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**AN ASSESSMENT OF HAZARDS RESULTING FROM
ATMOSPHERIC PROPANE EXPLOSIONS AT LLL**

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February 1975

MASTER

Prepared for U.S. Atomic Energy Commission under contract no. W-7405-Eng-48

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AN ASSESSMENT OF HAZARDS RESULTING FROM ATMOSPHERIC PROPANE EXPLOSIONS AT LLL

INTRODUCTION

Due to recent shortages of natural gas, LLL has plans for creating a liquid propane tank farm, consisting of eight 30,000 gallon (maximum volume) storage tanks, to meet its interruptable gas service requirements. We[†] were asked by Hazards Control¹ to assess the hazards that would result if a propane explosion were to occur. In an earlier memo², Hazards Control was apprised of foreseen hazards based on preliminary calculations. The present document reports subsequent, more refined, calculations performed for two classes of accident initiation:

1. Catastrophic Failure and Explosion of a Tank

This is likely to be the situation that would occur if the tank were subjected to fire heating, causing catastrophic failure of the tank due to high internal pressures. The fuel then expands violently, mixing with air and subsequently burning. Due to the rapid nature of this phenomenon, frequently called a "Bleeve",^{††} it is best characterized as an instantaneous energy release.

2. Failure of a supply line resulting in uncontrolled steady spillage of either liquid or vapor. Then, due to prevailing wind conditions, a downwind vapor cloud forms whose location and dimensions are steady with time. It is this vapor cloud which is assumed to ignite and burn. This class of accident is termed a slow leak release.

For each of these accident classifications, two types of calculations were performed:

1. Blast wave analysis to calculate explosion overpressure values.
2. Radiative flux analysis to determine the heat radiation rate from the hot burned gases.

We have assumed that only one of the eight tanks can fail at any one time, and have not considered the effects that one exploding tank may have on the

[†]Thermo Fluid Mechanics Group, Nuclear Test Engineering Division.

^{††}"Bleeve" is an acronym for boiling liquid expanding vapor explosions.

other tanks. Plant Engineering³ proposes that the tanks will be filled to 86.5% of their maximum volume. Since however, overfills have reportedly occurred, calculations were performed for both 100% and 86.5% fill situations. Calculational details are summarized below. For future reference propane properties are summarized in Table I.

OVERPRESSURE CALCULATIONS

For a number of years, researchers have been attempting to develop accurate techniques for predicting blast wave overpressures from unconfined atmospheric explosions. A number of technical obstacles have continually plagued their efforts. Exact combustion phenomenon are virtually impossible to predict. The combustion process is strongly dependent on atmospheric disturbances, e.g., large scale mixing and turbulence; and air-fuel mixture nonuniformity and mixture cloud shape. In addition, atmospheric characteristics, e.g., large vortices, turbulence, and humidity influence prediction of blast wave propagation.

Two principle approaches to the problem have evolved. Efforts have been made to numerically solve the elementary wave equations. However, only moderate successes have resulted largely due to the aforementioned combustion and atmosphere variants. Significantly more effort has been employed to develop scaling laws, allowing one to relate predicted explosions to experimental observations. Again, due to the combustion and atmosphere variants, exact predictions are virtually impossible. However, results of this method tend to be more reliable due to the extensive efforts to relate predictions to experimental observations. It is this latter method that we have chosen to use here.

The scaling law method is described by Decker⁴. Since the explosive effects from high explosives, primarily TNT, have been extensively studied and because high explosive phenomenon are generally very predictable the scaling laws attempt to relate gaseous explosions to TNT explosions. It has been observed that TNT closely follows Sack's cube root law

$$\frac{R_2}{R_1} = \left(\frac{W_2}{W_1} \right)^{1/3}$$

where

R_1, R_2 = ranges from respective sources where a particular overpressure occurs.

W_1, W_2 = source energies

This equation can be rearranged into what is commonly called the scaled range form:

$$\frac{R_1}{W_1^{1/3}} = \frac{R_2}{W_2^{1/3}} = \lambda \quad (1)$$

This formalism allows one to relate effects of a TNT explosion to catagorized effects of another TNT explosion of a strikingly different energy value. A typical scaled range overpressure curve for TNT is shown in Figure 1.

It has also been observed that gas and chemical explosion behavior frequently follow these same relations. Thus in theory it seems possible to relate gas and chemical explosion effects to TNT explosive effects which have been much more closely studied and are much more predictable. This is precisely what is done in the scaling law method of studying gas and chemical explosions. This use of curves based on TNT data to predict explosion overpressures resulting from chemical or gas explosions entails several simplifications. There are major differences between TNT burns and gas burns. Typically both burn pressures and burn velocities are much larger in TNT, which burns in a detonation fashion, than gas fuel-air mixtures which can either detonate or deflagrate. Also, the percent of theoretical energy released in a TNT explosion is typically larger than in gas or chemical explosions. To account for these differences, Decker⁴ calculates the gas or chemical energy in terms of equivalent pounds of TNT using the equation

$$\text{TNT Eq.} = \frac{\epsilon \cdot V_F \cdot \Delta H_C}{2.11 \times 10^6} \quad (2)$$

where

V_F = total volume of fuel within the combustible limits

ΔH_C = combustion energy in units of joules per unit volume at S.T.P.

ϵ = an empirically determined multiplication factor to account for incomplete combustion as well as differences between TNT blast and gas explosions.

It is important to note that the effects of these differences can be minimized to well within the uncertainty bands associated with combustion and atmospheric variants.

The major difficulty still remaining is to determine appropriate values of the empirical factor ϵ . Brasie and Simpson⁵ as well as Decker⁴ discuss appropriate values of this multiplication factor for various explosion situations. Decker concludes that for instantaneous releases, involving hydrocarbon fuels, an appropriate value is .10. This value assumes a deflagration burn type as well as accounts for incomplete combustion. For slow release situations he concludes that an ϵ of 1.0 is appropriate. This larger value is justified from observed phenomenon. For free atmosphere clouds, deflagration waves are typically the burn type. However, detonation waves, which result in significantly higher pressures, have reportedly occurred in a number of slow release accidents. Also, combustion is observed to be very near complete. Thus using an ϵ of 1.0 represents a worst case as well as conservative prediction for the slow release situation. Brasie and Simpson suggest lower values (.03-.05) for chemical explosions (non-hydrocarbon deflagration burns). However for hydrogen, a fuel generally considered more explosive than hydrocarbon fuels, they suggest .3. We will employ the suggestions of Decker since they will generally result in the most conservative prediction. In this light, it is important to note that the overpressure variation with yield is not linear. From equation 1 we see that the location of a particular pressure varies as the cube-root of the yield. Thus variations in ϵ of a factor of 5 will result in only moderate variations in the overpressure.

Further validity is obtained if one relates predicted overpressure to observed damage. Brasie and Simpson⁵ compiled damage data, i.e., damage vs. range, for various source energies. The source energy was calculated using equation 2, after estimating the volume of fuel present in the explosion. Appropriate values of ϵ , which are thoroughly discussed in their paper and are dependent on the fuel type, were used to account for departures from TNT behavior. Then using Figure 1, they estimated the blast pressure. By comparing damage class to predicted overpressure appropriate damage criteria for use with gas and chemical sources was developed. This data, further summarized by Decker, is repeated as our Table II.

To calculate overpressures in the case of a catastrophic failure, i.e., case of instantaneous energy release (Class 1), we assume that the explosion phenomenon occur too rapidly to be affected by atmospheric dispersion and disturbances. We use equation 2 and Figure 1 to determine overpressures. In this situation, V_F is the volume the fuel would occupy at standard temperature and pressure. Note that in the case of a fuel originally in a liquid state, we must determine its vapor equivalent volume at standard conditions. As mentioned previously, in equation 2 we use an ϵ of .10 to account for incomplete combustion as well as differences between TNT and gas explosion behavior.

For the case of a slow leak (Class 2), we must first determine the dispersed cloud location and volume. Consider the coordinate system in Figure 2, where the X-direction is the wind flow direction, the Y-direction is perpendicular to the wind flow direction and parallel to the ground, and the Z-coordinate represents the vertical direction. The contaminant source is located at the coordinate system origin at ground level. The steady release of the contaminant will create a variable concentration plume downwind of the contaminant source location given by

$$X_{CL} = \frac{2.223 \times 10^{-7} Q}{\pi \sigma_y \sigma_z \bar{u}} \quad (3)$$

where

- X_{CL} = centerline concentration downwind in cubic metres of contaminant per cubic metre of mixture (volume fraction).
- Q = contaminant release rate in cubic metres per second (at S.T.P.).
- $\bar{u}$ = mean wind speed in metres per second.
- σ_y = horizontal diffusion coefficient in metres, as a function of the X distance from the source.
- σ_z = vertical diffusion coefficient in metres, as a function of the X distance from the source.

Values of σ_y and σ_z vary with wind speed, degree of atmospheric turbulence, and distance from the source. Table III⁴ is a summary of σ_y and σ_z values for various atmospheric conditions. Further, the Y and Z coordinate values of the upper explosive limit concentration (UEL) and the lower explosive limit concen-

tration (LEL) are given by

$$\begin{aligned} Y_{UEL} &= \left[2 \ln \left(\frac{X_{CL}}{X_{UEL}} \right) \right]^{1/2} \cdot \sigma_y \\ Z_{UEL} &= \left[2 \ln \left(\frac{X_{CL}}{X_{UEL}} \right) \right]^{1/2} \cdot \sigma_z \\ Y_{LEL} &= \left[2 \ln \left(\frac{X_{CL}}{X_{LEL}} \right) \right]^{1/2} \cdot \sigma_y \\ Z_{LEL} &= \left[2 \ln \left(\frac{X_{CL}}{X_{LEL}} \right) \right]^{1/2} \cdot \sigma_z \end{aligned}$$

where

X_{UEL} = upper explosive limit volume fraction.

X_{LEL} = lower explosive limit volume fraction.

Note that Y_{UEL} , Z_{UEL} , Y_{LEL} , Z_{LEL} are all implied functions of the X distance downwind. Thus one can then generate, as shown in Figure 3, a set of concentration contours which define the downwind contaminant plume.

To determine the blast source strength, it is necessary to know the volume of gas located in the combustible range, i.e., between the LEL and UEL contours. One will note that the contours approximately represent elliptical curves. Thus by rotation about the principle (major) axis, a prolate spheroid is generated. Because we are only dealing with a half space, the approximate gas volume within a contour is then given by

$$V = \left(\frac{1}{2} \cdot \frac{2\pi}{3} a b^2 \right) \quad (5)$$

where

a = Ellipse semi-major axis length.

b = Ellipse semi-minor axis length.

The volume within the combustible range is the volume of gas between the two prolate spheroid surfaces, or,

$$V = V_{LEL} - V_{UEL}$$

Since the Y and Z curves are in general different, we must average the combustible volumes given by rotation of the curves. Thus,

$$V_T = \frac{1}{2} \left\{ (V_{LEL} - V_{UEL})_{Y_{curves}} + (V_{LEL} - V_{UEL})_{Z_{curves}} \right\} \quad (6)$$

Now, V_F for use in equation 2 is given by

$$V_F = V_T X_F$$

where

X_F = average volume fraction of fuel in
air-fuel mixture.

Also, an ϵ of 1.0 is assumed since free atmosphere clouds have reportedly detonated. Thus, equation 2 and Figure 1 can be used to determine approximate overpressures.

HEAT FLUX CALCULATIONS

In determining radiated heat flux values, it is necessary that we know the volume of burned gases, the gas temperature, and the composition of the burned gas. In all cases, we have assumed that the gas volume after combustion is approximately the same as before ignition. During a gas cloud burn, there will undoubtedly be some expansion of the burned gases before all the gas has undergone combustion. However, we have no way to assess this expansion so we are forced to assume constant volume. We will now discuss the methods used to determine the radiating gas volume.

In a slow leak situation (class 2), for the blast wave calculations, the volume of gas mixture within the combustible limits was calculated using equation 6. Since we assume complete combustion, this is identically the volume of burned radiating gas and will be used in the heat flux calculations.

In the case of an instantaneous release, due to incomplete combustion, the burned gas volume will be less than the total air-fuel mixture volume. The total mixture volume is given by

$$V_M = V_F / X_F$$

where

V_F = volume of volume of volatilized fuel

X_F = average volume fraction of fuel in the mixture

We can now take the volume of fuel-air mixture that actually burned to be

$$\begin{aligned} V &= \gamma V_m \\ &= \gamma V_F / X_F \end{aligned} \quad (7)$$

No guidance exists for selection of an appropriate value of γ . Since the incomplete combustion phenomenon is largely reflected in the value of ϵ in equation 2, we elect to approximate γ as .10, the same as the value of ϵ .

In all cases we have taken the burned gas temperature to be the observed flame temperature in air. For propane the temperature is 2198°K. This should be a good approximation to the radiating temperature at early times when the heat flux is greatest.

The computer code CCC⁶ was used to determine the equilibrium composition at the flame temperature. The code accounts for generalized species dissociation and recombination. In general, by accounting for dissociation and recombination we are allowing a decrease in the concentration of triatomic molecules and an increase in the concentration of diatomic molecules such as NO, OH, CO, O₂. It should be noted that for heat radiating purposes, diatomic molecules, e.g., N₂, NO, CO, may be regarded as transparent and non-radiating. It is only substances such as CO₂ and H₂O which have appreciable emissivities and absorptivities. Thus, by including dissociation and recombination, our results will be much more reasonable than if these effects were excluded. Since radiative heat transfer rates vary as T^{4*} , we may neglect radiation from the atmosphere impinging on the volume of burned gases because $(T_g^4 - T_{air}^4) \approx T_g^4$. If we consider the gas to be enclosed by a transparent, non-reflecting surface, then the radiation from the burned gas impinging on this surface is given by⁷

$$Q/A_s = \epsilon \sigma T_g^4 \quad (8)$$

*The symbol T represents temperature.

where

ϵ = gas emissivity

σ = Stephan-Boltzman constant

T_g = the burned gas temperature

A_s = surface area of transparent membrane surrounding the gas.

For most hydrocarbon burns, where the only significant triatomic molecules in the burned gases are CO_2 and H_2O , the emissivity of the burned gas is given by

$$\epsilon_g = \epsilon_{CO_2} + \epsilon_{H_2O} - \Delta\epsilon \quad (9)$$

where

ϵ_{CO_2} = Emissivity of the CO_2 gas.

ϵ_{H_2O} = Emissivity of the water vapor.

$\Delta\epsilon$ = A correction factor to account for overlapping absorption and emission bands of the two gases.

Referring to Siegel and Howell⁷,

$$\begin{aligned} \epsilon_{CO_2} &= C_{CO_2} \cdot \left(\epsilon_{CO_2} \right)_{atm} \\ \epsilon_{H_2O} &= C_{H_2O} \cdot \left(\epsilon_{H_2O} \right)_{atm} \end{aligned} \quad (10)$$

where

$\left(\epsilon_{CO_2} \right)_{atm}, \left(\epsilon_{H_2O} \right)_{atm}$ = Emissivities of the gases when the total gas pressure is one atmosphere

C_{CO_2}, C_{H_2O} = Correction factors to account for a gas mixture whose total pressure is not one atmosphere

Referring to Figures 4, 5 and 6, one will note that these parameters are functions of the gas partial pressure and the mean beam length^{††}, L_e . The gas partial pressures are given by

$$\begin{aligned} P_{H_2O} &= x_{H_2O} P \\ P_{CO_2} &= x_{CO_2} P \end{aligned} \quad (11)$$

where

$$x_{H_2O}, x_{CO_2} = \text{volume fractions}$$

$$P = \text{gas mixture total pressure}$$

If we assume that the gas volume is approximately spherical in shape;

$$L_e = .65 D \quad (\text{from Reference 7})$$

where

$$D = \text{the gas sphere diameter.}$$

Using these relations and charts, one can determine the gas mixture emissivity and from equation 8 the heat flux impinging on the transparent spherical boundary. Since the atmosphere is composed primarily of diatomic gases (> 98%), which are non-absorbing and non-radiating, we will regard the surrounding air as transparent. Thus the radiative flux may be scaled as

$$Q_2 = Q_1$$

or

$$\frac{Q_2}{A_2} = \frac{Q_1}{A_1} \frac{A_1}{A_2} = \frac{Q_1}{A_1} \times \left(R_1/R_2 \right)^2 \quad (12)$$

where

$$Q_i = \text{total energy crossing surfaces at } R_i$$

^{††}The mean beam length is the average distance a radiated photon must travel to leave the radiating gas.

and

Q_1/A_1 = flux value obtained from equation 8

A_2 , A_1 = spherical surface areas

R_1 , R_2 = radii of spherical surfaces.

The above relations can be used to obtain plots of heat flux vs. range from source center.

CALCULATIONAL DETAILS

In the previous section we developed the necessary equations to perform overpressure and heat flux calculations. We will now give details of calculations performed for the LLL propane tank farm.

Overpressure Calculations

First we will consider the instantaneous release case (class 1) representing an upper limit situation. Atmospheric dispersion need not be considered. Calculations were performed for tanks filled to both 100% and 86.5% of the maximum volume. The equivalent energy calculations, obtained from equation 2 are summarized in Table IV. The resulting overpressure curves, extracted from Figure 1 and making the appropriate unit changes are given in Figure 7.

Slow leak calculations (class 2), where we must consider atmospheric dispersion and vapor cloud formation, were performed for both gaseous and liquid discharges. We will now describe the methods used to determine propane flow rates. First consider the liquid discharge case. Figure 8 is a schematic representation of the liquid discharge situation. We will apply Bernoulli's equation to determine the liquid discharge rate under the assumptions that

1. The opening at 2 is small such that the variation of h with time is negligible or that the pressure at 1 is much larger than the pressure head due to the fluid column of height h .
2. The fluid velocity at surface 1 is negligible compared to the velocity at 2; i.e., $v_1^2 \ll v_2^2$.

With these restrictions, the exit velocity is given by

$$V_2 = \sqrt{2g h + 2v (P_1 - P_2)} .$$

Discharge is to the atmosphere, $P_2 = 1 \text{ atm} = 100 \text{ KPa}$. Also, P_1 is the vapor pressure of propane at 70°F , which from Table I is 956.6 KPa , and h is the tank height which is 3.048 m . From Table I, the specific volume (v) of liquid propane is $1.967 \text{ m}^3/\text{Mg}$.

One will note that the pressure at 1 is much larger than the pressure head due to the fluid column. Also it seems reasonable that for a 3 inch opening at 2, the surface velocity (V_1) will be negligible compared to V_2 . Thus both assumption 1 and assumption 2 are satisfied. Therefore $V_2 = 57.50 \text{ m/sec}$.

For a 3 inch pipe opening ($A = 4.56 \times 10^{-3} \text{ m}^2$) the mass flow rate is

$$\begin{aligned} \dot{m} &= \rho V A \\ &= 1.335 \times 10^5 \text{ gm/sec (liquid release)} \end{aligned}$$

Let us now consider a vapor release situation, the maximum flow rate occurs when the gas exits at choked conditions; i.e., sonic velocity (mach number, $M = 1$). Using one-dimensional isentropic flow, the flow conditions at the throat are given by

$$M = 1; P/P_o = .525$$

$$\rho/\rho_o = .632$$

$$T/T_o = .833$$

where the o subscript denotes stagnation or reservoir conditions. Assuming an ideal gas we may write

$$V = MC = M \sqrt{\gamma R T}$$

where

V = fluid velocity

C = fluid sound speed

M = fluid mach number

γ = ratio of specific heats (C_p/C_v)

R = the fluid gas constant

T = the fluid temperature

From Table I; $\gamma = 1.12$, $R = .189 \frac{\text{Joules}}{\text{gm } ^\circ\text{K}}$. Thus, $V = 224. \text{ m/sec}$.

As a result, the mass flow rate is $\dot{m} = \rho VA = 1.953 \times 10^4$ gm/sec. (Vapor release.)

We have now determined appropriate mass flow rates. In order to calculate the dispersed cloud shape and location we need to know prevailing atmospheric conditions. If one looks at wind currents over the LLL site, the most common wind velocity is 12 miles/hour (or 5.35 m/sec) which from Table II corresponds to a B_1 stability classification. The calculation could be further extended to determine the worst case situations, i.e., worst velocity-direction combination, and the probabilities associated with such an occurrence. Employing equations 3 and 4, for Class 2, we get the concentration profiles shown in Figure 9 (liquid release) and Figure 10 (vapor release). The equivalent energy calculations are summarized in Table V, and the resulting overpressure vs. range curves given in Figure 11.

To estimate damage resulting from an atmospheric explosion we use the data of Brasie and Simpson (Table II). One can infer[†] potential explosion damage to existing LLL facilities by reference to Figure 12, an overlay of predicted blast shock strength on an LLL site map. In the worst possible situation (class 1) structural damage (1 to 2 psi overpressure) could conceivably occur as far as 550 metres from the explosion center. Irregardless of the explosion type (class 1 or class 2) it is apparent that building 612 could be subjected to pressures sufficient to cause major structural damage (> 3 psi overpressure). Also, it is clear that glass breakage could conceivably occur as far as 1000 metres from the explosion source.

RADIATIVE FLUX CALCULATIONS

Results of the CCC calculation, for a gas mixture of 6.1% propane (C_3H_8) and 93.9% air, are given in Table VI. The remaining heat flux calculations are summarized in Table VII. The resulting heat flux vs. range curves are given in Figure 13.

[†]Conclusions reached in consultation with R. Murray⁸, Structural Mechanics Group, Nuclear Test Engineering Division.

We have assessed structure heating damage, due to the radiative heat flux, using the analyses techniques of Simms⁹ and Martin¹⁰. For wood, Martin has found that the necessary duration time of an impinging constant heat flux to start ignition is given by

$$H \sqrt{t} = 3.35 \times 10^5$$

where

$$H = \text{heat flux} \left(\frac{\text{Joules}}{\text{m}^2 \text{ sec}} \right)$$

$$t = \text{necessary duration time (seconds)}$$

For the calculated flux values, as given in Table VII and Figure 13, the necessary duration time at very short ranges (~50 meter) is greater than 10 seconds for either class of burn, while, at 100 meters this time increases to over four minutes. Since the heat flux emanating from the gas ball is expected to last only on the order of a few seconds (<5), we expect no heating damage (excluding singeing) to surrounding structures. Experimental data on transient fluxes is unavailable. There is however, significant data for steady fires. Fu¹¹ has measured the heat fluxes emanating from aviation fuel pool fires. Parker¹² has experimentally and theoretically studied thermal radiation fluxes from large gas fuel fires. In both cases, the measurements are for steady (steady fuel flow), long duration fires. Accounting for fire size differences, our early time calculated values compare favorably with the flux measurements in both papers.

SUMMARY

We have presented a viable technique for determining blast wave overpressure and radiative heat flux values for hypothetical explosions and failures of propane tanks. Calculated overpressure and heat flux values have been determined for instantaneous energy releases and slow leak releases for a typical 30,000 liquid gallon propane tank at LLL. Based on these calculations, the following preliminary conclusions regarding hazards may be drawn:[†]

[†]Reached in consultation with Structural Mechanics Group, Nuclear Test Engineering Division.

1. A great potential exists for glass breakage throughout the LLL site in the event of a single tank propane explosion of any type.
2. Minor structural damage in the worst possible explosion situation (class 1), could conceivably occur as far as 550 meters from the explosion center provided the blast wave contacted no major obstacles, i.e., buildings, in transit.
3. Due to the short duration of radiated heat fluxes, no fire potential exists for combustible materials, primarily wood, located greater than 50 metres from the explosion center.
4. Finally, we must stress that these calculations appear conservative, i.e., worst conceivable situation.

We have not mentioned, nor have we extensively studied, possible solutions to these hazards. We do however feel that the following measures deserve further consideration and study:

1. Revetment for trenching of the tanks - The revetments could be used to isolate the tank complex as a whole, as well as isolate tanks from one another. The revetments will offer blast shielding protection only for catastrophic accident (ground level blast) situations (class 1). The explosion center for slow leak cases (class 2) will in general be too far above ground level for revetmenting to be effective.
2. Detection devices to determine the advent of a slow leak (class 2) - Because we are dealing with a wind blown cloud, there appears to be little else that can be done to protect personnel other than to provide ample warning if evacuation is necessary.

TABLE I
PROPERTIES OF LIQUID AND GASEOUS PROPANE

Molecular weight	44.
Density of liquid at S.T.P.	.5078 $\frac{\text{Mg}}{\text{m}^3}$
Specific volume of gas at S.T.P.	.534 $\frac{\text{m}^3}{\text{kgm}}$
Vapor pressure at 70°F	954.9 KPa
Observed flame temperature in air	2198 °K
Combustibility limits in air-volume % fuel	
Upper	10.1%
Lower	2.1%
Heating value of gas at S.T.P.	$9.6 \times 10^7 \frac{\text{J}}{\text{m}^3}$
Gas constant	.189 $\frac{\text{Joules}}{\text{gm}^\circ\text{K}}$
Specific heat ratio (γ)	1.12

TABLE II
FAILURE LEVELS FOR
TYPICAL STRUCTURE CONFIGURATIONS

Structural Element	Usual Failure	Peak Blast Overpressure
Glass Windows	Shattering	0.5 - 1.0 psi
Corrug. Asbestos Siding	Shattering	1.0 - 2.0 psi
Corrug. Steel Paneling	Connection Failure	1.0 - 2.0 psi
Wood Siding	Connection Failure	1.0 - 2.0 psi
Concrete or Cinder Block Wall (not reinforced)	Wall Shattering	2.0 - 3.0 psi
Telephone Pole	Sheared	5.0 psig
Brick Wall Panel 8-12 in. thick (not reinforced)	Shearing & Flexure Failures	7.0 - 80 psi

TABLE III
SUMMARY OF ATMOSPHERIC CONDITIONS⁴

Classification	Fluctuation of Horizontal Wind Direction	Frequency of Occurrence Per cent of Time	Wind Speed m/sec	Plume Dispersion	Coefficients, m
				σ_y	σ_z
A - Extremely unstable	> 90°	1	1.798	—	—
B ₂ - Unstable	45° - 90°	3	3.78	.3595 [X] ^{0.91}	.3685 [X] ^{0.91}
B ₁ - Unstable	15° - 45°	42	6.95	.3048 [X] ^{0.86}	.2806 [X] ^{0.86}
C - Neutral	> 15°	14	10.67	.2476 [X] ^{0.78}	.1693 [X] ^{0.78}
D - Stable	< 15°	40	—	.2185 [X] ^{0.71}	.0437 [X] ^{0.71}

TABLE IV

SUMMARY OF EQUIVALENT ENERGY
CALCULATIONS FOR INSTANTANEOUS ENERGY RELEASE (CLASS 1)

Property	100% Fill	86.5% Fill
Liquid Volume (Gallons)	30,000	25,590
Gas Volume (M ³)	30,509	26,390
Heat of Combustion (J/M ³)	9.6466×10^7	9.6466×10^7
ϵ	.10	.10
T.N.T. EQ (LB)	139,509	120,675

TABLE V

SUMMARY OF EQUIVALENT ENERGY
CALCULATIONS FOR SLOW LEAK CASES

Property	Liquid Release	Vapor Release
Combustible Gas Volume - (m ³)	7750.3	266.57
Volume Fraction Fuel - (%)	6.05	6.05
Fuel Volume - (m ³)	468.98	16.112
Heat of Combustion - (J/m ³)	9.6466×10^7	9.6466×10^7
ϵ	1.0	1.0
T.N.T. EQ (LB)	21,444	736.9

TABLE VI
SUMMARY OF CCC CALCULATIONAL RESULTS

Unburned Gas Constituents

<u>Constituent</u>	<u>Volume %</u>
C_3H_8	6.10
N_2	74.20
O_2	19.70

Burned Gas Constituents

<u>Constituent</u>	<u>Volume %</u>
CO	11.56
CO_2	4.18
H	.05
H_2	7.28
H_2O	13.67
NO	.002
N_2	63.25
OH	.013

Burned Gas Properties

P , atm	- 8.63
T , deg K	- 2198
Mol Wt	- 25.408
$C_p, \frac{Cal}{gm^{\circ}K}$	- .3882
γ	- 1.2590

TABLE VII
SUMMARY OF HEAT FLUX CALCULATIONS (CLASSES 1 and 2)

Property	Instantaneous Release (100%)	Instantaneous Release (86.5%)	Slow Leak Liquid Release	Slow Leak Vapor Release
Volume Per cent Fuel X_F	6.10	6.10	6.10	6.10
Combustible Volume - m^3	50015.	43262	7750	266.6
Combustible Ball Radius				
- m	22.86	21.78	12.28	3.78
- ft	75.0	71.46	40.29	12.40
Gas Pressure - atm	8.63	8.63	8.63	8.63
Gas Temperature - °K	2198	2198	2198	2198
- °R	3956	3956	3956	3956
Gas Product Composition				
X_{CO_2}	.0418	.0418	.0418	.0418
X_{H_2O}	.137	.137	.137	.137
Gas Optical Length, L_e				
- m	29.718	28.31	15.96	4.91
- ft	97.5	92.89	52.38	16.12
Gas Partial Pressures, 1 atm total pressure,				
- atm				
P_{CO_2}	.0418	.0418	.0418	.0418
P_{H_2O}	.137	.137	.137	.137
$(P_{CO_2} L_e)_{1 \text{ atm}}$				
- atm - m				
- atm - ft	4.08	3.88	2.19	.674
$(P_{H_2O} L_e)_{1 \text{ atm}}$				
- atm - m				
- atm - ft	13.36	12.73	7.18	2.21
$(\epsilon_{CO_2})_{1 \text{ atm}}$ (Figure)	.12	.118	.10	.068
$(\epsilon_{H_2O})_{1 \text{ atm}}$ (Figure)	.28	.27	.23	.12
Actual Gas Partial Pressures				
- atm				
P_{CO_2}	.361	.361	.361	.361
P_{H_2O}	1.182	1.182	1.182	1.182
$(P_{CO_2} L_e)_{8.6 \text{ atm}}$				
- atm - m				
- atm - ft	35.17	33.51	18.89	5.84
$(P_{H_2O} L_e)_{8.6 \text{ atm}}$				
- atm - m				
- atm - ft	115.25	109.80	61.91	19.05
C_{CO_2} (Figure)	1.0	1.0	1.0	1.0
CH_2O (Figure)	1.0	1.0	1.0	1.15
$\Delta \epsilon$ (Figure)	.10	.10	.095	.065
ϵ (Equations 9 and 10)	.30	.288	.235	.123
σ $.173 \times 10^{-8}$				
Q/A				
- $\frac{BTU}{HR \text{ FT}^2}$	1.27×10^5	1.22×10^5	9.96×10^4	5.21×10^4
- $\frac{Joules}{sec \text{ m}^2}$	4.01×10^5	3.85×10^5	3.14×10^5	1.64×10^5

FIGURE 1 - A PLOT OF OVERPRESSURE VS. SCALED RANGE
TAKEN FROM DECKER⁴.

FIGURE 2 - COORDINATE SYSTEM FOR SLOW LEAK CALCULATIONS

FIGURE 3 - EXAMPLE OF CONCENTRATION ENVELOPES
FOR SLOW LEAK CALCULATION

4a - TOTAL EMITTANCE OF CARBON DIOXIDE IN A MIXTURE HAVING A TOTAL PRESSURE OF 1 atm

4b - PRESSURE CORRECTION FOR CO_2 EMITTANCE FOR TOTAL PRESSURE VALUES OTHER THAN 1 atm

FIGURE 4 - EMITTANCE AND CORRECTION FACTORS FOR CARBON DIOXIDE (CO_2)⁷

5a - TOTAL EMITTANCE OF WATER VAPOR IN LIMIT OF ZERO PARTIAL PRESSURE IN MIXTURE OF 1 atm TOTAL PRESSURE

5b - PRESSURE CORRECTION FOR WATER VAPOR EMITTANCE FOR PARTIAL AND TOTAL PRESSURE VALUES OTHER THAN 0 AND 1 atm, RESPECTIVELY

FIGURE 5 - EMITTANCE AND CORRECTION FACTORS FOR WATER VAPOR (H_2O)⁷

FIGURE 6 - BAND OVERLAP CORRECTION TO TOTAL EMITTANCE WHEN BOTH CO_2 AND WATER VAPOR ARE PRESENT⁷

a) GAS TEMPERATURE $T_g = 720^\circ R$; b) $T_g = 1460^\circ R$;

c) $T_g = 2160^\circ R$.

FIGURE 7 - RANGE VS. OVERPRESSURE VALUES FOR CLASS 1 100% AND 86.5% FILL SITUATIONS (REFER TO TABLE III)

CONVERSION: -1 PSI = 6.895 kPa

FIGURE 8 - DIAGRAMATIC REPRESENTATION OF CLASS 2 LIQUID DISCHARGE SITUATION

9a - CONCENTRATION CONTOURS IN X-Z PLANE

9b - CONCENTRATION CONTOURS IN X-Y PLANE

FIGURES 9 - 2.1% (LEL) AND 10.1% (UEL) CONCENTRATION CONTOURS FOR CLASS 2 LIQUID DISCHARGE THROUGH A 3 INCH DIAMETER OPENING

10a - CONCENTRATION CONTOURS IN X-Z PLANE

10b - CONCENTRATION CONTOURS IN X-Y PLANE

FIGURES 10 - 2.1% (LEL) AND 10.1% (UEL) CONCENTRATION CONTOURS FOR CLASS 2 VAPOR DISCHARGE THROUGH A 3 INCH DIAMETER OPENING

FIGURE 11 - RANGE VS. OVERPRESSURE VALUES FOR CLASS 2 LIQUID AND VAPOR RELEASES THROUGH A 3 INCH DIAMETER OPENING (REFER TO TABLE IV). CONVERSION: 1 PSI = 6.895 KPa

FIGURE 12 - AN OVERLAY OF PREDICTED BLAST SHOCK STRENGTH VS. RANGE ON AN LLL SITE MAP FOR A 100% VOLUME INSTANTANEOUS RELEASE (SOLID LINES) AND A LIQUID RELEASE SLOW LEAK CASE (DASHED LINES).

FIGURE 13 - PLOTS OF RADIATED HEAT FLUX VS. RANGE FOR CLASS 1 (100% AND 86.5% FILL SITUATIONS) AND CLASS 2 (LIQUID RELEASE AND VAPOR RELEASE) CALCULATIONS.

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Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$ ____*; Microfiche \$2.25

<u>* Pages</u>	<u>NTIS Selling Price</u>
1-50	\$4.00
51-150	\$5.45
151-325	\$7.60
326-500	\$10.60
501-1000	\$13.60