the information product:**

A. The content of the information is helpful, beneficial, or serviceable to its intended users, or that information supports the usefulness of other disseminated information by making it more accessible or easier to read, see, understand, obtain, or use.

Product is a modification of an existing model and follows Division past practice for user testing for usefulness and usability by its intended audience. Interface protocols for the existing ALOHA have been maintained.

B. The information product is disseminated in a manner that allows it to be accessible and understandable to a broad range of users.

Product is available electronically at http://response.restoration.noaa.gov.

V. **Document how the following standards for <u>integrity</u> are met by the information product:**

A. **All electronic information disseminated by NOAA adheres to the standards set out in Appendix III, "Security of Automated Information Resources," OMB Circular A-130; the Computer Security Act; and the Government Information Security Reform Act.**

As with all electronic information disseminated by NOAA, the information product adheres to the referenced standards.

B. **Confidentiality of data (i.e., census, business, or financial data) collected by NOAA is safeguarded under legislation such as the Privacy Act and Titles 13, 15, and 22 of the U.S. Code.**

Not applicable.

C. Additional protections (for fisheries statistics) are provided as appropriate by 50 CFR Part 600, Subpart E, Confidentiality of Statistics of the Magnuson-Stevens Fishery Conservation and Management Act, NOAA Administrative Order 216-100 – Protection of Confidential Fisheries Statistics.

Not applicable – this information product does not contain census, business, or financial data collected by NOAA.

VI. Document how the following standards for objectivity are met by the information product:

A. Data and information sources are identified in this information product or are available upon request.

Data and information sources are identified in the Technical documentation and software quality assurance for Project-Eagle report available from The Hazardous Materials Response Division

B. Data used for this information product is of known quality or from sources acceptable to the relevant scientific and technical communities to ensure that the product is valid, credible, and useful.

Data was supplied from existing ALOHA databases or from recognized expert published scientific sources.

C. The information product has been created using methods that are either published in standard methods manuals, documented in accessible formats by the disseminating office, or generally accepted by the relevant scientific and technical communities.

Methods are published in the Technical documentation and software quality assurance for Project-Eagle report available from The Hazardous Materials Response Division.

D. The products or procedures (e.g., statistical procedures, models, other analysis tools) used to create the information product have been reviewed to ensure their validity.

Product was externally reviewed by a panel of outside experts using Agency peer review protocols similar to those recommend by OMB Bulletin for Peer Review, Dec 15, 2004.

E. The methods by which the information product was created are included in the information product or are available upon request.

Methods are published in the Technical documentation and software quality assurance for Project-Eagle report available from The Hazardous Materials Response Division.

APPENDIX B - Workshop notes and usability comments

Note that these comments refer to an early prototype, not the existing version.

WORKSHOP NOTES

Invited Experts:

James Belke, EPA
Don Ermak, LLNL
Martin Goodrich, Baker Risk (absent due to family emergency)
Greg Jackson, U. of Maryland
Tom Spicer, U. of Arkansas
Doug Walton, NIST
Kin Wong, DOT

Agenda

WEDNESDAY, FEB. 23

2.PM	INTRODUCTORY REMARKS	Miller, Belke

2:15 PM	VAPOR CLOUD	Lehr

THURSDAY FEB 24

8:30 AM	FLARE	Simecek-Beatty
10 AM	POOL FIRE	Lehr
11 AM	BLEVE	Lehr
1 PM	USER INTERFACE	Muhasky
2:30 PM	PANEL DISCUSSIONS	All
3:30 PM	EXPERT PRESENTATIONS	Walton

*Vapor Cloud Note*s

Efficiency factor: Currently, the model uses 5 % of the cloud mass for calculating explosive energy if the incident is designated as an accident and 20% if it is deliberate. Alternative suggestions were to take the actual fraction of gas between the UFL and LFL or take the mass fraction that is above 0.9 LFL. Recommended that BakerRisk comment on appropriate efficiency factor.

Fireball LOC: Current footprint follows Risk Management Program (RMP) guidance by matching fireball hazard to LFL. Several felt that this was not conservative enough. Suggestions included using 0.9 or 0.6 LFL or calculating actual radiation hazard. Pointed out that fireball could be secondary effect from vapor cloud explosion.

Overpressure: Model currently transforms cloud into semi-ellipsoid shape, uses expanding piston approach and Baker-Strehlow method to calculate overpressure. Baker-Strehlow was considered an acceptable approach although multi-energy was mentioned as an alternative. The turbulent flame speeds are now calculated based on fuel reactivity and obstacle density utilizing the tables in Woodward's book. However, none of the Mach numbers exceeds 1, implying no detonation case. It was suggested using the highest Mach number curve in the Baker-Strehlow graphs, assuming that there was a hard ignition source strong enough to start detonation. If this were done, then questions of reactivity and obstacle density would not have to be asked. Consideration was also given to new table values sent by BakerRisk.

There was a lot of discussion of impulse versus overpressure. Impact from the overpressure wave is a function of both. Problem is similar to mapping concentration

versus dosage for chemical inhalation. Also there was some discussion on setting ignition location. Center of cloud seemed to be conservative consensus.

Flare notes

View factor : There was discussion about using a cylindrical optically dense flame, as in the pool fire model rather than using point source view factor. One recommendation was to always assume a clear, dry day. This is equivalent to neglecting atmospheric dampening.

gas exist velocity: Model currently assumes that flame will blow out when Mach number exceeds 0.5. Suggested that there may be a better number or that this restriction be dropped (flame could simply start farther away from source). Match rate of combustion to release rate to achieve steady state case. Most felt that horizontal jets also be allowed rather than only vertical ones. Model will not work well with oil fires due to smoke generation.
2-phase: Model currently transforms 2-phase release into gas release. Some pointed out that 2-phase incident could produce both flare and pool fire. Suggested reviewing existing references on 2-phase flow to see how to handle for flare situation

BLEVE

fireball size: Experts agreed that limits should be placed upon fireball size. One suggestion is to limit fireball mass to three times the fraction that is adiabatically flashed. Another is to restrict user input to largest common propane tank. Compare our simplified model to results from more sophisticated models.

terminology: Consensus was that careful wordsmithing needs to be done to maintain consistency of language, technical accuracy, and fit within common usage.

other hazards: Model only considers thermal hazard. People agreed that user should be warned about all hazards, including overpressure and shrapnel. Some discussion on shrapnel models

Pool fire

pool size: Model currently stops spreading when the burn rate equals the chemical release rate. Recommendation was to eliminate this restriction and stop spreading only when minimum thickness was reached. Need to ascertain upper limit on model applicability for large fires.

pool shape: Suggested that LOC footprint be circular rather than elliptical in order to be more conservative.

burn regression rate: Approximation of burn regression rate as ratio of heat of combustion to heat of vaporization may not be good approximation, particularly for

cryogenic spills. Model should estimate fires of diesel and gasoline as well as existing ALOHA flammables.

User interface

mixed risk: There was considerable discussion but no consensus on the best way to handle display of competing hazards. Some thought user should simply see worst risk while others favored displaying all risks.

User guidance: There was considerable discussion but no consensus on the best way to interact with the user; whether to have the user trek through a specific scenario or use check boxes to look at simultaneous scenarios.

USABILITY TESTS (performed by Mary Evans)

Table 1, below, lists usability-related observations made last week during the International Oil Spill Conference, along with related design inferences.

How observations were made:

These observations were made during five usability tests of the new version of ALOHA incorporating fires and explosions modeling. During each test, a Coast Guard member experienced in hazmat response served as the test participant. I observed each participant as he or she used ALOHA to respond to a hypothetical scenario involving a release from a benzene tank, propane cylinder, or natural gas pipeline. Following the test, each participant was asked a series of questions to elicit his or her understanding of fires and explosions-related terminology, interface features, and output plots in ALOHA.

Summary of findings:

Overall, the new version of ALOHA was enthusiastically received ("Wow!," "I like this!" "I think this is really good"), and test participants remarked that the new functionality will be useful for them. However, they generally found it difficult to understand some of the new terminology related to fires and explosions modeling and to interpret output plots. While using the model for fires and explosions modeling, they felt unsure at points where they had to make choices between available alternatives. They recommend that explanations, legends, and help texts be added to the model to boost their understanding of key concepts, use of the model, and the model's output. The tests also uncovered pre-existing usability problems, which are listed in Table 1.

Table 1. ALOHA usability findings.

Observation	Design inference
Participants don't understand the term "overpressure."	**ADDRESS IN HELP, USING**

(*"Are we talking BLEVE?""Some firefighters will know this is a BLEVE." "I guess it's over, beyond where explosion could happen--??" "I'm guessing that's the level of gas pressure inside the explosive plume." "Wait,..it's telling me where the damage is from the pressure wave itself, not the fire. I just had to think through it.*")	**TERMS FAMILIAR TO RESPONDERS. COULD THIS CHOICE BE REWORDED TO SOMETHING LIKE "VAPOR CLOUD EXPLOSION (FOOTPRINT WILL SHOW AREA OF IMPACT FROM OVERPRESSURE WAVE)"?**

Participants don't understand the term "vapor cloud flash fire." (*"…the fireman doesn't know what this means." "So this is more like flash point, and this is more like fire point?"* "*I don't know why I should be concerned about this*")	Revise language, use just-in-time documentation, and address in help, using terms familiar to responders. Could this choice be reworded to something like "Vapor cloud flash fire (footprint will show area affected by heat from the burning cloud)"?
Most participants could not identify the release point on an overpressure plot, when asked. (*"The railcar could be anywhere here. The ground zero is where the ignition happens within the cloud." "Can't tell—the wind is from the east, but…This is kind of confusing. It would be helpful if it was marked…." "Looks like the release point would be at the center of the circle."* "*Where's the center…Where's the cylinder on this? I'd want to know where's the leak? Where's this supposed to be? I know I'm supposed to look at this and tell…I need to know where I need to evacuate…" "At the 0, 0, I assume, though it seems to be a little off center. It really doesn't say.*")	Label the release point. Consider drawing wind direction arrow on plot.
MOST PARTICIPANTS DON'T UNDERSTAND THE DISTINCTION BETWEEN HARD AND SOFT IGNITION. ("*I HAVEN'T HEARD OF THAT BEFORE." "I'M GUESSING SOFT IGNITION." "I WOULD CLICK HELP TO FIND OUT ABOUT THIS CHOICE" "I DIDN'T NECESSARILY KNOW WHAT THEY MEANT, BUT WITH THE BLURBS AFTER THEM IT WAS PRETTY CLEAR. MY FIRST THOUGHT IS IF THESE TWO SHIPS HIT WOULD THAT QUALIFY AS A HARD IGNITION.*")	**CONSIDER PARTICIPANT'S RECOMMENDATION TO CHANGE LANGUAGE TO "INTENTIONAL" AND "NONINTENTIONAL." USE JUST-IN-TIME DOCUMENTATION (E.G., EXAMPLES OF HIGH POWER EXPLOSIVE DEVICES IN PARENTHESES) AND ADDRESS FURTHER IN HELP.**

Participants noted that "Obstacle congestion" could be interpreted differently in different places and circumstances. Also, the same location—the area around the convention center—was evaluated differently by different participants, who chose either medium or high. (*"What that means to someone in a city may be different from someone in a small town. NYC would be 100% congestion all the time. Coming from a city, I'm sure it's medium or high." "If we have a chemical that's heavier than air, an obstacle can be a foot high." "I guess it's what's around the area: Are there a lot of trees and buildings to impede movement of cloud?" "I'd infer that means the number of objects in the vicinity of the explosion." "This is pretty qualitative. What is 10-40%? Here, I'd go medium because there's no tall buildings. From a maritime perspective, I'd probably choose low."* "*…the deck of a ship is pretty low. At most it's probably medium, but low is probably going to give me the worst case so I'll choose it.*" "*That one, I would really need the help screen. Would it be single-storied buildings or normal ground? How does it apply to a ship? To a container ship, stacked high, vs. a tanker? I'd want to go worse-case scenario, to CYA. Maybe have the worst case choice be the default.*")	Address in help and in just-in-time documentation (e.g., list some real-life examples in parentheses following each choice). Consider adding subcategories (e.g., urban/rural).
The term "high power explosive device" is not clear to participants. ("*…high power explosive device—TNT? What are we talking about here? This explosion is going to ignite another explosion?" "What's a high power explosive device: a grenade or an atom bomb?"*)	**DEFINE THIS TERM IN HELP, OR REWORD IN INTERFACE. CONSIDER JUST-IN-TIME DOCUMENTATION.**
Participants appear to think in percentages rather than fractions. (*"0.6 LEL. I assume that's 60% of the LEL."*)	Reword as "60% LEL"
Participant would like to see both LEL and UEL as LOCs under the downwind dispersion option. (*"I teach that you shelter in place for toxic hazards, evacuate for flammable hazards…Knowing LEL is important, knowing if you're above UEL is also important, because you have to go through the flammable range to go back to where you're safe."*)	Consider including LEL as LOC along with fractions commonly used by responders, especially 10% LEL. Consider including UEL as an LOC choice for the downwind dispersion option.
Most participants select Computational when completing a scenario, though it's generally not a needed step for their work, and leaves them confused.	Consider moving this option to an Options submenu.

Four of five participants setting up a scenario have difficulty recognizing what to do next after entering location, chemical, weather, and source strength. They mouse around in menus and select other options (Computational, Source Strength, Conc & Dose) before eventually selecting Footprint. ("*Now I think I've filled out everything it needs..I'm looking for a button…*")	Generally arrange menus so the items one must select to complete a model run are in proper sequence and other things are out of the way. Consider moving Footprint to top of Display menu and moving other items in this menu to a single Display Options dialog.
When source strength is too low for a footprint to be generated, the resulting message disorients participants. They appear to take it as an error message.	Revise message wording to make the distance estimate more prominent.
Participant 2, trying to model vapor cloud ignited by lightening, can't tell which Footprint option to choose (downwind dispersion, overpressure, or flash fire). ("*This is that area where it would be dispersed to, but how the lightening would affect that…I don't see how to find that.*") Others have difficulty making this choice as well ("*Now, this isn't intuitive…*")	Use just-in-time documentation, with examples if space allows, to explain the three choices. Relate choices to real-life circumstances responders could encounter. Consider including a decision key to help users choose between explosion and flash fire.
Some participants understand the default LOCs for overpressure, but additional explanation would help others. ("*I'd figure it would show you footprint, with red area where 50% would die.*" *"It's in units of PSI so it's obviously some pressure issue, but it's related to fatalities…so I'm not understanding what this is about. It must mean that this pressure [points to red LOC] would relate to half the people being killed."*) One participant expected to see inhalation LOCs along with overpressure LOCs (*"This seems like it would be the sound of it---eardrum rupture—but would it just hurt your ears? What about respiratory hazards?"*)	Include interpretation guidance in Help. Explain that users should select Downwind dispersion option to assess respiratory hazards.

Participants don't understand the wind direction confidence lines on flash fire footprint (*"The dashed line could be the high flammability limit—this would just be a guess." "I'm wondering if this is the LEL…I'm not sure how to interpret those…" "I'm assuming that the dashed line would be the extent of the flash…no it must be limited to the inner zone…so I don't know what the dashed line indicates. It should go in the legend."* "*Just the dispersion area of the propane? I don't know. It should go in the legend*." "*I assume that would be possible wind shifts, but I'm not sure and there's no key*.")	**INCLUDE LEGEND WITH DEFINITION ON PLOTS.**
Participant 4 (a toxicologist) really likes ALOHA's error messages (he had typed "mph" into the wind direction box). (*"Nice error handler!!"*)	Continue including error messages in same format.
Two participants left "Gas in tank" as the default for a liquefied gas scenario; one was able to recover only when prompted. Both backed up repeatedly, trying different options, until they finally chose to model a liquid in a tank.	Consider just-in-time documentation. Reconsider the existing default for gases that are usually liquefied in containers. Is it possible to change the default to liquid for those chemicals that are normally stored liquefied above their boiling point?
Participants occasionally access ALOHA's Helps by clicking interface buttons.	Help buttons right next to items of concern appears to be an effective way to provide Help (in contrast to CAMEO's single-entry Help, which no one used).
Participant was confused by 1-hour cutoff on source graph (*"Maybe I don't understand something, but I'd expect the pressure to decline over time, not a sudden cutoff like this."*)	Add explanatory note to graph.
Participant did not know what lines represent on Concentration graph (*"I need a legend to tell me what this blue line and this red line is"*)	Add legend to Concentration graph for indoor and outdoor lines.
Participant did not understand area of flash fire (*"I'm assuming that's the area that would be engulfed by flame in an explosion."*)	**RECONSIDER TERMINOLOGY, USE JUST-IN-TIME DOCUMENTATION.**

Participant recommends including reference for .6 LFL use along with help. (*"ALOHA uses .6 LFL, but why? A link to a help would be good here."*)	In the Help for this dialog box, describe reference for the .6 LFL choice and include interpretation help. Explain why it's .6 and not the 10% LEL value commonly used by responders. Consider showing 10% LEL isopleth on the plot, since it seems to be commonly used to find the isolation distance.
Participants would like an indication of wind direction and release timeframe (duration) on plots. ("*This scenario doesn't include a timeframe…a wind direction arrow or timeframe: a scrollbar to let me scroll the time out and back.*" "*Time should show up on the plot.*")	**ADD WIND DIRECTION ARROW TO FOOTPRINT PLOTS. CONSIDER OPTIONS FOR INDICATING TIMEFRAME: PERHAPS A NOTE INDICATING DURATION?**
Participants don't know how to make decisions about time of ignition, and make choices in a variety of ways. ("*I keyed on 'after the beginning of the release' and assumed 'what if it happened right now? We're 15 minutes into the release.'" "do I have to put a number here?…I'll put 10 minutes…"*)	Consider participant's suggestion to include an ignition time slidebar on the plot window.
Participant commented that ALOHA interface is more cumbersome to work with than other interfaces he's encountered. ("*One thing about ALOHA is that you have to go back through all the screens to change something. Other interfaces, you can click tabs, and quickly adjust a tank dimension, for example.*")	**IN NEXT MAJOR UPGRADE, CONSIDER REVISING INTERFACE TO BE MORE LIKE ADIOS II (IN WHICH IT'S POSSIBLE TO ADJUST INDIVIDUAL INPUTS FROM THE MAIN PROGRAM WINDOW).**
Plots using red, orange, and yellow zones are well-received ("*I like this—red, orange, yellow footprints make sense intuitively. This is the kind of thing I want to see graphically.*")	Maintain color scheme, as well as existing pattern scheme supporting color-blind users.
Participants would like to see detailed, complete legends and helps, and titles on plots ("*…having a help screen here, definitely, understanding what psi is, what 50% fatalities means…From the responder perspective, define down to Nth degree.*" "*There should be a title on the graph, with everything labeled. So you could hand it off to a decision-maker.*" "*This product has to explain everything to the layman.*" "*…the legend isn't intuitive—there are a lot of equal signs, and what's the*	**ADD DETAIL TO EXISTING LEGENDS; ADD TITLES WHERE MISSING; PREPARE DETAILED HELPS GEARED FOR A RESPONDER AUDIENCE.**

graph telling me?" "*So is this hazardous? Am I going to drop dead? Is this on fire? What does this mean?*")	
ALOHA printouts need timestamps. ("*There's no date and time on this, so no one knows when this is. Later, another gets printed out, they get mixed together, no one knows which is current. The person who made it may not be in the room.*")	**ADD TIMESTAMPS TO ALL PRINT OUTPUT.**
LEL is more meaningful to responders than LFL, according to one participant. ("*Most responders operate in the world of LEL. Might want to define LFL.*")	Research to find out whether LEL is indeed more commonly used. Consider using LEL in place of LFL.
For puddle cases, participant would like to see ground type choices for marine situations, especially steel deck (he chose Concrete, reasoning that it would not soak up product like the other ground types). ("*In ALOHA, when it says choose your surface, a lot of times we're going to use this on a ship. It seems more based towards ground and land based properties. On decks, the sun's going to send heat. There's a problem with latent heat. A lot of decks are going to be covered in dark paint and absorb heat.*")	Consider including other ground type choices or using just-in-time documentation to suggest best choices for common situations. Is it possible to offer these choices only for the case of cryogenic puddles?
Participant sees a need to predict concentrations above ground level (as a response option, he would consider sending in a helicopter to survey the scene). ("*There used to be an option for how high vertically this could go to. I'd be concerned about sending a helicopter in.*")	Consider adding above-ground concentration prediction in a future version.
The overpressure LOC labels ("50% Fatalities," "Eardrum rupture") help participants assess hazard. ("*First time exposed, I really wasn't sure—I had no idea about the psi, no experience. I looked at the descriptions rather than the psi.*")	Keep these labels and consider other locations where similar labels could help users understand ALOHA output in terms of their experience and language.
All participants correctly understood the >= symbol used in the flash fire plot legend, but some caution that some users may not.	Consider writing out as "reaches or exceeds"