APPENDIX D

HAZARD ANALYSIS

WORST-CASE CONSEQUENCE ANALYSIS BP CARSON REFINERY SAFETY, COMPLIANCE, AND OPTIMIZATION PROJECT

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WORST-CASE CONSEQUENCE ANALYSIS FOR BP CARSON REFINERY SAFETY, COMPLIANCE, AND OPTIMIZATION PROJECT

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SECTION 1
INTRODUCTION

Quest Consultants Inc. was retained by Environmental Audit, Inc. to perform a worst-case consequence analysis on the process unit modifications and additions to BP's Carson Refinery. BP is proposing a project at its existing Carson Refinery (Refinery) to enhance safety to comply with South Coast Air Quality Management District (SCAQMD) rules (e.g., SCAQMD Rule 1105.0 – PM10 and Ammonia Emissions from Fluid Catalytic Cracking Units) and a settlement agreement between the SCAQMD and BP, and to optimize operations relating to various existing Refinery units including the Fluid Feed Hydrodesulfurization (FFHDS) Unit, the Fluidized Catalytic Cracking Unit (FCCU), the Alky Merox Unit, the Alkylation Unit, the Hydrocracker Unit, and the Sulfur Plant at the Refinery. The portion of the proposed project related to enhanced safety will focus on the Coker Gas Fractionation area, and compliance equipment that will be added to the FCCU. The proposed project will involve physical changes and additions to multiple process units as well as operational and functional improvements within the confines of the existing Refinery.

The study was divided into three tasks.

Task 1. Determine the maximum credible potential releases, and their consequences, for existing process units proposed for modification.

Task 2. Determine the maximum credible potential releases and their consequences for units which have been proposed for modification by BP.

Task 3. Determine whether the consequences associated with the proposed modifications or additions generate a potential hazard that is larger than the potential hazard which currently exists in the unit.

Potential hazards from the existing, modified, and new equipment are associated with accidental releases of toxic/flammable gas, toxic/flammable liquefied gas, and flammable and combustible liquids. Hazardous events associated with gas releases include toxic gas clouds, torch fires, and vapor cloud explosions. Hazardous events associated with potential releases of toxic/flammable liquefied gases include toxic clouds, torch fires, flash fires, and vapor cloud explosions. Releases of flammable or combustible liquids may result in pool fires.

One hazard of interest for a release of toxic/flammable gas or liquefied gas is exposure to a gas cloud. For such releases, this study evaluates the extent of possible exposure to gas clouds containing hydrogen sulfide (H_2S) and sulfur dioxide (SO_2).

The hazard of interest for flash fires is direct exposure to the flames. Flash fire hazard zones are determined by calculating the maximum size of the flammable gas cloud prior to ignition. These hazard zones are defined by the lower flammable limit (LFL) of the released hydrocarbon mixture. For vapor cloud explosions, the hazard of interest is the overpressure created by the blast wave. The hazard of interest for torch fires and pool fires is fire radiation. For Boiling Liquid–Expanding Vapor Explosions (BLEVEs), the hazard of interest is the radiation produced by the fireball.

For each type of hazard identified (toxic, radiant, overpressure), maximum distances to potentially injurious levels are determined. The hazard levels are based on events that could cause an injury.

SECTION 2
OVERVIEW OF BP'S CARSON REFINERY

2.1 Facility Location

BP's Carson Refinery is located in the southern portion of Los Angeles County at 1801 East Sepulveda Boulevard, Carson, California. The Refinery is bounded by 223rd Street to the north, Wilmington Avenue to the west, Sepulveda Boulevard to the south, and Almeda Street to the east. The Dominguez Channel passes through the middle of the facility. Layout of the Refinery and major roads bounding the facility are presented in Figure 2-1.

The process units and other Refinery modifications included in the project are listed in Table 2-1. Table 2-1 identifies which of the existing units involved in the project will be modified as part of the project. Unit locations within the Refinery are shown in Figure 2-1.

2.2 Meteorological Data

Meteorological data for the Los Angeles area were reviewed to determine representative values for temperature and relative humidity. Wind speed and stability class were also reviewed to determine the range of conditions that are possible at the site. In this study, a low wind/stable condition (1.5 m/s wind, "F" stability) was evaluated for each dispersion calculation. These conditions often approximate the worst-case weather conditions for dispersion analysis. For the purposes of this analysis, the vapor cloud was assumed to travel in any direction with equal probability. When performing pool fire and torch fire calculations, a high wind that "bends" the flame is considered a worst-case condition. In this study, all fire radiation calculations were performed using 6 m/s winds.

2.3 Description of Units Involved in the Carson Refinery Safety, Compliance, and Optimization Project

The proposed Refinery modifications are outlined in this section. All components of the proposed project are associated with enhancing safety, aiding in compliance, or optimizing the operation of the existing Refinery. Most of the project components are related to the Fluid Catalytic Cracking Unit (FCCU) modifications and the subsequent changes to other related units.

2.3.1 Modify Existing Fluid Catalytic Cracking Unit

The proposed project will involve several changes to the FCCU, including changes to allow for compliance with SCAQMD Rule 1105.1 and changes to allow for more efficient operation of the FCCU. A new flue gas pollution control system for the FCCU is being installed in order to bring the Refinery into compliance with Rule 1105.1. The two existing dry Electrostatic Precipitators (ESP) will be replaced with one new dual chamber ESP.

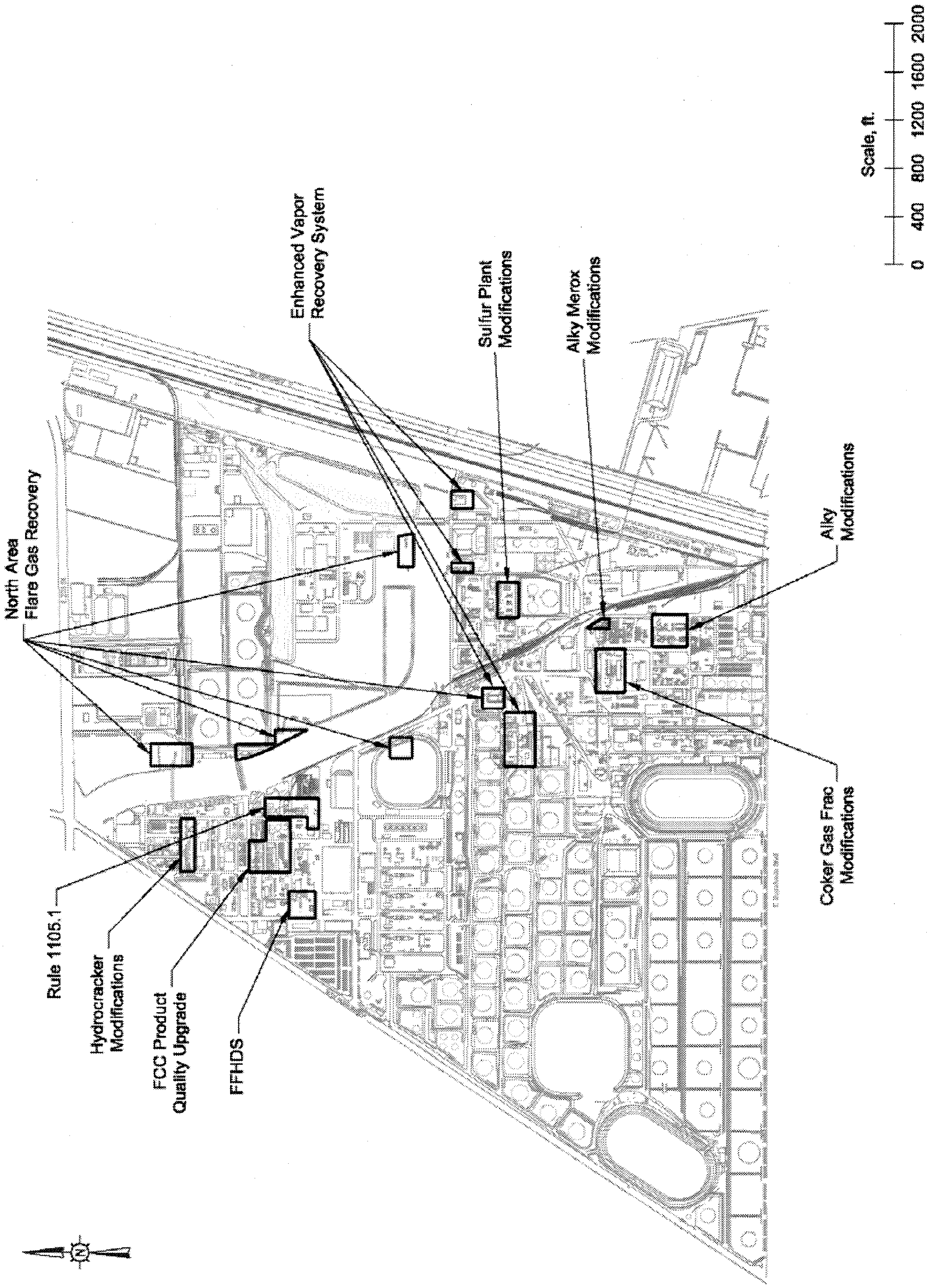

Figure 2-1
Location of Process Units to be Modified or Added within the Carson Refinery

Table 2-1
Process Units and Facilities Involved in the Refinery Safety, Compliance, and Optimization Project

Designation	Description	Existing/New	To Be Modified
Process Units			
ALKY	Alkylation Unit	Existing	Yes
FFHDS	Fluid Feed Hydrodesulferization Unit	Existing	Yes
HCU	Hydrocracker Unit	Existing	Yes
SULFUR	Sulfur Plant	Existing	Yes
FCCU	Fluid Catalytic Cracker Unit	Existing	Yes
MEROX	Alky Merox Unit	Existing	Yes
Other Refinery Modifications			
VAPOR RECOVERY	Vapor Recovery System	Existing	Yes
COKER PRV	Coker Debutanizer Relief	New	---
FLARE GAS	Flare Gas Recovery	Existing	Yes

The FCCU upgrades heavier feedstocks, known as gas oils, into lighter components used for gasoline blending. The modifications to upgrade the FCCU fall into three categories: Gas Plant modifications, Reactor-Regenerator modifications, and downstream unit modifications. The Gas Plant modifications mainly involve improvements to reboiler and condensing capacity on distillation columns. These improvements increase separation efficiency and produce purer products. The unit modifications primarily involve heat exchangers, pumps, and piping.

Modifications to the Reactor-Regenerator optimize performance by reducing velocities and pressure drop. Some piping between the Reactor and Regenerator vessels may be replaced to provide better air and catalyst mixing. The downstream unit modifications include increasing the capacity of the Alkylation Unit. Other modifications to the FCCU are primarily related to changes to piping, heat exchangers, pumps, and modification to the internal configuration of vessels. The overall impact of these upgrades does not increase the capacity of the FCCU.

2.3.2 Install New Fluid Feed Hydrodesulfurization Reactor

Currently there is one Fluid Feed Hydrodesulfurization (FFHDS) reactor that removes sulfur compounds from the feed to the FCCU in order to produce lower sulfur end products as well as lower stack emissions. A second FFHDS reactor will be installed to run in parallel with the existing FFHDS reactor so that the FFHDS can run for longer periods of time between turnarounds.

2.3.3 Modify Existing Alky Merox Unit

The purpose of the Alky Merox unit is to remove sulfur containing compounds from the olefin streams, to reduce the sulfur in the feed to the *iso*Octene and Alkylation units, and produce low sulfur gasoline blending component products from the *iso*Octene and Alkylation Units. Currently, the Alky Merox unit does not have the capability of processing all of the sulfur containing compounds produced at the Refinery.

The capacity of the Alky Merox unit is limited to processing 1,000 barrels per hour. Olefins are fed through the Extractor to the Water Wash Tower. Sour olefins are fed to the extractor to reduce the concentration of sulfur containing compounds. The Extractor is currently limited to processing 600 barrels per hour. The modifications to the Alky Merox unit will increase the Extractor capacity to 1,000 barrels per hour, which will allow all of the olefins produced at the Refinery to be processed. The modifications include installing new vessels, piping, and other ancillary equipment.

2.3.4 Modify Existing Alkylation Unit

The main function of the Alkylation unit is to convert olefins into alkylate. The Alkylation throughput is currently limited to 16,000 barrels per day. The modifications to the Alkylation unit will primarily affect piping, pumps, and other ancillary equipment. Additionally, existing trays will be replaced with new trays in the Debutanizer Tower within the Alkylation Unit to improve efficiency.

2.3.5 Modify Existing Hydrocracker Unit

The Hydrocracker Unit processes high sulfur diesel feeds into both ultra-low sulfur diesel and gasoline blending components. The throughput of the Hydrocracker Unit is currently limited by the availability of the fractionation gas plant, the capacity of the distillation tower, and product cooling constraints. Hydraulic constraints in the reaction section of the Hydrocracker Unit also limit the feed rate. Increased fractionation gas plant capacity will be achieved by converting the lean oil absorber tower to a low pressure diethanol amine (DEA) scrubber tower. Additional product cooling will be provided by installing new higher horsepower motors, as well as modifying water coolers, to allow more cooling water flow. In addition more heavy hydrocrackate cooling will be provided by installing a new air cooler. These limitations are removed by increasing the feed throughput to the Hydrocracker unit by approximately 10 percent. This is accomplished by modifying piping, controls, and ancillary equipment.

2.3.6 Modify Existing Coker Gas Debutanizer Pressure Relief Valve

The pressure relief valve on the Debutanizer Tower will be removed and piping installed to route the future emergency gas releases to an existing flare. This modification will remove the potential for a flammable release.

2.3.7 Modify Existing Sulfur Plant

The existing Sulfur Plant currently converts hydrogen sulfide and ammonia-rich acid gases into elemental sulfur, water, and nitrogen. The current capacity of the Sulfur Plant is 449 long tons per day (LT/D) of elemental sulfur from the four Claus Units (A, B, C and D). The proposed modifications will help the sulfur plant in consistently operating at higher production rates closer to the permitted capacity.

The following modifications are proposed to the Sulfur Plant.

- Change the solvent in the main amine system from DEA to methyl diethanol amine (MDEA) to allow more amine circulation since MDEA is effective at higher concentrations
- Change the "C" Claus for oxygen enrichment up to 28 percent.
- Add oxygen injection to "D" Claus Unit.

2.3.8 Enhanced Vapor Recovery Systems

The existing vapor recovery system collects vent gases from process units and tanks and routes them to various flares located throughout the Refinery. The vapor recovery system is comprised of multiple compressors and has a combined maximum compression capacity of 355,000 standard cubic feet per hour (SCFH). The system currently operates below this level because one vapor recovery compressor (the No. 7 unit) permitted at 95,000 SCFH is not functional.

As part of a Supplemental Environmental Project (SEP), the capabilities of the existing vapor recovery system to collect and treat vent gases that would otherwise vent to the Refinery flares will be increased. The SEP increases the total vapor compression capacity by a minimum of 195,000 SCFH. This is accomplished by replacing the No. 7 vapor recovery compressor with a new 95,000 SCFH vapor recovery compressor, intercooler, and knockout drum. This will restore the compression capacity in the Vapor Recovery Unit to 355,000 SCFH.

The SEP requires operators to achieve the remaining 100,000 SCFH of vapor compression capacity. This will reduce emissions from the Refinery by increasing the capability of the Refinery's existing vapor recovery system to collect and treat vent gases and will add the capability to collect and treat gases that previously would vent to the Refinery's flares. The Coker Flare was selected due to its higher sulfur content, which will maximize the reduction of sulfur emissions. These modifications will remove the potential for a flammable release.

2.3.9 North Area Flare Gas Recovery Project

The North Area Flare Gas Recovery Project is designed to comply with SCAQMD Rule 1118 – *Control of Emissions from Refinery Flares*. The North Area Flare Gas Recovery project will recover gas from the FCCU, Hydrocracker, and FFHDS flares by installing new compressors, coolers, knockout drums, piping and amine gas treating columns. The new facilities will reduce the overall sulfur emissions from the Refinery.

SECTION 3
POTENTIAL HAZARDS

3.1 Hazards Identification

The potential hazards associated with BP's existing Carson Refinery and those associated with the proposed modifications to the existing units identified in Section 2 are common to most refineries worldwide, and are a function of the materials being processed, processing systems, procedures used for operating and maintaining the facility, and hazard detection and mitigation systems. The hazards that are likely to exist are identified by the physical and chemical properties of the materials being handled and the process conditions. For hydrocarbon fuel and petrochemical facilities, the common hazards are:

- toxic gas clouds (gas or liquefied gas with sulfur dioxide or hydrogen sulfide)
- torch fires (gas and liquefied gas releases)
- flash fires (liquefied gas releases)
- pool fires (flammable/combustible liquid releases)
- vapor cloud explosions (gas and liquefied gas releases)
- BLEVEs (major failures of liquefied gas storage tanks)

The BP facility under evaluation was divided into two types of areas as shown in Table 2-1. The hazards expected to be identified are listed in Table 3-1.

Table 3-1
Summary of Hazards

Area Description	Type of Hazards Found in Area
Process areas ALKY FFHDS HCU SULFUR FCC MEROX	Breach of liquid line or vessel resulting in: Pool fire Breach of flashing liquid line or vessel resulting in: Flash fire Vapor cloud explosion Pool fire Torch fire Toxic cloud (hydrogen sulfide) Breach of vapor line or vessel resulting in: Torch fire Vapor cloud explosion Toxic cloud (hydrogen sulfide, sulfur dioxide)

3.2 Introduction to Physiological Effects of Toxic Gases, Fires, and Explosions

The analysis performed on the BP Refinery modifications involved the evaluation of hundreds of potential hazardous material releases. The potential releases may result in one or more of the following hazards:

- Exposure to toxic gas
  - Hydrogen sulfide
  - Sulfur dioxide

- Exposure to flame radiation
  - Pool fire (tank fire, spill into diked areas)
  - Torch fire (rupture of line followed by ignition)
  - BLEVE (Boiling Liquid–Expanding Vapor Explosion of a pressurized storage vessel)
  - Flash fires (ignition of slow-moving flammable vapors)
- Exposure to explosion overpressure
  - Vapor cloud explosion (release, dispersion, and explosion of a flammable vapor cloud)
  - Confined explosion (ignition and explosion of flammable vapors within a building or confined area)

In order to compare the hazards associated with each type of hazard listed above, a common measure of consequence or damage must be defined. In consequence and risk analysis studies, a common measure for such hazards is their impact on humans. For each of the toxic, fire, and explosion hazards listed, there are data available that define the effect of the hazard on humans.

When comparing a toxic hazard to a flammable or explosive hazard, the magnitude of the hazard's impact on humans must be identically defined. For instance, it would not be meaningful to compare human exposure to nonlethal overpressures (low overpressures which break windows) to human exposure to lethal fire radiation (34,500 Btu/(hr·ft^2) for five seconds). Thus, in order to compare the hazards of toxic gases, fires, and explosions on humans, equivalent levels of hazard must be defined.

The endpoint hazard criterion defined in this study corresponds to a hazard level which might cause an injury. With this definition, the injury level must be defined for each type of hazard (toxic, radiant heat, or overpressure exposure). Table 3-2 presents endpoint hazard criteria approved by SCAQMD for previous studies of this type. Additional information on endpoint criteria is presented in Appendix A.

Table 3-2
Consequence Analysis Hazard Levels
(Endpoint Criteria for Consequence Analysis)

Hazard Type	Injury Threshold		
	Exposure Duration	Hazard Level	Reference
Hydrogen sulfide inhalation	Up to 60 min	30 ppm	ERPG-2 [AIHA, 1988] 40 CFR 68 [EPA, 1996]
Sulfur dioxide inhalation	Up to 60 min	3 ppm	ERPG-2 [AIHA, 1988] 40 CFR 68 [EPA, 1996]
Radiant heat exposure	40 sec	1,600 Btu/(hr•ft^2)*	40 CFR 68 [EPA, 1996]
Explosion overpressure	Instantaneous	1.0 psig**	40 CFR 68 [EPA, 1996]
Flash fires (fireballs)	40 sec	1,600 Btu/(hr•ft^2)*	40 CFR 68 [EPA, 1996]
Flash fires (flammable vapor clouds)	Instantaneous	LFL	40 CFR 68 [EPA, 1996]

ERPG-2. The maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to one hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair an individual's ability to take protective action.
40 CFR 68. United States Environmental Protection Agency RMP endpoints.
* Corresponds to second-degree skin burns.
** Corresponds to partial demolition of houses.

3.3 <u>Selection of Accidental Release Case Studies</u>

3.3.1 Overview of Methodology

The purpose of the hazard case selection methodology is to define the maximum credible hazard scenario for each unit that might result in an impact to the public. The methodology is developed in seven increments:

- Initial review
- Detailed review of process flow diagrams
- Review of process material balances
- Review of available safety studies
- Development of hazard scenarios
- Screening of hazard scenarios via hazards analysis
- Final selection of hazard cases

3.3.2 Initial Review

The analysis begins with a general review of the process. Any written description of the new or modified processes is studied to determine the physical and chemical transformations occurring and the general flow of material in the unit. After the process features are known, process flow diagrams (PFDs) are reviewed and compared to the written descriptions.

3.3.3 Detailed Review of Process Flow Diagrams

The detailed review of the PFDs begins by tracing the major process flow lines in the unit. When the major flows within the unit are found, the material balances are reviewed for each major line to determine the exact nature of the material within the line or vessel.

Each of the major flow lines is taken individually and evaluated to determine the potential for producing a major hazard if a leak or rupture occurred. At this point in the analysis, a list of potential areas of concern is started; this list is continually refined and added to during the remaining analysis steps.

Several factors are involved in the initial selection of hazard areas:

- Flammability and/or toxic nature of the chemicals
- Potential for aerosol formation (releases of streams considerably above their atmospheric boiling point)
- Line size
- Normal flow rate in the line
- Severity of the process conditions

The factors described above are not weighted equally in the evaluation. The flammability and/or toxic nature, potential for aerosol formation, and process conditions are given more weight than the other factors.

3.3.4 Review of Process Material Balances

Although the process material balances have been reviewed for each major process flow line, they are more thoroughly reviewed during this stage of the analysis to locate points in the process where toxic materials and/or materials sensitive to detonation are used.

A spreadsheet describing the material balances for the identified hazard locations is begun. The material balance gives the molar flows, the mass flows, and the mole fraction of the components of each process stream. The stream temperature, pressure, and line size are also noted in the spreadsheet. As additional hazard areas are found, their stream summaries are added to the spreadsheet.

3.3.5 Review of Previous Safety Studies

Previous safety studies, including HAZOP reports, "What if?" analyses, safety audits, etc., are reviewed to determine if all potential hazard areas have been adequately identified. Any potential hazards identified in these work products are added to the list of potential areas of concern that was started during the detailed review of the PFDs.

3.3.6 Development of Hazard Scenarios

The list of potential hazard areas developed in the preceding analysis stages is put into a spreadsheet. The spreadsheet contains the following information:

- Case number
- Description of the area where release originates (line, vessel, etc.)
- Stream number found on the PFDs
- Stream or vessel temperature
- Stream or vessel pressure
- Assessment of the physical state of the stream (gas, liquid, two-phase)
- Total volume of the vessel or the nearest vessel
- Liquid volume of the vessel or the nearest vessel
- Line size
- Normal flow rate of the line or vessel

3.3.7 Initial Screening via Hazard Zone Analysis

The hazard zones resulting from the worst-case releases of similar hazard scenarios are evaluated to determine the process areas that could release material with a potential for public impact. When performing site-specific consequence analysis studies, the ability to accurately model the release, dilution, and dispersion of gases and aerosols is important if an accurate assessment of potential exposure is to be attained. For this reason, Quest uses a modeling package, CANARY by Quest®, that contains a set of complex models that calculate release conditions, initial dilution of the vapor (dependent upon the release characteristics), and the subsequent dispersion of the vapor introduced into the atmosphere. The models contain algorithms that account for thermodynamics, mixture behavior, transient release rates, gas cloud density relative to air, initial velocity of the released gas, and heat transfer effects from the surrounding atmosphere and the substrate. The release and dispersion models contained in the QuestFOCUS package (the predecessor to CANARY by Quest) were reviewed in a United States Environmental Protection Agency (EPA) sponsored study [TRC, 1991] and an

American Petroleum Institute (API) study [Hanna, Strimaitis, and Chang, 1991]. In both studies, the QuestFOCUS software was evaluated on technical merit (appropriateness of models for specific applications) and on model predictions for specific releases. One conclusion drawn by both studies was that the dispersion software tended to overpredict the extent of the gas cloud travel, thus resulting in too large a cloud when compared to the test data (i.e., a conservative approach).

A study prepared for the Minerals Management Service [Chang, et al.,1998] reviewed models for use in modeling routine and accidental releases of flammable and toxic gases. CANARY by Quest received the highest possible ranking in the science and credibility areas. In addition, the report recommends CANARY by Quest for use when evaluating toxic and flammable gas releases. The specific models (e.g., SLAB) contained in the CANARY by Quest software package have also been extensively reviewed. Technical descriptions of the CANARY models used in this study are presented in Appendix B.

3.3.8 Final Selection of Hazard Cases

Using the data collected in the hazard area spreadsheet and the initial screening hazard zone calculations, a final selection of hazard cases is made. These selections generally define the maximum extent of any credible potential hazard that could occur in the process area being evaluated.

SECTION 4
WORST-CASE CONSEQUENCE MODELING RESULTS

The results of the worst-case consequence modeling calculations for the existing and modified units are presented in this section. In addition, several hazard zones are overlaid onto the facility map in order to demonstrate the possible public exposure to the defined hazard levels.

4.1 Releases Resulting in the Largest Downwind Hazard Zones

With the completion of the hazard identification and consequence modeling calculations described in Section 3 for both the existing and proposed BP configurations, the release from each unit which generates the largest hazard zone can be identified. These releases are listed in Table 4-1. As can be seen from Table 4-1, most of the proposed modifications do not affect the equipment location where the largest potential release originates. That is to say, the potential releases which would result in the largest hazard zones are already in place for many of the units. For example, in Unit D of the sulfur plant, a rupture of the combustion gas stream leaving the waste heat boiler results in the largest potential hazard zone (toxic SO_2 cloud). The modifications to Unit D do not result in release scenarios which could create hazard zones larger than those from the existing unit.

4.2 Description of Potential Hazard Zones

4.2.1 Toxic Vapor Clouds

For a potential accident (e.g., pipe break, hole in a vessel, etc.), one particular set of release conditions/atmospheric conditions will create the largest potential hazard zone. As an example, consider a rupture of the line leaving the waste heat boiler in Unit D in the sulfur unit. This release scenario exists for both the existing and modified unit and is affected by changes in the operating conditions of the unit. In the worst-case release scenario, a possible exposure to a cloud containing SO_2 downwind of the release occurs. Under the worst-case atmospheric conditions evaluated, the toxic hazard zone (as defined by the ERPG-2 SO_2 concentration level, 3 ppm) extends 3,510 ft downwind from the point of release. The hazard "footprint" associated with this event is illustrated in two ways in Figure 4-1. One method presents the hazard zone as a circle which extends 3,510 ft around the point of release from the Claus Unit. This presentation, referred to as a vulnerability zone, is misleading since everyone within the circle cannot be simultaneously exposed to a 3 ppm SO_2 level from any single accident. A more realistic illustration of the potential hazard zone around the release point is given by the darkened cloud in Figure 4-1. The cloud area illustrates the SO_2 hazard footprint that would be expected IF a rupture of the waste heat boiler line were to occur, AND the wind is blowing at a low speed to the east southeast, AND the atmosphere is calm, AND the vapor cloud does not ignite following release.

4.2.2 Vapor Cloud Explosions

One of the possible results of a flammable liquid or gas release is the ignition of flammable vapors, which could result in a vapor cloud explosion (VCE). An example of an event tree showing the sequence of events that could lead to a VCE is presented in Figure 4-2. As an example, the 1.0 psig vapor cloud explosion overpressure hazard footprint following a rupture of the liquid reflux line leaving the debutanizer overhead

Table 4-1
Potential Accidents Resulting in Maximum Potential Hazard

Process Unit/Area	Status of Potential Hazard (E) Existing, (M) Modified, (N) New	Potential Release (Hazard)
ALKY	E	Rupture of liquid line leaving alkylation contactor feed coalescer (flash fire)
	M	Rupture of liquid line leaving alkylation contactor feed coalescer (flash fire)
FFHDS	E	Rupture of vapor line leaving cold flash drum (H_2S toxicity)
	M	Rupture of vapor line leaving cold flash drum (H_2S toxicity)
HCU	E	Rupture of vapor line leaving fractionator overhead and entering absorber (H_2S toxicity)
	M	Rupture of vapor line leaving fractionator overhead and entering absorber (H_2S toxicity)
SULFUR	E	Rupture of combustion gas stream leaving waste heat boiler [unit D] (SO_2 toxicity)
	M	Rupture of combustion gas stream leaving waste heat boiler [unit D] (SO_2 toxicity)
FCCU	E	Rupture of liquid line leaving light cycle oil stripper tower (flash fire)
	M	Rupture of liquid line leaving light cycle oil stripper tower (flash fire)
MEROX	E	Rupture of liquid line leaving extractor (flash fire)
	M	Rupture of liquid line leaving extractor (flash fire)

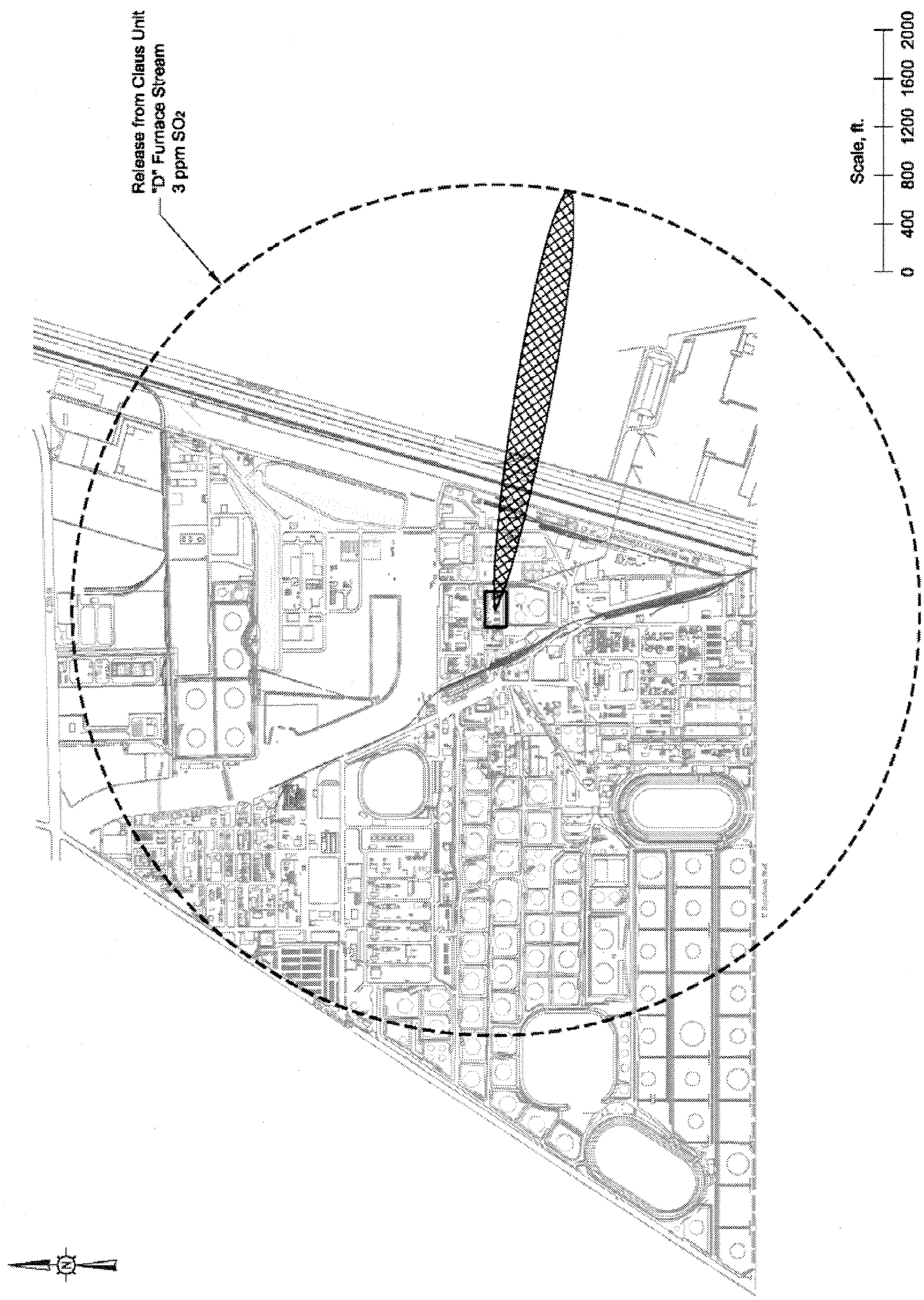

Figure 4-1
Worst-Case Consequence Analysis Hazard Footprint - SULFUR (SO_2 Toxicity)

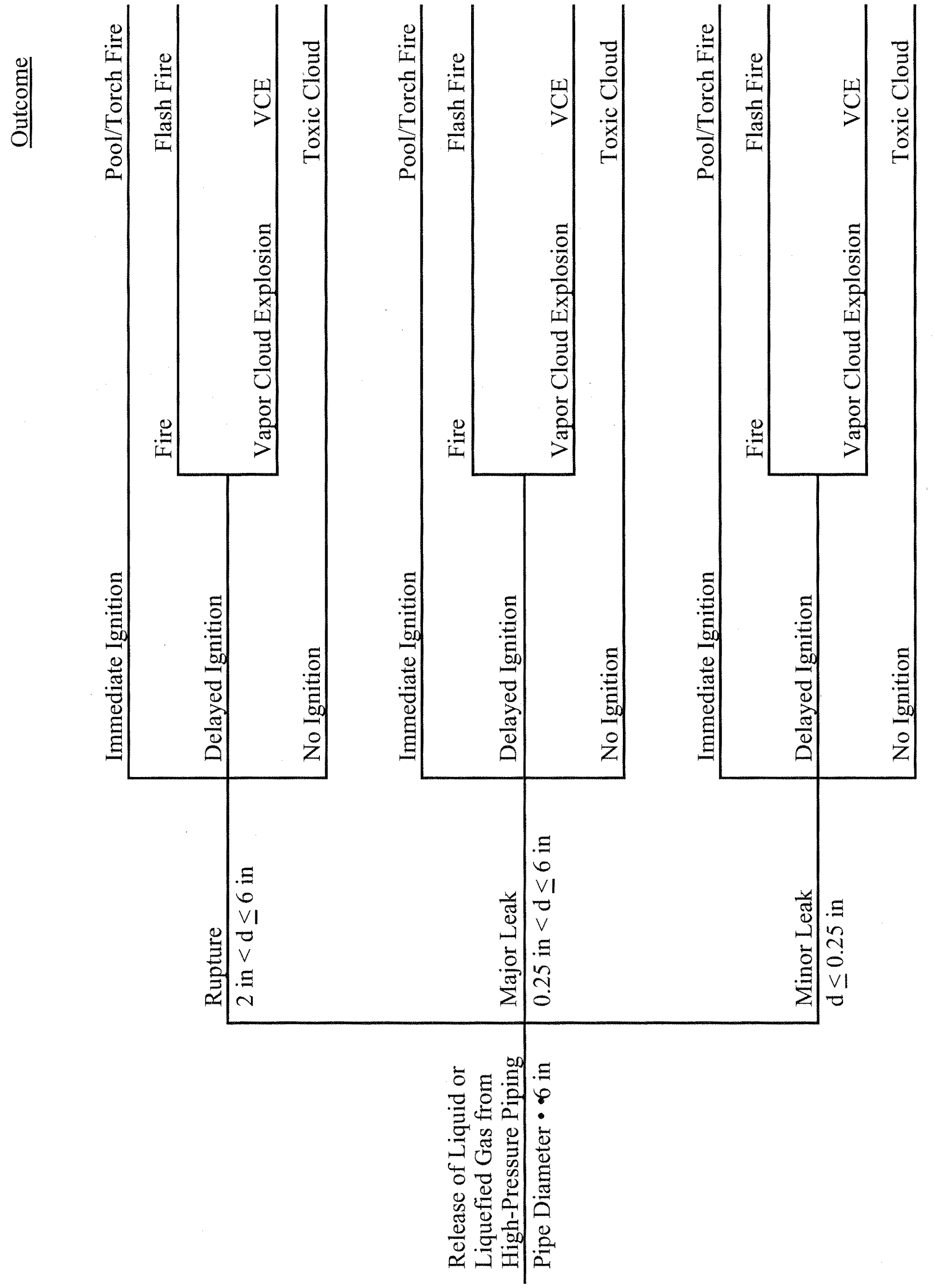

Figure 4-2
Event Tree for a Flammable/Toxic Release

accumulator in the ALKY is presented in Figure 4-3. This hazard extends 295 ft from the process area where flammable vapors are confined. For explosions that originate in a process area, the explosion hazard footprint is contained within the flash fire vulnerability zone.

4.2.3 Flash Fires

A release of flammable fluid, if not ignited immediately, will create a vapor cloud that travels downwind and disperse. The extent of the flammable zone is defined by the lower flammable limit (LFL). If the flammable cloud is ignited after reaching its full extent, the largest possible flash fire will result. The hazard footprint for a rupture of the liquid line leaving the debutanizer overhead accumulator in the ALKY is shown in Figure 4-4. This hazard extends 780 ft downwind from the point of release for the existing unit and 795 ft for the modified unit. The flash fire hazard zone is similar to the toxic hazard zone in that the vulnerability zone (circle) covers a much larger area than the actual vapor cloud (the hazard footprint represented by the shaded area).

4.2.4 Fire Radiation

The most significant fire radiation hazards that might occur are torch fires from liquefied gas releases. Unlike the dispersion calculations, the worst-case atmospheric conditions for torch fire radiation calculations occur when the winds are high, allowing the flame to "bend" downwind. Examples of radiant hazard zones for an immediately ignited rupture of the liquid line leaving the debutanizer overhead accumulator in the ALKY are presented in Figure 4-5.

4.3 Summary of Maximum Hazard Zones

Table 4-2 presents a listing of the type and size of potential hazards which dominate each of the units evaluated. Note that for each unit, the status is defined as E, M, or N (existing, modified, or new). The largest hazards are listed for releases from the existing units and the units after the proposed modifications.

Overall, the proposed additions and modifications result in a limited number of small increases in the size of potential hazards. Many of the increases in hazard zones are restricted to BP's property.

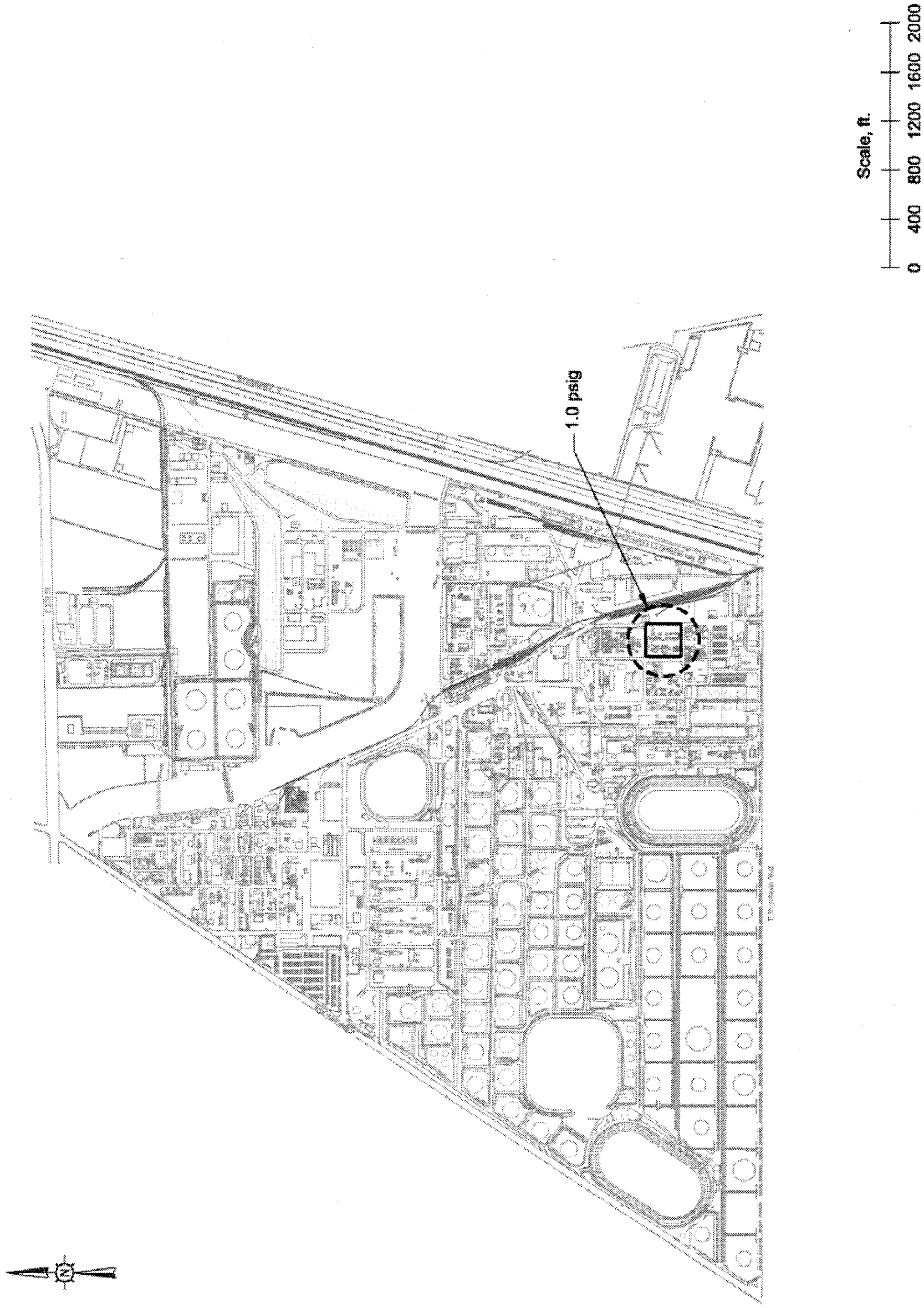

Figure 4-3
Worst-Case Consequence Analysis Hazard Footprint - ALKY (Explosion Overpressure)

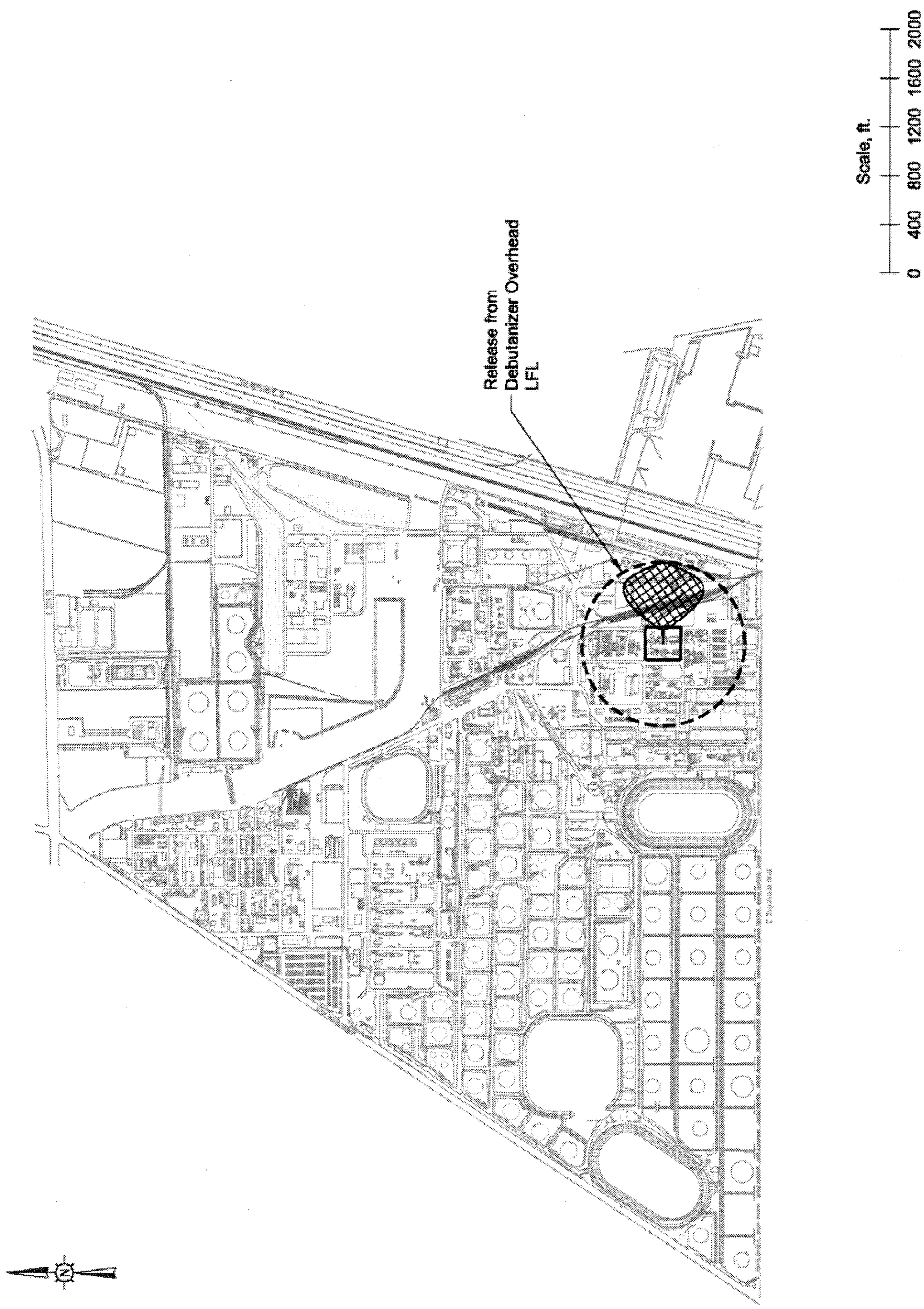

Figure 4-4
Worst-Case Consequence Analysis Hazard Footprint - ALKY (Flash Fire)

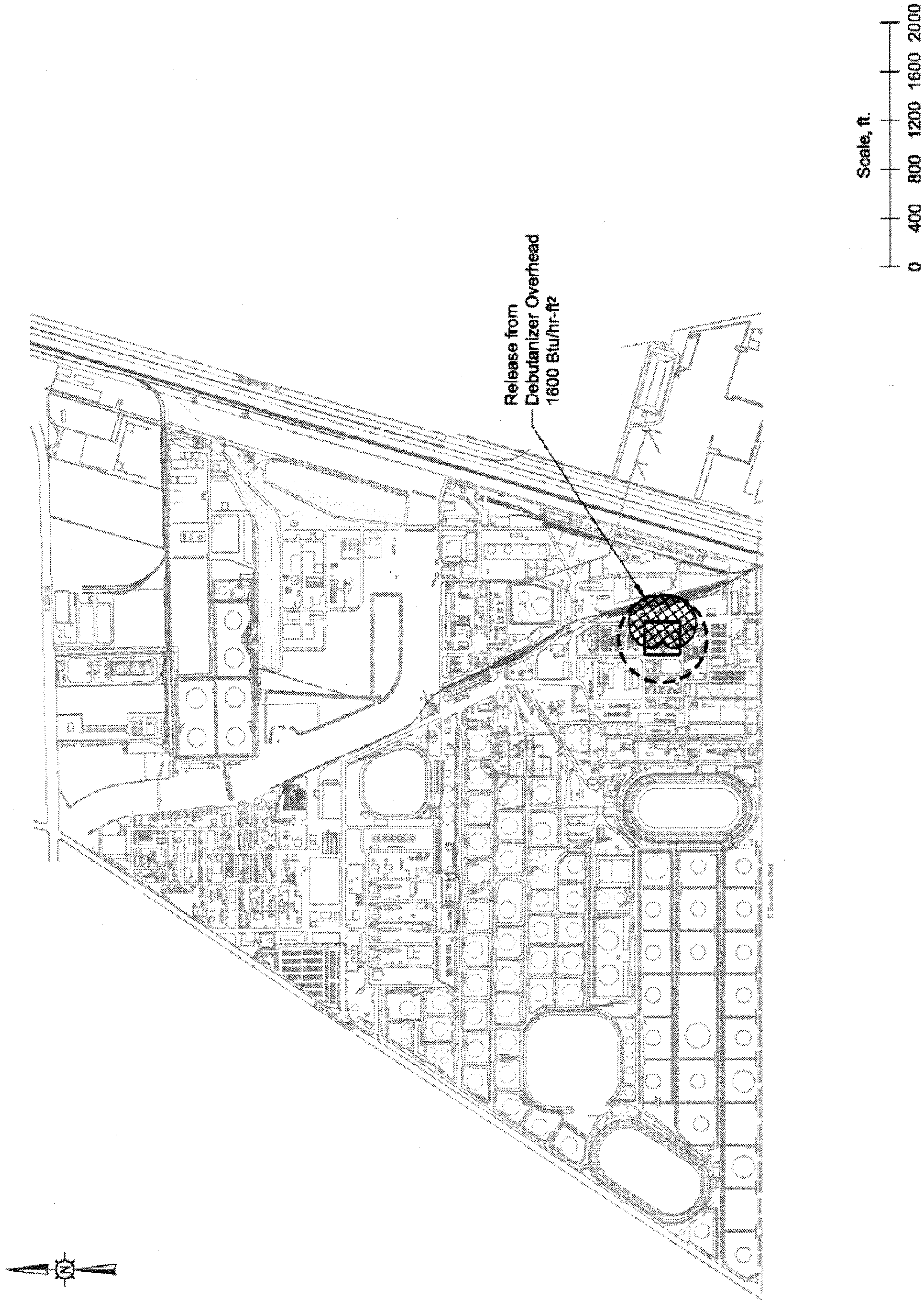

Figure 4-5
Worst-Case Consequence Analysis Hazard Footprints - ALKY (Torch Fire)

Table 4-2
Maximum Hazard Distances for Maximum Credible Event in Each Process Unit/Area

Process Unit	Release	Status of Potential Hazard (E) Existing (M) Modified (N) New	Maximum Distance (ft) from Center of Unit to: Flash Fire (LFL)	Explosion Overpressure (1.0 psig)	Pool/Torch Fire Thermal Radiation (1,600 Btu/(hr•ft²))	H_2S Gas Concentration (30 ppm for 60 min)	SO_2Concentraton (3 ppm for 60 min)
ALKY	Release from liquid line leaving debutanizer overhead accumulator	E	780	295	290	—	—
		M	795	295	295	—	—
	Release from liquid line leaving alkylation contactor feed coalescer	E	610	245	350	—	—
		M	670	265	360	—	—
FFHDS	Release from cold flash drum	E	170	60	190	2,805	—
		M	170	60	190	2,750	—
	Release from sour water flash drum	N	30	15	50	755	—
HCU	Release from fractionator overhead line entering absorber	E	90	35	100	1,790	—
		M	190	75	90	1,860	—
	Release from fractionator hot reflux condensor	E	890	335	670	—	—
		M	770	305	540	—	—
SULFUR	Release from combustion gas stream leaving waste boiler [unit D]	E	—	—	—	1,275	3,510
		M	—	—	—	1,240	3,490
FCCU	Liquid line leaving extractor	E	800	305	530	—	—
		M	890	320	620	—	—
MEROX	Liquid line leaving extractor	E	1,085	405	565	—	—
		M	1,370	510	415	—	—

SECTION 5
CONCLUSIONS

Quest Consultants Inc. was retained by Environmental Audit, Inc. to perform a worst-case consequence analysis on the process unit modifications and additions to BP's Carson Refinery.

The following three tasks were completed as part of the study.

Task 1. Determine the maximum credible potential releases, and their consequences, for existing process units proposed for modification.

Task 2. Determine the maximum credible potential releases and their consequences for units which have been proposed for modification by BP.

Task 3. Determine whether the consequences associated with the proposed modifications or additions generate a potential hazard that is larger than the potential hazard which currently exists in the unit.

The primary conclusion that can be drawn from the completion of these tasks is that for the proposed modifications to existing process units and the additions to various units for vapor recovery do not result in significantly larger potential hazard zones than those posed by the existing Carson Refinery configuration. This result is primarily due to the nature of many of the modifications, which can best be described in the following manner.

- Modification of a unit such that the largest potential hazard is changed only slightly (e.g., Alky Unit).
- Addition of equivalent equipment such that the potential hazards are essentially the same as those which already exist (e.g., the SULFUR).

With the maximum hazard zones defined for each release, the units can be divided into three categories, dependent on their potential to impact the public. The categories are defined as:

- Units with no potential pre- or post-project off-site impacts (hazard zones are contained on-site).
  - VAPOR RECOVERY
  - COKER DEBUTANIZER RELIEF
  - FLARE GAS RECOVERY
- Units with potential pre- or post-project off-site impacts, but post-project impacts are no larger than pre-project (existing) impacts.
  - SULFUR
  - FFHDS
- Units with potential off-site impacts. Post-project impacts are larger than pre-project impacts.
  - ALKY
  - FCCU
  - MEROX
  - HCU

Two specific conclusions can be drawn from a review of the worst-case consequence modeling results. First, for those units where post-project off-site impacts are larger than pre-project off-site impacts, all of the increases in the hazard zones are small (the largest increase was for the modification to the Alky Merox Unit). The changes in the Alky Merox Unit result in a worst-case flash fire impact extending 1,370 ft from the release point. The existing unit has the ability to produce a worst-case flash fire impact extending 1,085 ft. Neither the existing or modified Alky Merox Unit has the capability to reach a residential area. The worst-case comparison is only valid for the maximum impact distances. All other potential releases are smaller and, in many cases, there is no difference between the pre- and post-project impacts.

Two of the existing or modified units have the ability to create a hazard that could extend into residential area. These two units, FFHDS and HCU each have the capability to reach nearby residential areas **before** the proposed modifications were installed. In both units, the differences between the existing and proposed unit's maximum worst-case hazard distances are minimal. For the HCU, the distances are slightly larger. For the FFHDS, the distances are slightly smaller.

It should be kept in mind that for the worst-case scenarios evaluated in this study to occur, the following conditions must be met.

(1) A full rupture of the line occurs.
(2) The release does not ignite within minutes of the rupture.
(3) The wind speed is low (less than 3 mph).
(4) The atmosphere is calm.

This sequence of events is highly unlikely and only results in an off-site hazard (toxic or flammable vapor dispersion) for a limited number of potential releases.

SECTION 6
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SECTION 7
GLOSSARY

The following definitions are intended to apply to Consequence Analysis and Quantitative Risk Analysis studies of facilities that produce, process, store, or transport hazardous materials. Due to the limited scope of such studies, some of these definitions are more narrow than the common definitions.

ACCIDENT. An unplanned event that interrupts the normal progress of an activity and has undesirable consequences, and is preceded by an unsafe act and/or an unsafe condition.

ACCIDENT EVENT SEQUENCE. A specific series of unplanned events that has specific undesirable consequences (e.g., a pipe ruptures, allowing flammable gas to escape; the gas forms a flammable vapor cloud that ignites after some delay, resulting in a flash fire).

ACCIDENT SCENARIO. The detailed description of an accident event sequence.

AIR DISPERSION MODELING. The use of mathematical equations (models) to predict the rate at which vapors or gases released into the air will be diluted (dispersed) by the air. The purpose of air dispersion modeling is to predict the extent of potentially toxic or flammable gas concentrations, in air, by calculating the change in concentration of the vapor or gas in the air as a function of distance from the source of the vapor or gas.

BLAST WAVE. An atmospheric pressure pulse created by an explosion.

BLEVE (Boiling Liquid–Expanding Vapor Explosion). The sudden, catastrophic failure of a pressure vessel at a time when its liquid contents are well superheated. (BLEVE is normally associated with the rupture, due to fire impingement, of pressure vessels containing liquefied gases.)

CONDITIONAL PROBABILITY. The probability of occurrence of an event, given that one or more precursor events have occurred (e.g., the probability of ignition of an existing vapor cloud).

CONSEQUENCES. The expected results of an incident outcome.

CONSEQUENCE ANALYSIS. Selection and definition of specific accident event sequences, coupled with consequence modeling.

CONSEQUENCE MODELING. The use of mathematical models to predict the potential extent of specific hazard zones or effect zones that would result from specific accident event sequences.

DEFLAGRATION. See explosion.

DETONATION. See explosion.

EFFECT ZONE. The area over which the airborne gas concentration, radiant heat flux, or blast wave overpressure is predicted to equal or exceed some specified value. In contrast to a hazard zone, the endpoint for an effect zone need not be capable of producing injuries or damage.

ENDPOINT. The specified value of airborne gas concentration, radiant heat flux, or blast wave overpressure used to define the outer boundary of an effect zone or hazard zone. Endpoints typically correspond to specific levels of concern (e.g., IDLH, LFL, onset of fatality, 50% mortality, odor threshold, etc.).

EVENT TREE. A diagram that illustrates accident event sequences. It begins with an initiating event (e.g., a release of hydrogen sulfide gas), passes through one or more intermediate events (e.g., ignition or no ignition), resulting in two or more incident outcomes (e.g., flash fire or toxic vapor cloud).

EXPLOSION. A rapid release of energy, resulting in production of a blast wave. There are two common types of explosions—physical explosions (sudden releases of gas or liquefied gas from pressurized containers) and chemical explosions (rapid chemical reactions, including rapid combustion). Chemical explosions can be further subdivided into deflagrations and detonations. In a deflagration, the velocity of the blast wave is lower than the speed of sound in the reactants. In a detonation, the velocity of the blast wave exceeds the speed of sound in the reactants. For a given mass of identical reactants, a detonation is capable of producing more damage than a deflagration. Solid and liquid explosives, such as dynamite and nitroglycerine, typically detonate, whereas vapor cloud explosions are nearly always deflagrations.

FIRE RADIATION. See thermal radiation.

FLAMMABLE VAPOR CLOUD. A vapor cloud consisting of flammable gas and air, within which the gas concentration equals or exceeds its lower flammable limit.

FLASH FIRE. Transient combustion of a flammable vapor cloud.

HAZARD. A chemical or physical condition that presents a potential for causing injuries or illness to people, damage to property, or damage to the environment.

HAZARD ZONE. The area over which a given incident outcome is capable of producing undesirable consequences (e.g., skin burns) that are equal to or greater than some specified injury or damage level (e.g., second-degree skin burns). (Sometimes referred to as a "hazard footprint.")

INCIDENT OUTCOME. The result of an accident event sequence. The incident outcomes of interest in a typical study are toxic vapor clouds; fires (flash fire, torch fire, pool fire, or fireball); and explosions (confined, unconfined, or physical).

INITIATING EVENT. The first event in an accident event sequence. Typically a failure of containment (e.g., gasket failure, corrosion hole in a pipe, hose rupture, etc.).

INTERMEDIATE EVENT. An event that propagates or mitigates the previous event in an accident event sequence (e.g., operator fails to respond to an alarm, thus allowing a release to continue; excess flow valve closes, thus stopping the release).

ISOPLETH. The locus of points at which a given variable has a constant value. In consequence modeling, the variable can be airborne gas concentration, radiant heat flux, or blast wave overpressure. The value of the variable is equal to the specified endpoint. The area bounded by an isopleth is an effect zone.

LOWER FLAMMABLE LIMIT. The lowest concentration of flammable gas in air that will support flame propagation.

MISSILES. See shrapnel.

POOL FIRE. Continuous combustion of the flammable gas emanating from a pool of liquid.

QUANTITATIVE RISK ANALYSIS. The development of a quantitative estimate of risk based on engineering evaluation and mathematical techniques for combining estimates of incident consequences and frequencies.

RISK. A measure of economic loss or human injury in terms of both the incident likelihood and the magnitude of the loss or injury.

RISK ASSESSMENT. The process by which the results of a risk analysis are used to make decisions, either through relative ranking of risk reduction strategies or through comparison with risk targets.

SHRAPNEL. Solid objects projected outward from the source of an explosion. Sometimes referred to as missiles or projectiles.

SUPERHEATED LIQUID. A liquid at a temperature greater than its atmospheric pressure boiling point.

THERMAL RADIATION. The transfer of heat by electromagnetic waves. This is how heat is transferred from flames to an object or person not in contact with or immediately adjacent to the flames. This is also how heat is transferred from the sun to the earth.

TORCH FIRE. Continuous combustion of a flammable fluid that is being released with considerable momentum.

TOXIC. Describes a material with median lethal doses and/or median lethal concentrations listed in OSHA 29 CFR 1910.1200, Appendix A.

TOXIC VAPOR CLOUD. A vapor cloud consisting of toxic gas and air, within which the gas concentration equals or exceeds a concentration that could be harmful to humans exposed for a specific time.

VAPOR CLOUD. A volume of gas/air mixture within which the gas concentration equals or exceeds some specified or defined concentration limit.

VAPOR CLOUD EXPLOSION. Extremely rapid combustion of a flammable vapor cloud, resulting in a blast wave.

VULNERABILITY ZONE. The area within the circle created by rotating a hazard zone around its point of origin. Any point within that circle could, under some set of circumstances, be exposed to a hazard level that equals or exceeds the endpoint used to define the hazard zone. However, except for accidents that produce circular hazard zones (e.g., BLEVEs and confined explosions), only a portion of the area within the vulnerability zone can be affected by a single accident.

API	American Petroleum Institute
BLEVE	Boiling Liquid–Expanding Vapor Explosion
CCPS	Center for Chemical Process Safety
DOT	Department of Transportation
EPA	Environmental Protection Agency
ESD	Emergency Shut Down
FTA	Fault Tree Analysis
IDLH	Immediately Dangerous to Life or Health
LFL	Lower Flammable Limit
LPG	Liquefied Petroleum Gas
NFPA	National Fire Protection Association
OREDA	Offshore Reliability Data
psig	Pounds per square inch, gauge
QRA	Quantitative Risk Analysis
RMP	Risk Management Plan
STEL	Short-Term Exposure Limit
TNO	Netherlands Organization of Applied Scientific Research (Nederlandse Organisatie voor toegepest-natuurwetenschallelijk onderzoek)
TNT	Trinitrotoluene
USCB	United States Census Bureau
USNRC	United States Nuclear Regulatory Commission

APPENDIX A
BACKGROUND INFORMATION
ON ENDPOINT SELECTION

Introduction

A release of hazardous fluid into the environment may pose one or more of the following hazards to persons in the vicinity of the release.

A. Heat from flames (if the release is ignited)
B. The blast wave created by an explosion (if the release is ignited and explodes)
C. Toxicity (if the released material is inhaled)

The following discussion looks at the physiological effects of these hazards on humans.

A. Physiological Effects of Heat from Flames

The physiological effects of fire on humans depend on the rate at which heat is transferred from the fire to a person, and the length of time the person is exposed to the fire. Very short duration exposure to a flame (e.g., passing your finger through a candle flame) can result in no injurious effects, while long-term exposure to relatively low levels of radiant energy (e.g., sunbathing) can result in first degree skin burns.

i) Flash fires

Flash fire is the name given to a fire that results from ignition of a flammable vapor cloud. Such fires are generally of short duration since, once ignited, the flames spread through the flammable vapor cloud rather rapidly and consume all the available fuel. A person who is inside the flammable vapor cloud at the time of ignition is likely to receive serious skin burns to those parts of the body that are not protected by clothing. In addition, the person's clothing might be ignited by the flash fire, causing further injuries.

The size of a flash fire can be defined as being equal to the size of the flammable vapor cloud just prior to ignition. Thus, in consequence analysis studies, the flash fire hazard zone for a given release is predicted by modeling the extent of the flammable vapor cloud (defined by the Lower Flammable Limit [LFL] contour) that would result from that release. Persons inside the flammable cloud at the time of ignition are assumed to receive serious (potentially fatal) skin burns (although there have been actual incidents in which persons escaped from flash fires without injuries or with only minor burns). Persons outside a flammable cloud at the time of ignition will not come into contact with the flames but will be exposed only to the radiant heat from the flash fire. Because a flash fire is of short duration, and the flames exist at any given point for an even shorter period of time, persons outside the flammable cloud at the time of ignition are unlikely to suffer more than minor skin burns, and then only if they are very close to the LFL boundary at the moment of ignition.

ii) Radiant heat from pool fires and torch fires

Unlike flash fires, which are of short duration, the duration of a pool fire or torch fire will be either the time required to burn all of the released fluid or the time required to extinguish the fire. Although a person could receive serious skin burns if contacted by the flames of a pool fire or torch fire, the primary hazard outside of such fires is radiant energy emitted by the flames. Table 1 lists some of the potential effects of exposure to radiant energy from fires.

Table 1
Approximate Radiant Flux Injury/Damage Criteria

Description	Exposure Duration	Radiant Flux		Reference
		kW/m^2	Btu/(hr·ft^2)	
Pain, unprotected skin	continuous	1.4	440	Buettner, 1951
Pain, unprotected skin	60 sec	1.73	550	Buettner, 1951
Pain, unprotected skin	16 sec	4.73	1,500	Buettner, 1951
Second degree burns, unprotected skin	30 sec	5.03	1,600	Stoll and Green, 1959
Pain, unprotected skin	6 sec	9.6	3,000	Buettner, 1951
Second degree burns, unprotected skin	13 sec	9.6	3,000	Stoll and Green, 1959
Spontaneous ignition of wood	continuous	19.8	6,700	Koohyar, 1967
Ignition of wooden structures	10-20 min	31.4	10,000	HUD guidebook

iii) Radiant heat from Boiling Liquid–Expanding Vapor Explosion (BLEVE) fireballs

A BLEVE is a major failure of a pressure vessel that contains a superheated liquid. When the liquid is released to the atmosphere, part of it will immediately flash to vapor. This will cause much of the remaining liquid to break into small drops, creating a rapidly expanding "ball" of vapor, liquid drops, and air. If the material is flammable and ignition occurs, the result will be a rapidly expanding fireball that will lift off the ground after a few seconds and then rise in the air. The "lifetime" of such a fireball is a matter of seconds since it lasts only until all of the fluid expelled from the failed vessel has been consumed in the fireball. Exposure to radiant energy from a BLEVE fireball will produce the same effects as exposure to radiant energy from a pool or torch fire. However, the duration of exposure to the radiant heat from a fireball will be limited to the short period of time the fireball actually exists.

B. Physiological Effects of Blast Waves from Explosions

Under certain circumstances, ignition of a flammable vapor cloud can lead to an explosion that will produce a blast wave. The amount of pressure rise (overpressure) associated with the blast wave depends on the strength of the explosion and the distance the blast wave has traveled from the source of the explosion.

The damaging effects of overpressure on structures depends on the peak overpressure that reaches a given structure, and the method of construction of that structure. Similarly, the effect of overpressure on a person in the path of the blast wave depends on the peak overpressure that reaches the person. Exposure to high overpressure levels may be fatal. If the person is far enough from the edge of the burning cloud, the overpressure is incapable of causing injuries. Table 2 illustrates a range of overpressure effects on structures, equipment and people.

Table 2
Damage and Injuries Produced by Blast Waves

Description	Overpressure (psig)	Reference
Annoying noise	0.02	Clancey, 1972
Loud noise (143 dB)	0.04	Clancey, 1972
Typical pressure for glass breakage	0.15	Clancey, 1972
10% window glass broken	0.3	Clancey, 1972
Minor damage to house structures	0.7	Clancey, 1972
Partial demolition of houses, made uninhabitable	1.0	Clancey, 1972
Partial collapse of walls and roofs of houses	2.0	Clancey, 1972
Lower limit of serious structural damage	2.3	Clancey, 1972
Steel frame building distorted and pulled away from foundations	3.0	Clancey, 1972
Frameless, self-framing steel panel building demolished	3 - 4	Clancey, 1972
Cladding of light industrial buildings ruptured	4.0	Clancey, 1972
Threshold of eardrum rupture	5.0	Glasstone and Dolan, 1977
Nearly complete destruction of houses	5.0 - 7.0	Clancey, 1972
Loaded railcars overturned	7.0	Clancey, 1972
Probable total destruction of buildings	10.0	Clancey, 1972
Threshold of lung damage	12.0	Glasstone and Dolan, 1977
Threshold of lethality	40.0	Glasstone and Dolan, 1977

C. Physiological Effects of Toxic Clouds

Release of a fluid with toxic properties may result in the formation of a toxic vapor cloud. Persons who inhale the toxic gas may be injured if the combination of toxic gas concentration being breathed and the duration of exposure to the toxic gas is great enough. This point is illustrated in Table 3, which lists the effects of breathing various concentrations of ammonia for various periods of time.

Table 3
Effects of Different Concentrations of Ammonia

Description	Exposure Duration	Concentration (ppmv)	Reference
TLV (Threshold Limit Value) / TWA (Time Weighted Average) -- The average concentration under which most people can work consistently for eight hours, day in, day out, with no harmful effects.	8 hrs	25	ACGIH
ERPG-1 – The maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hr without experiencing other than mild transient adverse health effects or perceiving a clearly defined objectionable odor.	60 min	25	AIHA
AEGL-1 – The airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic nonsensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.	10 min 30 min 60 min	30 30 30	AEGL
ERPG-2 – The maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hr without experiencing or developing irreversible or other serious health effects or symptoms that could impair their ability to take protective action.	60 min	150	AIHA
AEGL-2 – The airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.	10 min 30 min 60 min	220 220 160	AEGL
IDLH – This level represents a maximum concentration from which one could escape within 30 minutes without any escape-impairing symptoms or any irreversible health effects.	30 min	300	NIOSH
ERPG-3 – The maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hr without experiencing or developing life-threatening health effects.	60 min	750	AIHA
AEGL-3 – The airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death.	10 min 30 min 60 min	2700 ppm 1600 ppm 1100 ppm	AEGL
Concentration causing coughing and bronchial spasms. Possibly fatal for exposure of less than one-half hour.	< 30 min	1,700	Matheson
Minimum concentration for the onset of lethality after 30-minute exposure (fatal to 1% of exposed population).	30 min	1,883	Perry and Articola
Minimum concentration for 50% lethality after 30-minute exposure (fatal to 50% of exposed population).	30 min	4,005	Perry and Articola
Minimum concentration for 99% lethality after 30-minute exposure (fatal to 99% of exposed population).	30 min	8,519	Perry and Articola

Hazard Endpoint References in Codes and Standards

The physiological impacts of flammable or toxic materials are referenced in a number of recognized codes and standards. In referring to any one code or standard, it is important to identify the object or "target" for whom the hazard endpoint was developed. Examples of this would be;

- Was the endpoint developed for a worker (on site) or a member of the public (off site)?
- Was the endpoint developed for an existing facility or a proposed facility?
- Was the endpoint developed for use by the industry handling the hazardous material or by some outside agency that plans to locate near a hazardous facility?

When reviewing the endpoint criteria listed in the following tables, these questions should be kept in mind. Seemingly conflicting endpoints for the same hazard can often be explained by reviewing the origin and use of the endpoints within their particular code or standard.

Absolute Worst Case, Prescribed Worst Case, and Alternate Case

In reviewing the application of various hazard endpoints referenced in the codes and standards, it is important to recognize what type of hazardous material releases the endpoints are to be applied to. In general, when a code or standard refers to a "worst case release," it is actually referring to a "prescribed" worst case release. For example, in the EPA RMP regulation, the worst case release from a vessel containing anhydrous ammonia is the instantaneous development of a hole of sufficient size such that the entire contents of the tank are released in 10 minutes. This definition allows for a consistent application of a hazardous scenario from one facility to another, but does not necessarily result in the worst (i.e., largest) possible impact. Using this approach as a guideline, the following types of releases can be defined.

Prescribed Worst Case - These are often large releases defined by the referencing code or standard. They rarely result in the absolute largest hazard possible from the piece of equipment/material being evaluated. Rather, the definition of a prescribed worst case offers a methodology by which different facilities can be compared on an apples-to-apples basis. Examples of prescribed worst case scenarios are;

Flash fire hazard - 10-minute release from process equipment (LNG); 49 CFR 193
Radiation hazard - Fully involved impoundment fire (LNG); 49 CFR 193
Overpressure hazard - Loss of full contents of pressurized bullet (LPG); 40 CFR 68
Toxic hazard -Loss of contents of pressurized bullet (anhydrous ammonia) in 10 minutes; 40 CFR 68

Alternate Case - These are most often releases of smaller magnitude than prescribed worst case releases. In some codes, the choice of the alternate case is defined by the applicant (e.g., EN 1473), in other codes the alternate case is bound by specific requirements (e.g., US EPA RMP).

Absolute Worst Case - In the context of this discussion and the available codes and standards, the absolute worst case would be defined by the largest impact resulting from any physically possible release, regardless of how it might occur. The only requirement would be that the event be possible. No restrictions on frequency of occurrence or credibility are applied. Examples of several absolute worst case scenarios are;

Flash fire hazard - Simultaneous, catastrophic failure of multiple LPG pressurized storage vessels.
Radiation hazard - Catastrophic failure of LNG storage tank due to aircraft impact.
Overpressure hazard - Catastrophic failure of containment system on underground LPG storage cavern.
Toxic hazard - Catastrophic failure of refrigerated anhydrous ammonia storage tank.

In each of the scenarios listed above, the hazard zone is potentially much larger than those calculated for prescribed worst case scenarios. It should be noted that no code or standard requires calculation of an absolute worst case scenario. Reasons for this include:

- Very large releases have very low frequencies of occurrence. Thus, even though the consequences may be severe the risk (consequence x frequency) posed by such an event is deemed small.

- The codes and standards do not define zones of "zero risk." The worst case releases and hazard endpoints prescribed by codes and standards define zones that each code or standard deems to have an acceptable level of risk.

If absolute worst case calculations were required, how would the following common industrial activities be evaluated?

Air travel - The range of consequences (crash impact, fire) from airline operations would cover the entire United States since every point in the country has the possibility of being a crash site. Thus, there is no location in the U.S. that is at "zero risk" from air travel.

Gasoline filling stations - The storage of gasoline on the premises of gasoline filling stations and convenience stores has the potential to generate impacts (fire, explosion, toxic clouds) in excess of the property boundaries.

In summary, the codes and standards presented in Tables 4 through 7 are those commonly used and referenced for work in the United States, Canada, and the European Union. In general, the siting guidelines (i.e., where an operation or facility can be placed relative to what is around it) are based on calculating the size of a potential injury zone using a prescribed worst case as the accident scenario.

Selection of Hazard Endpoints for Worst Case Analysis for the South Coast Air Quality District Hazards Analysis Studies

Following a review of the codes and standards presented in Tables 4 through 7, a set of hazard endpoints for use in defining injury levels to members of the public can be defined. These endpoints are selected from the codes and standards that evaluate the extent to which existing or proposed hazardous material facilities might impact members of the public who are outside the property line of the facility being evaluated.

Each of these hazard endpoints defines an injury threshold. Although it is difficult to equate injury due to fires to injury due to overpressure to injury due to toxic exposure, this set of endpoints represents a reasonable approach to this problem.

Hazard	Hazard Endpoint	Public Response
Flash Fire Exposure	LFL	Persons outside the LFL have very little risk of injury.
Radiant Exposure	1,600 Btu/hr-ft^2	When people see a fire, it is easy for them to determine which direction they should move to increase the distance between them and the fire and thus lower the impact of the fire on them, or they can find a building or other solid structure to go behind to reduce or eliminate the radiant impact. If a person is already inside a building, they will be protected from the radiant impact. [This radiant level is not high enough to ignite a building.]
Overpressure Exposure	1 psig	1 psig may knock down a person standing outside, and thus cause injury. If a person were inside a normal building when it is exposed to 1 psig, injuries might occur due to damage to the building.
Toxic Gas Exposure	ERPG-2	Outdoor exposure to the ERPG-2 concentration level gives a person up to 30 minutes to leave the area or seek shelter. Persons indoors during this time would be exposed to a lower overall dose of the toxic material.

Table 4
Code-Specified Vapor Dispersion Endpoints (Flash Fire Impacts)

Code or Standard	Specified Endpoint	Release Scenarios	"Targets" of Interest
49 CFR 193	1/2 LFL	Prescribed (less than worst case)	Public outside any proposed plant boundary that can be built upon
EN 1473	LFL	Less than worst case	Public near proposed facilities
NFPA 59A - 2006	1/2 LFL	Prescribed (less than worst case)	Public outside any proposed plant boundary that can be built upon
CSA Z276-01	1/2 LFL or LFL †	Prescribed (less than worst case)	Public outside any proposed plant boundary that can be built upon
RMP	LFL	Alternate (less than worst case)	Public near existing or proposed facilities
HUD	NA		
IP9	LFL	Prescribed (less than worst case)	Persons outside the facility boundary
API RP521	NA		

NA – Not Applicable (this code or standard does not address this hazard)

† – Choice of 1/2 LFL or LFL is dependent on prescribed scenario

Table 5
Code-Specified Thermal Radiation Endpoints

Code or Standard	Specified Endpoint	Release Scenarios	"Targets" of Interest
49 CFR 193	1,600 Btu/hr •ft^2	Prescribed (less than worst case)	Persons at the proposed fenceline of the facility
		Prescribed worst case (tank impounding area fire)	Groups of 50 or more persons outside the proposed fenceline
EN 1473	13 kW/m^2 (4,160 Btu/hr •ft^2)	Less than worst case	Persons at the proposed fenceline in a remote area
	5 kW/m^2 (1,600 Btu/hr •ft^2)	Less than worst case	Persons at the proposed fenceline in an urban area
	1.5 kW/m^2 (480 Btu/hr •ft^2)	Less than worst case	Persons in places difficult or dangerous to evacuate in an emergency (e.g., sports stadium, playground, outdoor theater)
			Plant personnel who must remain in an unshielded area during an emergency, without protective clothing
NFPA 59A - 2006	1,600 Btu/hr •ft^2	Prescribed (less than worst case)	Persons at the proposed fenceline of the facility
		Prescribed worst case (tank impounding area fire)	Groups of 50 or more persons outside the proposed fenceline
CSA Z276-01	1,600 Btu/hr •ft^2	Prescribed (less than worst case)	Persons at the proposed fenceline of the facility
		Prescribed worst case (tank impounding area fire)	Groups of 50 or more persons outside the proposed fenceline
RMP	1,600 Btu/hr •ft^2	Prescribed (less than worst case)	Public near existing or proposed facilities
HUD	450 Btu/hr •ft^2	Prescribed worst case (tank impounding area fire)	Persons in HUD-assisted projects to be built in the vicinity of one or more existing hazardous facilities

Table 5
Code-Specified Thermal Radiation Endpoints
(Continued)

Code or Standard	Specified Endpoint	Release Scenarios	"Targets" of Interest
IP9	4,000 Btu/hr •ft^2	Prescribed (less than worst case)	Persons at the proposed fenceline in a remote area
	1,500 Btu/hr •ft^2	Prescribed (less than worst case)	Persons at the proposed fenceline in an urban area
	500 Btu/hr •ft^2	Prescribed (less than worst case)	Persons in places difficult or dangerous to evacuate in an emergency (e.g., a sports stadium)
			Plant personnel who must remain in an unshielded area during an emergency, without protective clothing
API RP521	2,000 Btu/hr •ft^2	Flaring	Plant personnel who may be required to perform emergency actions lasting up to 1 minute while wearing appropriate clothing
	1,500 Btu/hr •ft^2	Flaring	Plant personnel who may be required to perform emergency actions lasting several minutes while wearing appropriate clothing
	500 Btu/hr •ft^2	Flaring	Plant personnel who maybe continuously exposed, while wearing appropriate clothing

Table 6
Code-Specified Explosion Overpressure Endpoints

Code or Standard	Specified Endpoint	Release Scenarios	"Targets" of Interest
49 CFR 193	NA		
EN 1473	NA		
NFPA 59A - 2006	NA		
CSA Z276-01	NA		
RMP	1 psi	Prescribed worst case	Public near existing or proposed facilities
		Alternate (less than worst case)	Public near existing or proposed facilities
HUD	0.5 psi	Prescribed worst case	Persons in HUD-assisted projects to be built in the vicinity of one or more existing hazardous facilities.
IP9	NA		
API RP521	NA		

NA – Not Applicable (this code or standard does not address this hazard)

Table 7
Code-Specified Toxic Vapor Endpoints

Code or Standard	Specified Endpoint	Release Scenarios	"Targets" of Interest
49 CFR 193	NA		
EN 1473	NA		
NFPA 59A - 2006	NA		
CSA Z276-01	NA		
RMP	ERPG-2	Prescribed worst case	Public near existing or proposed facilities
		Alternate (less than worst case)	Public near existing or proposed facilities
HUD	NA		
IP9	NA		
API RP521	NA		

NA – Not Applicable (this code or standard does not address this hazard)

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APPENDIX B
CANARY BY QUEST® MODEL DESCRIPTIONS

The following model descriptions are taken from the CANARY by Quest User Manual.

Section A	Engineering Properties
Section B	Pool Fire Radiation Model
Section C	Torch Fire and Flare Radiation Model
Section E	Fluid Release Model
Section F	Momentum Jet Dispersion Model
Section G	Heavy Gas Dispersion Model
Section I	Vapor Cloud Explosion Model

Engineering Properties

Purpose

The purpose of this model is to provide an accurate means of computing physical and thermodynamic properties of a wide range of chemical mixtures and pure components using a minimum of initial information.

Required Data

(a) Fluid composition
(b) Temperature and pressure of the fluid prior to release

Methodology

Basic thermodynamic properties are computed using the Peng-Robinson equation of state [Peng and Robinson, 1976]. The necessary physical and thermodynamic properties are calculated in the following manner.

Step 1: The temperature and pressure of the fluid at storage conditions and the identity and mole fraction of each component of the fluid are obtained. Mixture parameters are determined using data from the extensive properties data base within CANARY.

Step 2: Each calculation begins with the computation of the vapor and liquid fluid composition. For cases where the temperature and pressure result in only one phase being present, the vapor or liquid composition will be the same as the initial feed composition. The composition calculation is an iterative procedure using a modification of the techniques described by Starling [1973].

Step 3: Once the vapor and liquid compositions are known, the vapor and liquid densities, enthalpies, entropies, and heat capacities can be computed directly. Other physical properties (viscosity, thermal conductivity, surface tension, etc.) are computed using correlations developed in Reid, Prausnitz, and Poling [1987].

Step 4: A matrix of properties is computed over a range of temperatures and pressures. Physical and thermodynamics properties required by other models within CANARY are then interpolated from this table.

Basic Thermodynamic Equations

$$Z^3 - (1-B)\cdot Z^2 + \left(A - 3\cdot B^2 - 2\cdot B\right)\cdot Z - \left(A\cdot B - B^2 - B^3\right) = 0 \qquad (1)$$

where: Z = fluid compressibility factor, $\frac{P\cdot V}{R\cdot T}$, dimensionless

P = system pressure, kPa

V = fluid specific volume, m^3/kmol

R = gas constant, 8.314 $m^3 \cdot kPa/(kmol \cdot K)$
T = absolute temperature, K

$$A = \frac{a \cdot P}{R^2 \cdot T^2}$$

$$a = 0.45724 \cdot \frac{R^2 \cdot T^2}{P_c} \cdot \alpha$$

$$\alpha = \left[1 + m \cdot \left(1 - T_r^{0.5}\right)^2\right]$$

$$m = 0.37464 + 1.54226 \cdot \omega - 0.26992 \cdot \omega^2$$

ω = acentric factor

$$T_r = \frac{T}{T_c}$$

T_c = pseudo-critical temperature, K
P_c = pseudo-critical pressure, kPa

$$B = \frac{b \cdot P}{R \cdot T}$$

$$b = 0.0778 \cdot R \cdot \frac{T_c}{P_c}$$

$$H = H^o + \frac{P}{\rho} - R \cdot T + \int_0^\rho \left[P - T \cdot \left(\frac{\partial P}{\partial T}\right)_\rho\right] \cdot \left(\frac{d\rho}{\rho^2}\right) \tag{2}$$

where: H = enthalpy of fluid at system conditions, kJ/kg
H^o = enthalpy of ideal gas at system temperature, kJ/kg

$$S = S^o - R \cdot \ln\left(\rho \cdot R \cdot T\right) + \int_0^\rho \left[\rho \cdot R - \left(\frac{\partial P}{\partial T}\right)_\rho\right] \cdot \left(\frac{d\rho}{\rho^2}\right) \tag{3}$$

where: S = entropy of fluid at system conditions, kJ/(kg·K)
S^o = entropy of ideal gas at system temperature, kJ/(kg·K)

$$R \cdot T \cdot \ln\left(\frac{f_i}{f_i^o}\right) = \left[\left(H_i - H_i^o\right) - T \cdot \left(S_i - S_i^o\right)\right] \tag{4}$$

where: f_i = fugacity of component i, kPa
f_i^o = standard state reference fugacity, kPa

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Pool Fire Radiation Model

Purpose

The purpose of this model is to predict the impact of fire radiation emitted by flames that are fueled by vapors emanating from liquid pools. Specifically, the model predicts the maximum radiant heat flux incident upon a target as a function of distance between the target and the flame.

Required Data

(a) Composition of the liquid in the pool
(b) Temperature of the liquid in the pool
(c) Wind speed
(d) Air temperature
(e) Relative humidity
(f) Elevation of the target (relative to grade)
(g) Elevation of the pool (relative to grade)
(h) Dimensions of the free surface of the pool
(i) Orientation of the pool (relative to the wind direction)
(j) Spill surface (land or water)

Methodology

Step 1: The geometric shape of the flame is defined. The flame column above a circular pool, square pool, or rectangular pool is modeled as an elliptical cylinder.

Step 2: The dimensions of the flame column are determined. The dimensions of the base of the flame are defined by the pool dimensions. An empirical correlation developed by Thomas [1965] is used to calculate the length (height) of the flame.

$$L = 42 \cdot D_h \cdot \left(\frac{\dot{m}}{\rho_a \cdot (g \cdot D_h)^{0.5}} \right)^{0.61}$$

where: L = length (height) of the flame, m
D_h = hydraulic diameter of the liquid pool, m
$\dot{m}$ = mass burning flux, kg/(m^2·s)
ρ_a = density of air, kg/m^3
g = gravitational acceleration, 9.8 m/s^2

Notes: Mass burning fluxes used in the Thomas equation are the steady-state rates for pools on land (soil, concrete, etc.) or water, whichever is specified by the user.

For pool fires with hydraulic diameters greater than 100 m, the flare length, L, is set equal to the length calculated for $D_h = 100$ m.

Step 3: The angle (Φ) to which the flame is bent from vertical by the wind is calculated using an empirical correlation developed by Welker and Sliepcevich [1970].

$$\frac{\tan(\Phi)}{\cos(\Phi)} = 3.2 \cdot \left(\frac{D_h \cdot u \cdot \rho_a}{\mu_a}\right)^{0.07} \cdot \left(\frac{u^2}{g \cdot D_h}\right)^{0.7} \cdot \left(\frac{\rho_v}{\rho_a}\right)^{-0.6}$$

where: Φ = angle the flame tilts from vertical, degrees
u = wind speed, m/s
μ_a = viscosity of air, kg/(m•s)
ρ_v = density of fuel vapor, kg/m^3

Step 4: The increase in the downwind dimension of the base of the flame (flame drag) is calculated using a generalized form of the empirical correlation Moorhouse [1982] developed for large circular pool fires.

$$D_w = 1.5 \cdot D_x \cdot \left(\frac{u^2}{g \cdot D_x}\right)^{0.069}$$

where: D_w = downwind dimension of base of tilted flame, m
D_x = downwind dimension of the pool, m

Step 5: The flame is divided into two zones: a clear zone in which the flame is not obscured by smoke; and a smoky zone in which a fraction of the flame surface is obscured by smoke. The length of the clear zone is calculated by the following equation, which is based on an empirical correlation developed by Pritchard and Binding [1992].

$$L_c = 55.05 \cdot D_h^{-0.6} \cdot \left(\frac{\dot{m}}{\rho_a}\right)^{1.13} \cdot (u+1)^{0.179} \cdot \left(\frac{C}{H}\right)^{-2.49}$$

where: L_c = length of the clear zone, m
$\frac{C}{H}$ = carbon/hydrogen ratio of fuel, dimensionless

Step 6: The surface flux of the clear zone is calculated using the following equation.

$$q_{cz} = q_{sm} \cdot \left(1 - e^{-b \cdot D_h}\right)$$

where: q_{cz} = surface flux of the clear zone, kW/m^2
q_{sm} = maximum surface flux, kW/m^2
b = extinction coefficient, m^{-1}

Average surface flux of the smoky zone, q_{cz}, is then calculated, based on the following assumptions.

- The smoky zone consists of clean-burning areas and areas in which the flame is obscured by smoke.
- Within the smoky zone, the fraction of the flame surface that is obscured by smoke is a function of the fuel properties and pool diameter.
- Smoky areas within the smoky zone have a surface flux of 20 kW/m^2 [Hagglund and Persson,1976].
- Clean-burning areas of the smoky zone have the same surface flux as the clean-burning zone.
- The average surface flux of the smoky zone is the area-weighted average of the surface fluxes for the smoky areas and the clean-burning areas within the smoky zone.

(This two-zone concept is based on the Health and Safety Executive POOLFIRE6 model, as described by Rew and Hulbert [1996].)

Step 7: The surface of the flame is divided into numerous differential areas. The following equation is then used to calculate the view factor from a differential target, at a specific location outside the flame, to each differential area on the surface of the flame.

$$F_{dA_t \to dA_f} = \frac{\cos(\beta_t) \cdot \cos(\beta_f)}{\pi \cdot r^2} \cdot dA_f \qquad \text{for } [\beta_t] \text{ and } [\beta_f] < 90^\circ$$

where: $F_{dA_t \to dA_f}$ = view factor from a differential area on the target to a differential area on the surface of the flame, dimensionless

dA_f = differential area on the flame surface, m^2

dA_t = differential area on the target surface, m^2

r = distance between differential areas dA_t and dA_f, m

β_t = angle between normal to dA_t and the line from dA_t to dA_f, degrees

β_f = angle between normal to dA_f and the line from dA_t to dA_f, degrees

Step 8: The radiant heat flux incident upon the target is computed by multiplying the view factor for each differential area on the flame by the appropriate surface flux (q_{cz} or q_{sz}) and by the appropriate atmospheric transmittance, then summing these values over the surface of the flame.

$$q_{ai} = \sum_{A_f} q_{sf} \cdot F_{dA_t \to dA_f} \cdot \tau$$

where: q_{ai} = attenuated radiant heat flux incident upon the target due to radiant heat emitted by the flame, kW/m^2

A_f = area of the surface of the flame

q_{sf} = radiant heat flux emitted by the surface of the flame, kW/m^2 (q_{sf} equals either q_{cz} or q_{sz}, as appropriate)

τ = atmospheric transmittance, dimensionless

Atmospheric transmittance, τ, is a function of absolute humidity and r, the path length between differential areas on the flame and target [Wayne, 1991].

Step 9: Steps 7 and 8 are repeated for numerous target locations.

Validation

Several of the equations used in the Pool Fire Radiation Model are empirical relationships based on data from medium- to large-scale experiments, which ensures reasonably good agreement between model predictions and experimental data for variables such as flame length and tilt angle. Comparisons of experimental data and model predictions for incident heat flux at specific locations are more meaningful and of greater interest. Unfortunately, few reports on medium- or large-scale experiments contain the level of detail required to make such comparisons.

One source of detailed test data is a report by Welker and Cavin [1982]. It contains data from sixty-one pool fire tests involving commercial propane. Variables that were examined during these tests include pool size (2.7 to 152 m^2) and wind speed. Figure B-1 compares the predicted values of incident heat flux with experimental data from the sixty-one pool fire tests.

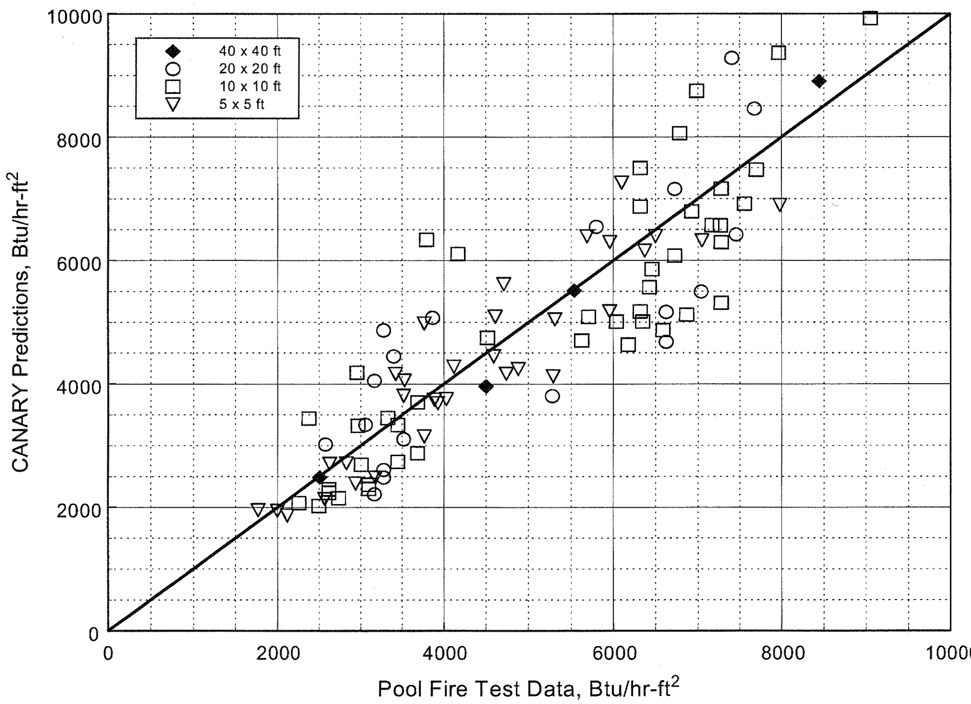

Figure B-1

In another series of tests, fire radiation measurements were taken for large liquefied natural gas (LNG) pool fires. The Montoir tests are the largest tests of LNG fires, involving pools up to 35 meters in diameter [Nédelka, Moorhouse, and Tucker, 1989]. Figure B-2 compares the radiation isopleths predicted by CANARY with the actual measurements taken in Test 2 of the Montoir series.

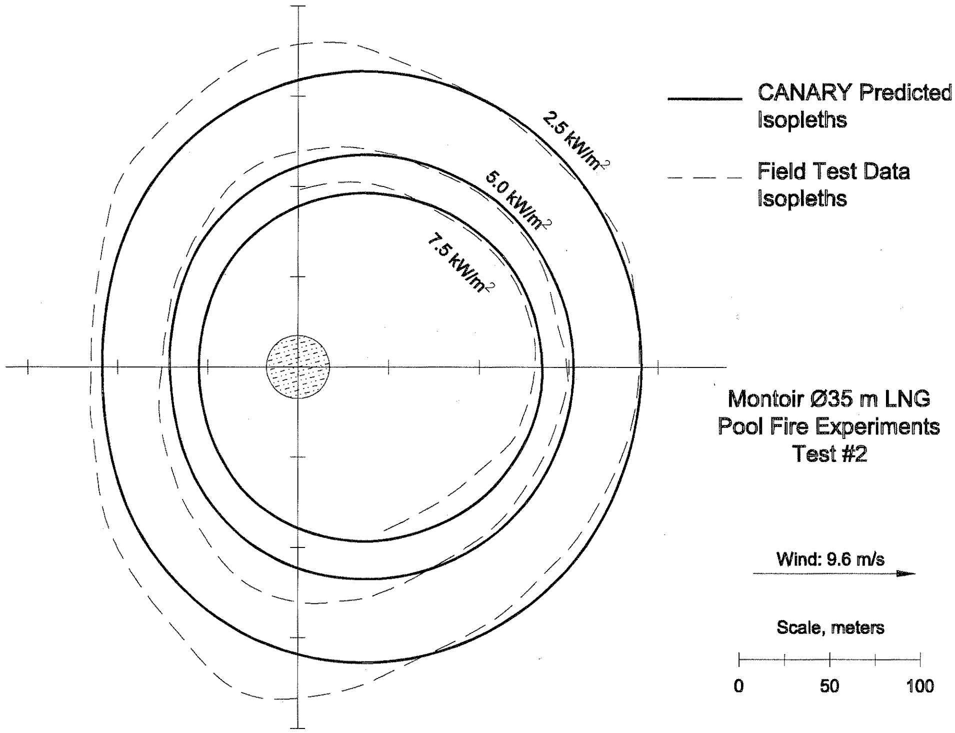

Figure B-2

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Torch Fire and Flare Radiation Model

Purpose

The purpose of this model is to predict the impact of fire radiation emitted by burning jets of vapor. Specifically, the model predicts the maximum radiant heat flux incident upon a target as a function of distance between the target and the point of release.

Required Data

(a) Composition of the released material
(b) Temperature and pressure of the material before release
(c) Mass flow rate of the material being released
(d) Diameter of the exit hole
(e) Wind speed
(f) Air temperature
(g) Relative humidity
(h) Elevation of the target (relative to grade)
(i) Elevation of the point of release (relative to grade)
(j) Angle of the release (relative to horizontal)

Methodology

Step 1: A correlation based on a Momentum Jet Model is used to determine the length of the flame. This correlation accounts for the effects of:

- composition of the released material,
- diameter of the exit hole,
- release rate,
- release velocity, and
- wind speed.

Step 2: To determine the behavior of the flame, the model uses a momentum-based approach that considers increasing plume buoyancy along the flame and the bending force of the wind. The following equations are used to determine the path of the centerline of the flame [Cook, et al., 1987].

$$\Phi_X = (\rho_{ja})^{0.5} \cdot \overline{u} \cdot \sin(\theta) \cdot \cos(\varphi) + (\rho_\infty)^{0.5} \cdot u_\infty \qquad \text{(downwind)}$$

$$\Phi_Y = (\rho_{ja})^{0.5} \cdot \overline{u} \cdot \sin(\theta) \cdot \sin(\varphi) \qquad \text{(crosswind)}$$

$$\Phi_Z = (\rho_{ja})^{0.5} \cdot \overline{u} \cdot \cos(\theta) + (\rho_\infty)^{0.5} \cdot u_b \cdot \frac{(i+1)}{n} \qquad \text{(vertical)}$$

where: Φ_{XYZ} = momentum flux in X, Y, Z direction
ρ_{ja} = density of the jet fluid at ambient conditions, kg/m^3
$\overline{u}$ = average axial velocity of the flame, m/s

θ = release angle in $X-Z$ plane (relative to horizontal), degrees
φ = release angle in $X-Y$ plane (relative to downwind), degrees
ρ_∞ = density of air, kg/m^3
u_∞ = wind speed, m/s
ρ_b = density of combustion products, kg/m^3
u_b = buoyancy velocity, m/s
n = number of points taken along the flame length

These correlations were developed to predict the path of a torch flame when released at various orientations. The model currently does not allow a release angle in a crosswind direction; the release angle is confined to the downwind/vertical plane (i.e., $\varphi = 0$).

Step 3: The angle of flame tilt is defined as the inclination of a straight line between the point of release and the end point of the flame centerline path (as determined in Step 2).

Step 4: The geometric shape of the flame is defined as a frustum of a cone (as suggested by several flare/fire researchers [e.g., Kalghatgi, 1983, Chamberlain, 1987]), but modified by adding a hemisphere to the large end of the frustum. The small end of the frustum is positioned at the point of release, and the centerline of the frustum is inclined at the angle determined in Step 3.

Step 5: The surface emissive power is determined from the molecular weight and heat of combustion of the burning material, the release rate and velocity, and the surface area of the flame.

Step 6: The surface of the flame is divided into numerous differential areas. The following equation is then used to calculate the view factor from a differential target, at a specific location outside the flame, to each differential area on the surface of the flame.

$$F_{dA_t \rightarrow dA_f} = \frac{\cos(\beta_t) \cdot \cos(\beta_f)}{\pi \cdot r^2} \cdot dA_f \qquad \text{for } [\,\beta_t\,] \text{ and } [\,\beta_f\,] < 90$$

where: $F_{dA_t \rightarrow dA_f}$ = view factor from a differential area on the target to a differential area on the surface of the flame, dimensionless
dA_f = differential area on the flame surface, m^2
dA_t = differential area on the target surface, m^2
r = distance between differential areas dA_t and dA_f, m
β_t = angle between normal to dA_t and the line from dA_t to dA_f, degrees
β_f = angle between normal to dA_f and the line from dA_t to dA_f, degrees

Step 7: The radiant heat flux incident upon the target is computed by multiplying the view factor for each differential area on the flame by the surface missive power and by the appropriate atmospheric transmittance, then summing these values over the surface of the flame.

$$q_{ai} = \sum_{A_f} q_{sf} \cdot F_{dA_t \rightarrow dA_f} \cdot \tau$$

where: q_{ai} = attenuated radiant heat flux incident upon the target due to radiant heat emitted by the flame, kW/m^2
A_f = area of the surface of the flame
q_{sf} = radiant heat flux emitted by the surface of the flame, kW/m^2
τ = atmospheric transmittance, dimensionless

Atmospheric transmittance, τ, is a function of absolute humidity and r, the path length between differential areas on the flame and target [Wayne, 1991].

Step 8: Steps 6 and 7 are repeated for numerous target locations.

Validation

Several of the equations used in the Torch Fire and Flare Radiation Model are empirical relationships based on data from medium- to large-scale experiments, which ensures reasonably good agreement between model predictions and experimental data for variables such as flame tilt angle. Comparisons of experimental data and model predictions for incident heat flux at specific locations are more meaningful and of greater interest. Unfortunately, few reports on medium- or large-scale experiments contain the level of detail required to make such comparisons.

One reasonable source of test data is a report by Chamberlain [1987]. It contains data from seven flare tests involving natural gas releases from industrial flares, with several data points being reported for each test. Variables that were examined during these tests include release diameter (0.203 and 1.07 m), release rate and velocity, and wind speed. Figure C-1 compares the predicted values of incident heat flux with experimental data from the seven flare tests.

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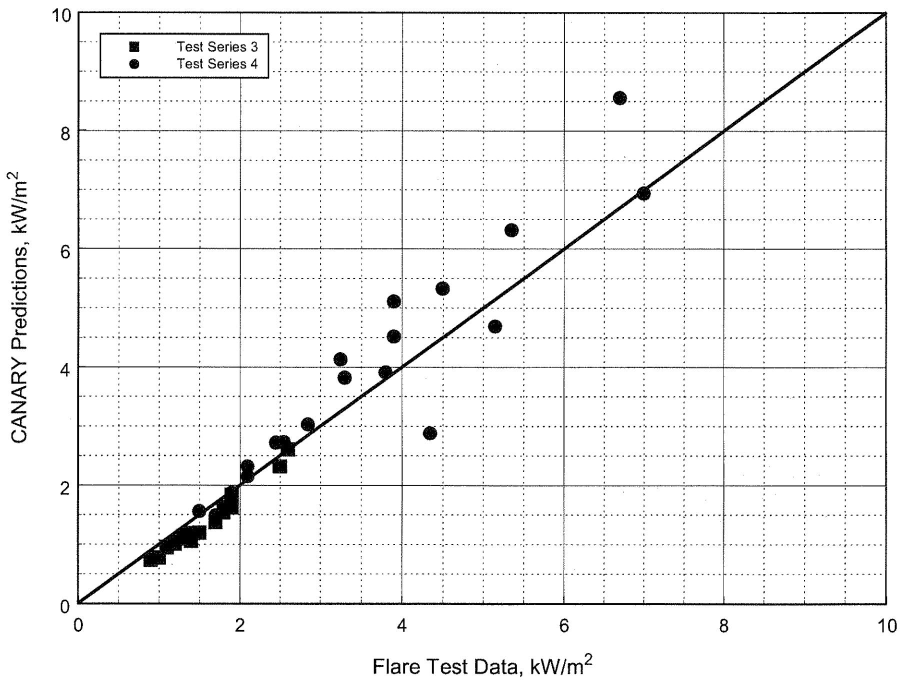
Test Series 3
Test Series 4
CANARY Predictions, kW/m2
Flare Test Data, kW/m2
0
2
4
6
8
10

Figure C-1

Fluid Release Model

Purpose

The purpose of the Fluid Release Model is to predict the rate of mass release from a breach of containment. Specifically, the model predicts the rate of flow and the physical state (liquid, two-phase, or gas) of the release of a fluid stream as it enters the atmosphere from a circular breach in a pipe or vessel wall. The model also computes the amount of vapor and aerosol produced and the rate at which liquid reaches the ground.

Required Data

(a) Composition of the fluid
(b) Temperature and pressure of the fluid just prior to the time of the breach
(c) Normal flow rate of fluid into the vessel or in the pipe
(d) Size of the pipe and/or vessel
(e) Length of pipe
(f) Area of the breach
(g) Angle of release relative to horizontal
(h) Elevation of release point above grade

Methodology

Step 1: Calculation of Initial Flow Conditions

The initial conditions (before the breach occurs) in the piping and/or vessel are determined from the input data, coupled with a calculation to determine the initial pressure profile in the piping. The pressure profile is computed by dividing the pipe into small incremental lengths and computing the flow conditions stepwise from the vessel to the breach point. As the flow conditions are computed, the time required for a sonic wave to traverse each section is also computed. The flow in any length increment can be all vapor, all liquid, or two-phase (this implies that the sonic velocity within each section may vary). As flow conditions are computed in each length increment, checks are made to determine if the fluid velocity has exceeded the sonic velocity or if the pressure in the flow increment has reached atmospheric. If either condition has been reached, an error code is generated and computations are stopped.

Step 2: Initial Unsteady State Flow Calculations

When a breach occurs in a system with piping, a disturbance in flow and pressure propagates from the breach point at the local sonic velocity of the fluid. During the time required for the disturbance to reach the upstream end of the piping, a period of highly unsteady flow occurs. The portion of the piping that has experienced the passage of the pressure disturbance is in accelerated flow, while the portion upstream of the disturbance is in the same flow regime as before the breach occurred.

To compute the flow rate from the breach during the initial unsteady flow period, a small time increment is selected and the distance that the pressure disturbance has moved in that time increment is computed using the sonic velocity profile found in the initial pressure profile calculation. The disturbed length is subdivided into small increments for use in an iterative pressure balance calculation. A pressure balance is achieved when a breach pressure is found that balances the flow from the breach and the flow in the disturbed section of piping. Another time increment is added, and the iterative procedure continues. The unsteady period continues until the pressure disturbance reaches the upstream end of the pipe.

Step 3: Long-Term Unsteady State Flow Calculations

The long-term unsteady state flow calculations are characterized by flow in the piping system that is changing more slowly than during the initial unsteady state calculations. The length of accelerated flow in the piping is constant, set by the user input pipe length. The vessel contents are being depleted, resulting in a potential lowering of pressure in the vessel. As with the other flow calculations, the time is incremented and the vessel conditions are computed. The new vessel conditions serve as input for the pressure drop calculations in the pipe. When a breach pressure is computed that balances the breach flow with the flow in the piping, a solution for that time is achieved. The solution continues until the ending time or other ending conditions are reached.

The frictional losses in the piping system are computed using the equation:

$$h = \left(\frac{4 \cdot f \cdot L \cdot U_{ls}^2}{2 \cdot g_c \cdot D_e} \right) \tag{1}$$

where: h = head (pressure) loss, ft of fluid
f = friction factor
L = length of system, ft
U = average flowing velocity, ft/sec
g_c = gravitational constant, 32.2 $lb_m \cdot ft/(lb_f \cdot sec^2)$
D_e = equivalent diameter of duct, ft

The friction factor is computed using the following equation:

$$\frac{1}{\sqrt{f}} = 1.74 - 2.0 \cdot \log_{10} \left[\frac{2 \cdot \varepsilon}{D_e} + \frac{18.7}{Re \cdot \sqrt{f}} \right] \tag{2}$$

where: ε = pipe roughness, ft
Re = Reynolds number, $D_e \cdot U \cdot \rho / \mu$, dimensionless
ρ = fluid density, lb/ft^3
μ = fluid viscosity, lb/(ft·sec)

Equations (1) and (2) are used for liquid, vapor, and two-phase flow regimes. Since the piping is subdivided into small lengths, changes in velocity and physical properties across each segment are assumed to be negligible. At each step in the calculation, a check is made to determine if the fluid velocity has reached or exceeded the computed critical (sonic) velocity for the fluid. If the critical velocity has been exceeded, the velocity is constrained to the critical velocity and the maximum mass flow rate in the piping has been set.

If the fluid in the piping is in two-phase flow, the Lockhart and Martinelli [1949] modification to Equation (1) is used. The Lockhart and Martinelli equation for head loss is shown below:

$$h_{TP} = \Phi^2 \cdot \left(\frac{4 \cdot f \cdot L \cdot U_{ls}^2}{2 \cdot g_c \cdot D_e} \right) \tag{3}$$

where: h_{TP} = head loss for two-phase flow, ft of fluid
Φ = empirical parameter correlating single- and two-phase flow, dimensionless
U_{ls} = superficial liquid velocity (velocity of liquid if liquid filled the pipe), ft/sec

This equation is valid over short distances where the flowing velocity does not change appreciably.

Validation

Validation of fluid flow models is difficult since little data are available for comparison. Fletcher [1983] presented a set of data for flashing CFC-11 flowing through orifices and piping. Figures E-1 through E-4 compare calculations made using the Fluid Release Model with the data presented by Fletcher. Figure E-1 compares fluid fluxes for orifice type releases. These releases had length-to-diameter (L/D) ratios less than 0.88. Figure E-2 compares computed and experimental release fluxes for an L/D ratio of 120 at several levels of storage pressure. Figure E-3 compares similar releases for an L/D of 37.5. Figure E-4 shows predicted and experimental release fluxes at a given pressure for L/D ratios from 1 to 200.

Figures E-5 and E-6 compare computed and experimental gas discharge rates for the complete breach of two pipes. One pipe had an internal diameter of 6.2 inches (0.157 m); the other had a diameter of 12 inches (0.305 m). These pipes were initially pressurized to 1,000 psia with air and then explosively ruptured. The experimental values were reported in a research paper for Alberta Environment, authored by Wilson [1981].

Aerosols and Liquid Droplet Evaporation

Liquids stored at temperatures above their atmospheric pressure boiling point (superheated liquids) will give off vapor when released from storage. If the temperature of storage is sufficiently above the normal boiling point, the energy of the released vapor will break the liquid stream into small droplets. If these droplets are small enough, they will not settle, but remain in the vapor stream as aerosol droplets. The presence of aerosol droplets in the vapor stream changes its apparent density and provides an additional source of vapor. Droplets large enough to fall to the ground will lose mass due to evaporation during their fall.

The prediction of aerosol formation and amount of aerosol formed is based on the theoretical work performed for the Center for Chemical Process Safety (CCPS) by CREARE. CREARE's work has been extended and corrected by Quest. The extension to the model computes the non-aerosol drop evaporation. In Figure E-7, the four experimental data sets available for comparison (chlorine (Cl_2), methylamine (MMA), CFC-11, and cyclohexane) are compared to the values computed by the CANARY Aerosol Model.

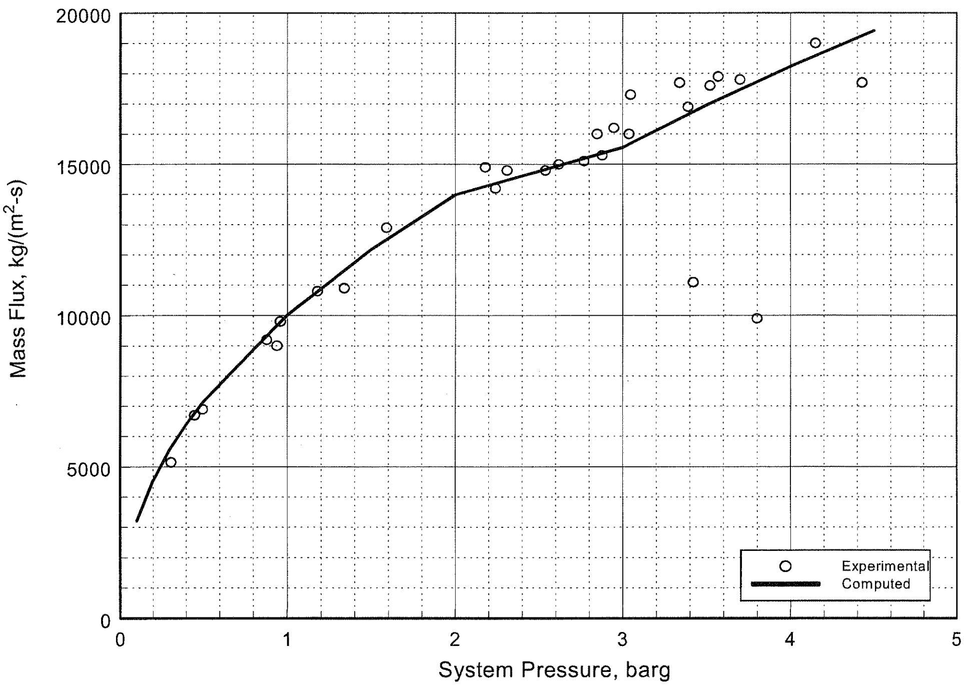

Figure E-1
Comparison of CFC-11 Orifice Releases as a Function of System Pressure

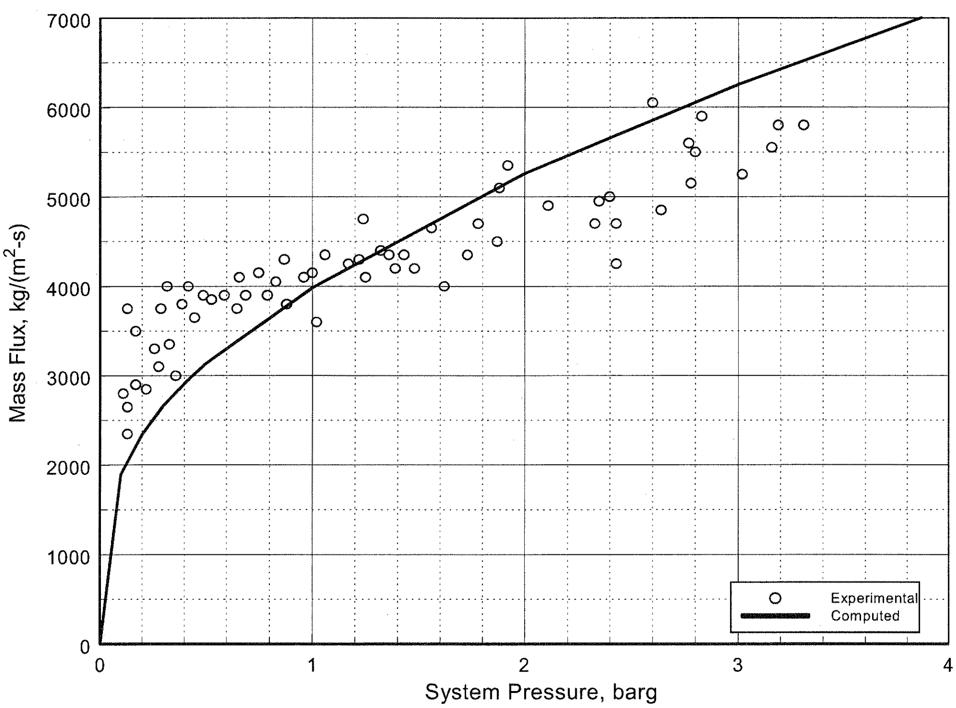

Figure E-2
CFC-11 Release Rate Comparison with L/D of 120

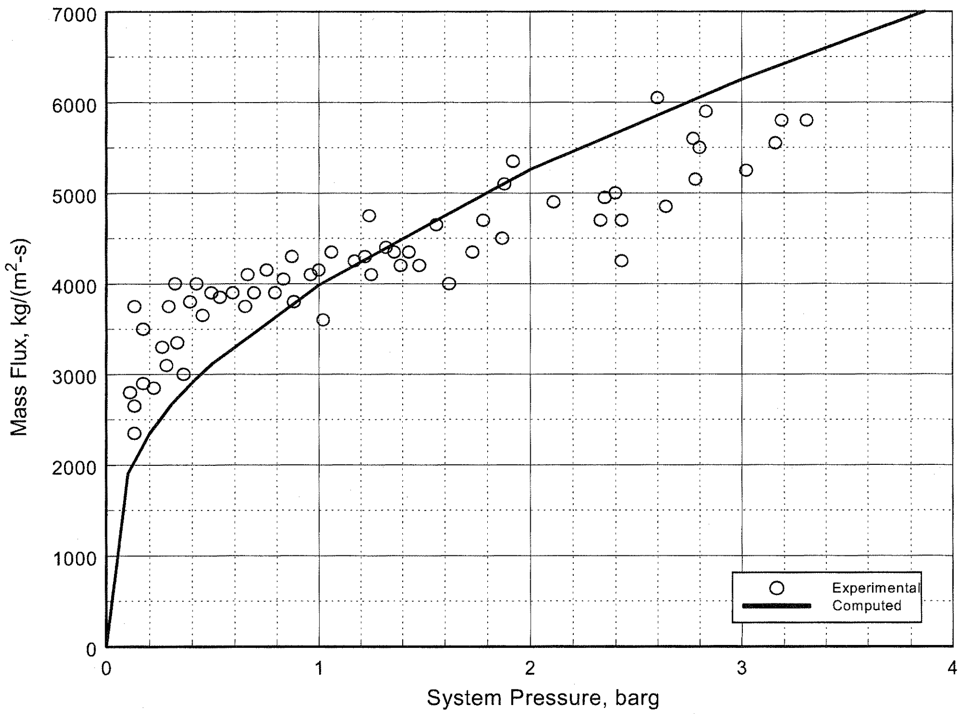

Figure E-3
CFC-11 Release Rate Comparison with L/D of 37.5

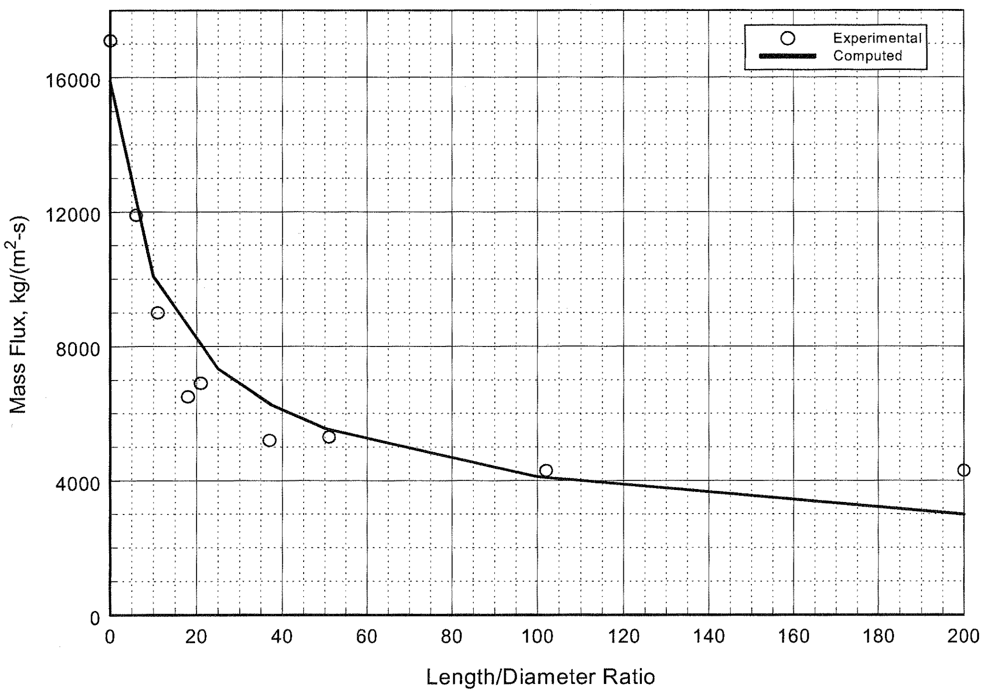

Figure E-4
CFC-11 Release Rate Comparison at Varying L/D Ratios

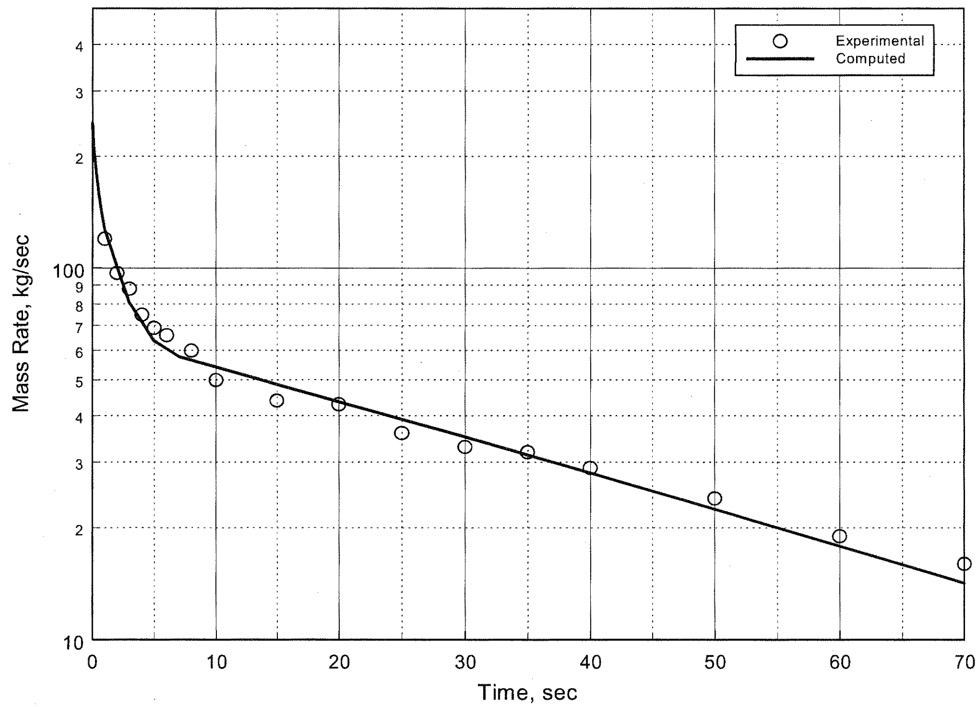

Figure E-5
Air Discharge Rates for 0.157 m Diameter Piping

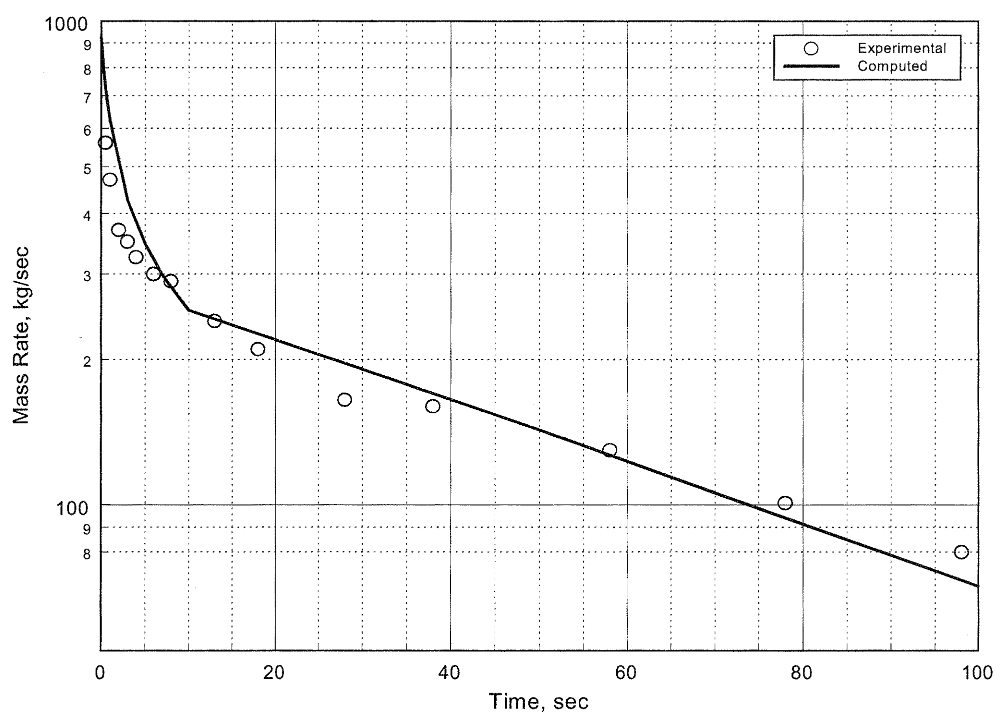

Figure E-6
Air Discharge Rates for 0.305 m Diameter Piping

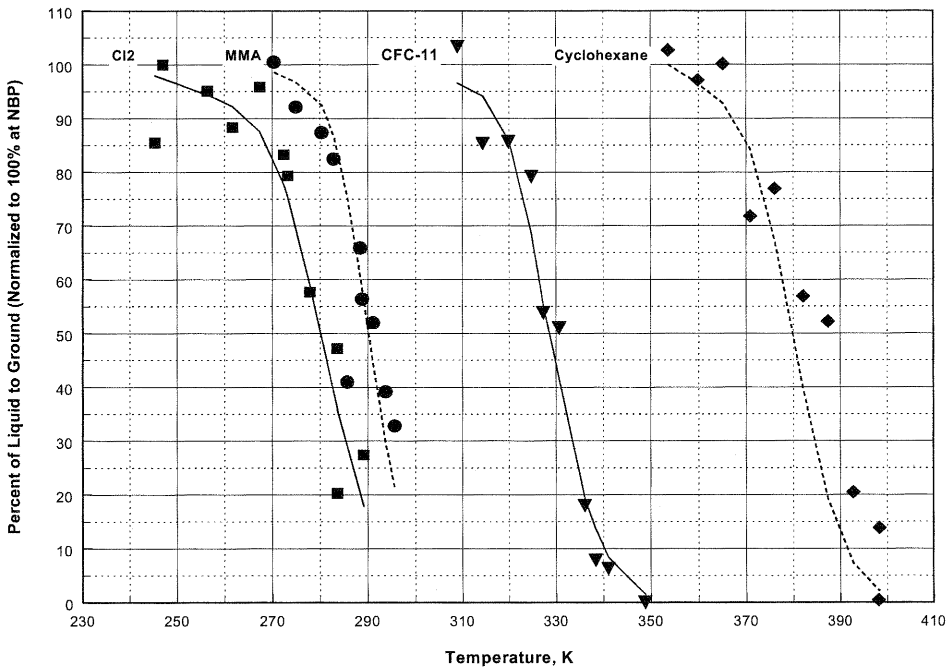

Figure E-7
Aerosol Formation as a Function of Storage Temperature

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Momentum Jet Dispersion Model

Purpose

The purpose of this model is to predict the dispersion of a jet release into ambient air. It is used to predict the downwind travel of a flammable or toxic gas or aerosol momentum jet release.

Required Data

(a) Composition and properties of the released material
(b) Temperature of released material
(c) Release rate of material
(d) Vertical release angle relative to wind direction
(e) Height of release
(f) Release area
(g) Ambient wind speed
(h) Ambient Pasquill-Gifford stability class
(i) Ambient temperature
(j) Relative humidity
(k) Surface roughness scale

Methodology

Step 1: An assumption is made that flow perpendicular to the main flow in the plume is negligible, that the velocity and concentration profiles in the jet are similar at all sections of the jet, that molecular transport in the jet is negligible, and that longitudinal turbulent transport is negligible when compared to longitudinal convective transport. The coordinate system is then defined in s and r, where s is the path length of the plume and r is the radial distance from the plume centerline. The angle between the plume axis and horizontal is referred to as θ. Relationships between the downwind coordinate, x, vertical coordinate, y, and plume axis are given simply by:

$$\frac{dx}{ds} = \cos(\theta) \tag{1}$$

and

$$\frac{dy}{ds} = \sin(\theta) \tag{2}$$

Step 2: Velocity, concentration, and density profiles are assumed to be cylindrically symmetric about the plume axis and are assumed to be Gaussian in shape. The three profiles are taken as:

$$u(s,r,\theta) = U_a \cdot \cos(\theta) + u^*(s) \cdot e^{\frac{-r^2}{b^2(s)}} \tag{3}$$

where: u = plume velocity, m/s
U_a = ambient wind speed, m/s
u^* = plume velocity relative to the wind in the downwind direction at the plume axis, m/s
$b(s)$ = characteristic width of the plume at distance s from the release, m

$$\rho(s,r,\theta) = \rho_a + \rho^*(s)\cdot e^{\frac{-r^2}{\lambda^2\cdot b^2(s)}} \tag{4}$$

where: ρ = plume density, kg/m^3
ρ_a = density of ambient air, kg/m^3
$\rho^*(s)$ = density difference between plume axis and ambient air, kg/m^3
λ^2 = turbulent Schmidt number, 1.35

$$c(s,r,\theta) = c^*(s)\cdot e^{\frac{-r^2}{\lambda^2\cdot b^2(s)}} \tag{5}$$

where: c = pollutant concentration in the plume, kg/m^3
$c^*(s)$ = pollutant concentration at plume centerline, kg/m^3

Step 3: The equation for air entrainment into the plume and the conservation equations can then be solved. The equation for air entrainment is:

$$\frac{d}{ds}\left(\int_0^{b\sqrt{2}} \rho\cdot u\cdot 2\cdot\pi\cdot dr\right) = 2\cdot\pi\cdot b\cdot\rho_a\cdot\left\{\alpha_1\cdot|u^*(s)| + \alpha_2\cdot U_a\cdot|\sin(\theta)|\cos(\theta) + \alpha_3\cdot u'\right\} \tag{6}$$

where: α_1 = entrainment coefficient for a free jet, 0.057
α_2 = entrainment coefficient for a line thermal, 0.5
α_3 = entrainment coefficient due to turbulence, 1.0
u' = turbulent entrainment velocity (root mean square of the wind velocity fluctuation is used for this number), m/s

Step 4: The equations of conservation of mass, momentum, and energy are given as:

$$\frac{d}{ds}\left(\int_0^{b\sqrt{2}} c\cdot u\cdot 2\cdot\pi\cdot dr\right) = 0 \tag{7}$$

$$\frac{d}{ds}\left(\int_0^{b\sqrt{2}} \left(\rho\cdot u^2\cdot\cos(\theta)\cdot 2\cdot\pi\cdot dr\right)\right) = 2\cdot\pi\cdot b\cdot\rho_a\cdot\left\{\alpha_1\cdot\left|u^*(s)\right| + \alpha_2\cdot U_a\cdot\left|\sin(\theta)\right|\cdot\cos(\theta) + \alpha_3\cdot u'\right\} + C_d\cdot\pi\cdot b\cdot\rho_a\cdot U_a^2\left|\sin(\theta)\right| \tag{8}$$

$$\frac{d}{ds}\left(\int_0^{b\sqrt{2}} \rho \cdot u^2 \cdot \cos(\theta) \cdot 2 \cdot \pi \cdot dr\right) = \int_0^{b\sqrt{2}} g \cdot (\rho_a - \rho)\, \pi \cdot r \cdot dr \pm C_d \cdot \pi \cdot b \cdot \rho_a \cdot U_a^2 \cdot \sin(\theta) \cdot \cos(\theta) \tag{9}$$

$$\frac{d}{ds}\left(\int_0^{b\sqrt{2}} \rho \cdot u \left(\frac{1}{\rho} - \frac{1}{\rho_{a0}}\right) \cdot 2 \cdot \pi \cdot r \cdot dr\right) = \rho_a \cdot 2 \cdot \pi \cdot b \left(\frac{1}{\rho_a} - \frac{1}{\rho_{a0}}\right) \cdot \left\{\alpha_1 \cdot |u^*(s)| + \alpha_2 \cdot U_a \ \sin(\theta)| \cdot \cos(\theta) + \alpha_3 \cdot \acute{u}\right\} \tag{10}$$

The subscript 0 refers to conditions at the point of release. These equations are integrated along the path of the plume to yield the concentration profiles as a function of elevation and distance downwind of the release.

Step 5: After the steady-state equations are solved, an along-wind dispersion correction is applied to account for short-duration releases. This is accomplished using the method outlined by Palazzi, et al. [1982].

Step 6: If the plume reaches the ground, it is coupled to the Heavy Gas Dispersion Model (described in Section G) and the dispersion calculations continue.

Validation

The Momentum Jet Dispersion Model used in CANARY was validated by comparing results obtained from the model with experimental data from field tests. Data used for this comparison and the conditions used in the model were taken from an American Petroleum Institute (API) study [Hanna, Strimaitis, and Chang, 1991]. For this model, comparisons were made with the Desert Tortoise, Goldfish, and Prairie Grass series of dispersion tests. Results of these comparisons are shown in Figure F-1.

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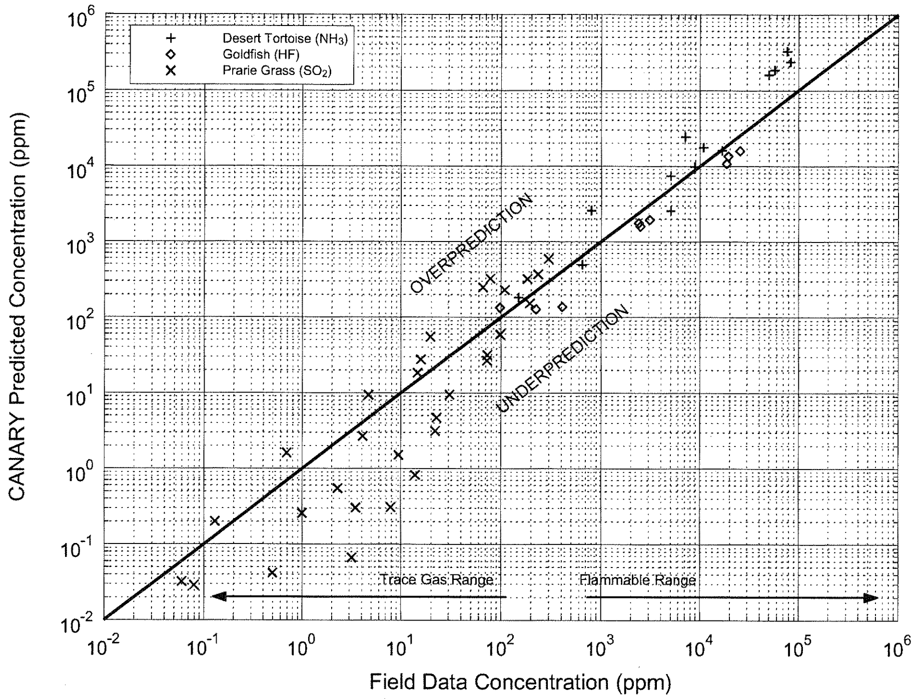

Figure F-1

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Heavy Gas Dispersion Model

Purpose

The purpose of this model is to predict the dispersion and gravity flow of a heavy gas released into the air from liquid pools or instantaneous gas releases. It is used to predict the downwind travel of a flammable or toxic vapor cloud.

Required Data

(a) Composition and properties of the released material
(b) Temperature of released material
(c) Vapor generation rate
(d) Vapor source area
(e) Vapor source duration
(f) Ambient wind speed
(g) Ambient Pasquill-Gifford atmospheric stability class
(h) Ambient temperature
(i) Relative humidity
(j) Surface roughness scale

Methodology

Step 1: For a steady-state plume, released from a stationary source, the Heavy Gas Dispersion Model solves the following equations:

$$\frac{d}{dx}\left(\rho \cdot U \cdot B \cdot h \cdot m\right) = \rho_s \cdot W_s \cdot B_s \tag{1}$$

$$\frac{d}{dx}\left(\rho \cdot U \cdot B \cdot h\right) = \rho_a \cdot \left(V_e \cdot h + W_e \cdot B\right) + \rho_s \cdot W_s \cdot B_s \tag{2}$$

$$\frac{d}{dx}\left(\rho \cdot U \cdot B \cdot h \cdot C_p \cdot T\right) = \rho_a \cdot \left(V_e \cdot h + W_e \cdot B\right) \cdot C_{pa} \cdot T_a + \rho_s \cdot W_s \cdot B_s \cdot C_{ps} \cdot T_s + f_t \tag{3}$$

$$\frac{d}{dx}\left(\rho \cdot U \cdot B \cdot h \cdot U\right) = -0.5 \cdot \alpha_g \cdot g \cdot \frac{d}{dx}\left[\left(\rho - \rho_a\right) \cdot B \cdot h^2\right] + \rho_a \cdot \left(V_e \cdot h + W_e \cdot B\right) \cdot U_a + f_u \tag{4}$$

$$\frac{d}{dx}\left(\rho \cdot U \cdot B \cdot h \cdot V_g\right) = g \cdot \left(\rho - \rho_a\right) \cdot h^2 + f_{vg} \tag{5}$$

$$U \cdot \frac{dZ_c}{dx} = -V_g \cdot \frac{Z_c}{B} \tag{6}$$

$$U \cdot \frac{dB}{dx} = \frac{\rho_a}{\rho} \cdot V_e + V_g \tag{7}$$

$$\rho \cdot T = \frac{\rho_a \cdot T_a \cdot M_s}{\left[M_s + (M_a - M_s) \cdot m\right]} \tag{8}$$

where: x = downwind distance, m
ρ = density, kg/m^3
U = velocity in the direction of the wind, m/s
B = cloud width parameter, m
h = cloud height parameter, m
m = mass fraction of source gas
T = temperature, K
C_p = specific heat, J/(kg • K)
f_t = ground heat flux, J/(m•s)
f_u = downwind friction term, kg/s^2
f_v = crosswind friction term, kg/s^2
V_e = horizontal entrainment rate, m/s
V_g = horizontal crosswind gravity flow velocity, m/s
W_e = vertical entrainment rate, m/s
W_s = vertical source gas injection velocity, m/s
M = molecular weight, kg/kmole
s = refers to source properties
a = refers to ambient properties

The first six equations are crosswind-averaged conservation equations. Equation (7) is the width equation, and Equation (8) is the equation of state.

Step 2: All of the gas cloud properties are crosswind averaged. The three-dimensional concentration distribution is calculated from the average mass concentration by assuming the following concentration profile:

$$C(x,y,z) = C(x) \cdot C_1(y) \cdot C_2(z) \tag{9}$$

$$C(x) = \frac{M_a \cdot m(x)}{M_s + (M_a - M_s) \cdot m(x)} \tag{10}$$

$$C_1(y) = \frac{1}{4 \cdot b} \cdot \left\{ erf\left(\frac{y+b}{2 \cdot \beta}\right) - erf\left(\frac{y-b}{2 \cdot \beta}\right) \right\} \tag{11}$$

$$B^2 = b^2 + 3 \cdot \beta^2 \tag{12}$$

$$C_2(z) = \left(\frac{6}{\pi}\right)^{1/2} \cdot \frac{1}{h} \cdot \exp\left(\frac{-3 \cdot z^2}{2 \cdot h^2}\right) \tag{13}$$

where: $C(x,y,z)$ = concentration in plume at x, y, z, kg/m^3
y = crosswind coordinate, m
z = vertical coordinate, m
b, B, β = half-width parameters, m

Step 3: As there are now two parameters used to define $C_1(y)$, the following equation is needed to calculate b:

$$U \cdot \left(\frac{db}{dx}\right) = V_g \cdot \frac{b}{B} \tag{14}$$

Step 4: The vertical entrainment rate is defined to be:

$$W_e = \frac{\sqrt{3} \cdot a \cdot k \cdot U_* \cdot \delta\left(\frac{h}{H}\right)}{\Phi_h\left(\frac{h}{L}\right)} \tag{15}$$

where: a = constant, 1.5
k = constant, 0.41
U_* = friction velocity, m/s
L = Monin-Obukhov length derived from the atmospheric stability class

Step 5: The profile function δ is used to account for the height of the mixing layer, H, and to restrict the growth of the cloud height to that of the mixing layer. H is a function of stability class and is defined as:

$$\delta\left(\frac{h}{H}\right) = 1 - \frac{h}{H} \tag{16}$$

The Monin-Obukhov function, Φ_h, is defined by:

$$\Phi_h\left(\frac{h}{L}\right) = \begin{cases} 1 + 5 \cdot \frac{h}{L} & L \geq 0 \text{ (stable)} \\ \left[1 - 16 \cdot \frac{h}{L}\right]^{-1/2} & L < 0 \text{ (unstable)} \end{cases} \tag{17}$$

Step 6: After the steady-state equations are solved, an along-wind dispersion correction is applied to account for short-duration releases. This is accomplished using the method outlined by Palazzi, et al. [1982].

Validation

The Heavy Gas Dispersion Model used in CANARY was validated by comparing results obtained from the model with experimental data from field tests. Data used for this comparison and the conditions used in the model were taken from an American Petroleum Institute (API) study [Hanna, Strimaitis, and Chang, 1991]. For this model, comparisons were made with the Burro, Maplin Sands, and Coyote series of dispersion tests. Results of these comparisons are shown in Figure G-1.

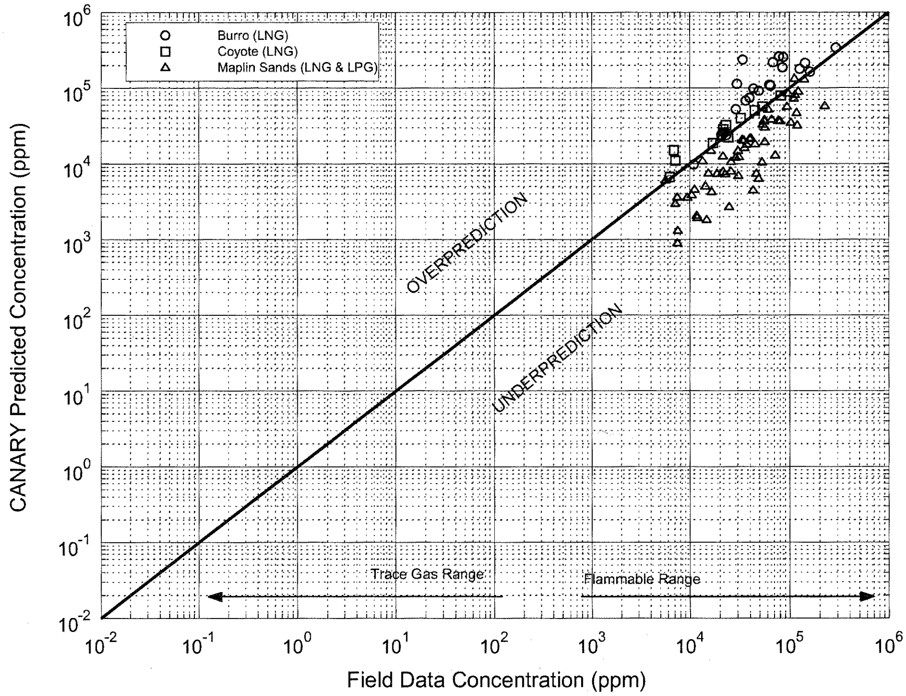

Figure G-1

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Vapor Cloud Explosion Model

Purpose

The purpose of this model is to predict the overpressure field that would be produced by the explosion of a partially confined and/or obstructed fuel-air cloud, based on the Baker-Strehlow methodology. Specifically, the model predicts the magnitude of the peak side-on overpressure and specific impulse as a function of distance from the source of the explosion.

Required Data

(a) Composition of the fuel (flammable fluid) involved in the explosion
(b) Total mass of fuel in the flammable cloud at the time of ignition or the volume of the partially-confined/obstructed area
(c) Fuel reactivity (high, medium, or low)
(d) Obstacle density (high, medium, or low)
(e) Flame expansion (1-D, 2-D, 2½-D, or 3-D)
(f) Reflection factor

Methodology

Step 1: The combustion energy of the cloud is estimated by multiplying its mass by the heat of combustion. If the volume of the flammable cloud is input, the mass is estimated by assuming that a stoichiometric mixture of gas and air exists within that volume.

Step 2: The combustion energy is multiplied by the reflection factor to account for blast reflection from the ground or surrounding objects.

Step 3: Flame speed is determined from the fuel reactivity, obstacle density, and flame expansion parameters, as presented in Baker, et al. [1994, 1998].

Fuel reactivity and obstacle density each have low, medium, and high choices. The flame expansion parameter allows choices of 1-D, 2-D, 2.5-D, and 3-D. The choices for these three parameters create a matrix of 36 possibilities, thus allowing locations that have differing levels of congestion or confinement to produce different overpressures. Each matrix possibility corresponds to a flame speed, and thus a peak (source) overpressure. The meanings of the three parameters and their options are:

Fuel Reactivity (High, Medium, or Low). The fuels considered to have high reactivity are acetylene, ethylene oxide, propylene oxide, and hydrogen. Low reactivity fuels are (pure) methane and carbon monoxide. All other fuels are medium reactivity. If fuels from different reactivity categories are mixed, the model recommends using the higher category unless the amount of higher reactivity fuel is less than 2% of the mixture.

Obstacle Density (High, Medium, or Low). High obstacle density is encountered when objects in the flame's path are closely spaced. This is defined as multiple layers of obstruction resulting in at least a 40% blockage ratio (i.e., 40% of the volume is occupied by obstacles). Low density areas are defined as having a blockage ratio of less than 10%. All other blockage ratios fall into the medium category.

Flame Expansion (1-D, 2-D, 2.5-D, or 3-D). The expansion of the flame front must be characterized with one of these four descriptors. 1-D expansion is likened to an explosion in a pipe or hallway. 2-D expansion can be described as what occurs between flat, parallel surfaces. An unconfined (hemispherical expansion) case is described as 3-D. The additional descriptor of 2.5-D is used for situations that begin as 2-D and quickly transition to 3-D.

Step 4: Based on the calculated flame speed, appropriate blast curves are selected from the figures in Baker, et al., 1994. For flame speeds not shown on the graph, appropriate curves are prepared by interpolation between existing curves.

Step 5: The Sachs scaled distance, $\overline{R}$, is calculated for several distances using the equation:

$$\overline{R} = \frac{R}{\left(\frac{E}{P_0}\right)^{1/3}}$$

where: R = distance from the center of the explosion
E = total energy calculated in step 2, above
P_0 = atmospheric pressure

Step 6: The peak side-on overpressure and specific impulse at each scaled distance are determined from the blast curves in Baker, et al., 1994.

References

Baker, Q. A., M. J. Tang, E. Scheier, and G. J. Silva, "Vapor Cloud Explosion Analysis." *28th Loss Prevention Symposium, AIChE,* 1994.

Baker, Q. A., C. M. Doolittle, G. A. Fitzgerald, and M. J. Tang, "Recent Developments in the Baker-Strehlow VCE Analysis Methodology." *Process Safety Progress*, 1998: p. 297.