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November 12, 1979

TO: Bob Benedict

FROM: J Costello/R Prados

SUBJECT: WATERFORD SES UNIT NO. 3
REPLY TO NRC CONCERN OVER THE EFFECT OF
CLOUD EXPANSION UPON BURNING

Attached herein is a report addressing the concerns raised by Jack Reed of the Accident Analysis Branch in a telephone conversation with R Iotti of Ebasco. If you have any questions pertaining to the enclosed material please contact us.

JC:RP:ku

cc: R Iotti
J Reed

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REPLY TO NRC CONCERN OVER THE EFFECT OF CLOUD EXPANSION UPON BURNING

In order to best address the concern raised, it is necessary to examine the modes in which the cloud can ignite and explode.

A vapor cloud of flammable concentration may burn (deflagrate) or detonate (if within the detonable limits) or both types of combustion may occur in case of transition from deflagration to detonation. Volumetric explosions may also occur, particularly, if partial confinement of the cloud exists. More likely pockets of gas in a cloud may explode volumetrically if heated to the autoignition limit by radiated heat or shock waves.

In general, therefore, one should consider deflagration, detonation, and volumetric explosion to be the common modes of combustion. In our case due to the unconfined nature of the cloud the latter mode cannot occur, and it is only necessary to address detonations and deflagrations.

For detonations all of the thermodynamic properties, detonation velocities and flow properties behind the detonation front are calculable from standard thermodynamic equilibrium calculations.

If one defines as U_1 and U_2 the velocity of the unburned gas and burned gas with respect to the stationary detonation wave, then with respect to a stationary observer, U_1 is the detonation velocity and $W = U_1 - U_2$ is the velocity of the gas behind the detonation wave front.

Further the thermodynamic states behind the detonation front are described by the Hugoniot equation.

$$DE = E_2 - E_1 = \frac{1}{2} (p_2 + p_1) (v_1 - v_2) \qquad (1)$$

wherein, p and v are the pressure and specific volume and E the energy and 1 and 2 denote the unburned and burned states respectively.

The actual detonation involves a passage through a family of Hugoniot curves. These proceed from the curve corresponding to no chemical reaction,

$\Delta E = E_2 - E_1 = \overline{C_v}\ (T_2 - T_1)$ ($\overline{C_v}$ is the average specific heat at constant volume between temperatures T_1 and T_2 before and after the passage of the wave front) to the curve corresponding to complete chemical reactor in which case $E_2 - E_1 = \overline{C_v}\ (T_2 - T_1) - \Delta E_c$ (2)

wherein ΔE_c is the energy released in the combustion process.

Figure 1 shows both Hugoniot curves. The Hugoniot curve for the complete reaction is distinguished by two branches. The branch from A to V is the "detonation" branch and the one from B to C is the "deflagration" branch. It has been shown that the only possible stable detonation is the detonation proceeding at the minimum detonation velocity (see reference 1). This is the Chapman-Jouguet detonation and the resulting detonation overpressure can be found by running a tangent line to the detonation branch from the original condition. The resulting C-J overpressure for stoichiometric propane air mixture has been determined to be $p_2/p_1 = 17.8$ from an initial state of 14.7 psi and 460°F.

That value is closely correspondent to that reported by J. H. Lee and others (reference 2 and 3). Point A corresponds to the overpressure resulting from an adiabatic constant volume explosion. The value obtained of $P_2/p_1=8.7$ differs slightly from that quoted in various references including reference 2, which reports 8.34. The difference is due essentially to the initial state assumed for these calculations which was 0°C, whereas others generally used 25°C.

Reference 1- Courant & Fredericks "Supersonic Flow and Shock Waves" Interscience Publishers, New York, N. Y.

Reference 2- J. H. Lee, at al "Blast Effects from Vapor Cloud Explosions" McGill University, Montreal, Canada

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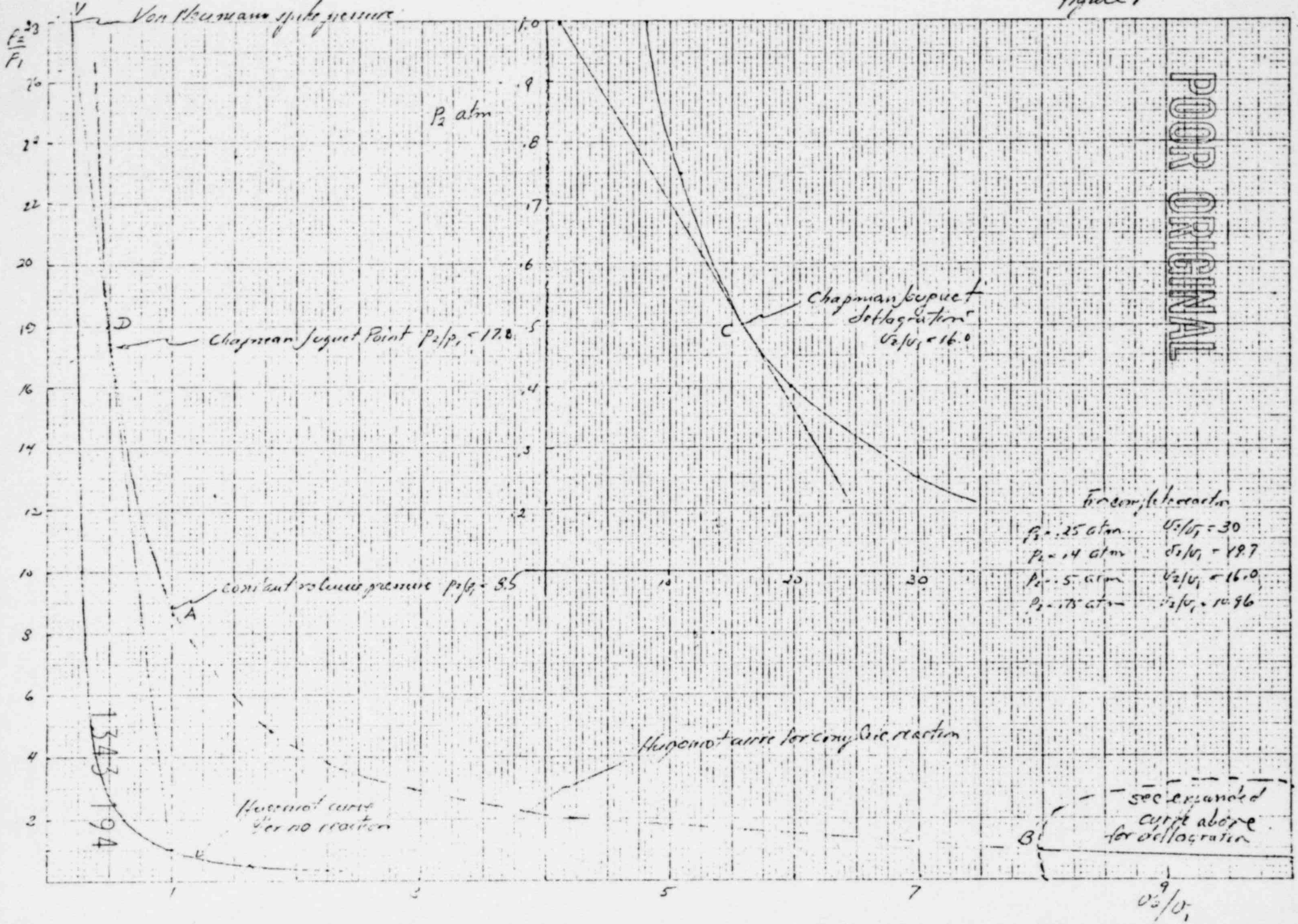
Figure 1


Von Neumann spike pressure
P_2/P_1
P_2 atm
Chapman Jouguet Point $P_2/P_1 = 17.8$
constant volume pressure $P_2/P_1 = 8.5$
Chapman Jouguet deflagration $v_2/v_1 = 16.0$
Hugoniot curve for complete reaction
Hugoniot curve for no reaction
For complete reaction
$P_2 = .25$ atm $v_2/v_1 = 30$
$P_2 = .4$ atm $v_2/v_1 = 19.7$
$P_2 = .5$ atm $v_2/v_1 = 16.0$
$P_2 = .75$ atm $v_2/v_1 = 10.96$
see expanded curve above for deflagration
v_2/v_1
A
B
C
D
V

The intersection of the tangent line with the Hugoniot curve for no reaction is the Von Neumann spike which precedes the C-J detonation pressure. Its computed value is approximately $p_2/p_1=28$, again in close agreement with values reported in the literature.

The detonation velocity which is given by

$$U_1 = D\, v_1 \sqrt{\frac{p_2 - p_1}{v_1 - v_2}}$$

is computed to be D= 5330 fps or 1610 mps. which is in reasonable agreement with literature data.

In the detonation branch the flow velocity of burned gas , W, is in the same direction as the detonation wave. In fact it can be shown that (reference 3)

$$D = W + C$$

where C is the velocity of sound in the burned medium.

Since the detonation wave travels supersonically with respect to the unburned medium, no disturbance precedes it, hence the cloud size remains at its initial size as the detonation propagates, i.e. the gas expansion occurs afterwards and has the effect of a rarefaction wave which tries to overtake the detonation wave at sonic velocity in the burned medium. This observation has been made by others (reference 2, page 12). Further discussion of the subsequent expansion is given later on.
Thus the effects of the detonation blast of the wave of the propane gas clouds has already been properly addressed in the FSAR sect 2.2.3.

Reference 3- Lewis & Von Elbe "Combustion Flames and Explosions of Gases" Academic Press, New York, N. Y.

The portion of the curve between A and B corresponds to no real physical state. The portion of the Hugoniot curve between B and C represents a decrease in pressure and increase in volume, corresponding to a rarefaction.

The burned gas flow velocity W therefore is always negative, i.e. the burned gas no longer moves in the same direction as the wave, but away from it.

The consequence of this is that in this deflagrative process a pre-compression wave is sent out into the explosive mixture to push that unburned gas with a velocity just sufficient to ensure that the gas may come to rest when it is swept over and burned by the deflagration front.

Physically no deflagration occurs past the point C (reference 1) which is known as a Chapman-Jouguet deflagration point. In fact weak deflagrations (essentially constant pressure explosions) are those to be considered for vapor clouds explosions, and are the ones that have been observed in experiments.

Whereas the C-J detonation velocity represents the minimum of all detonation velocities, the C-J deflagration velocity is in fact the largest possible deflagration velocity which is calculable from eqn (3).

For the propane-air mixture studied (stoichiometric) the C-J deflagration velocity was computed to be 168 fps.

For weak detonations however the deflagration velocity is the same as the laminar burning velocity 1.5-2.0 fps, hence a thousand times less than detonation velocities.

However the spatial deflagration velocity, which would be that seen by a stationary observer, is higher than the deflagration velocity computed by eqn. (3). This is due to the displacement of the unburned gases ahead of the propagating flame caused by the specific volume increase across the flame front. Since this increase is about eight fold, the spatial deflagration velocity is roughly eight times that computed by eqn (3).

Hence for a C-J deflagration, spatial velocities of the order of 1300-1400 fps could occur. In actual tests however (reference 5 and 6) the spatial flame velocity has been measured to be of the order of 30-40 fps. for mixtures difficult to detonate (like propane-air) and ten times larger for mixtures rich in oxygen.

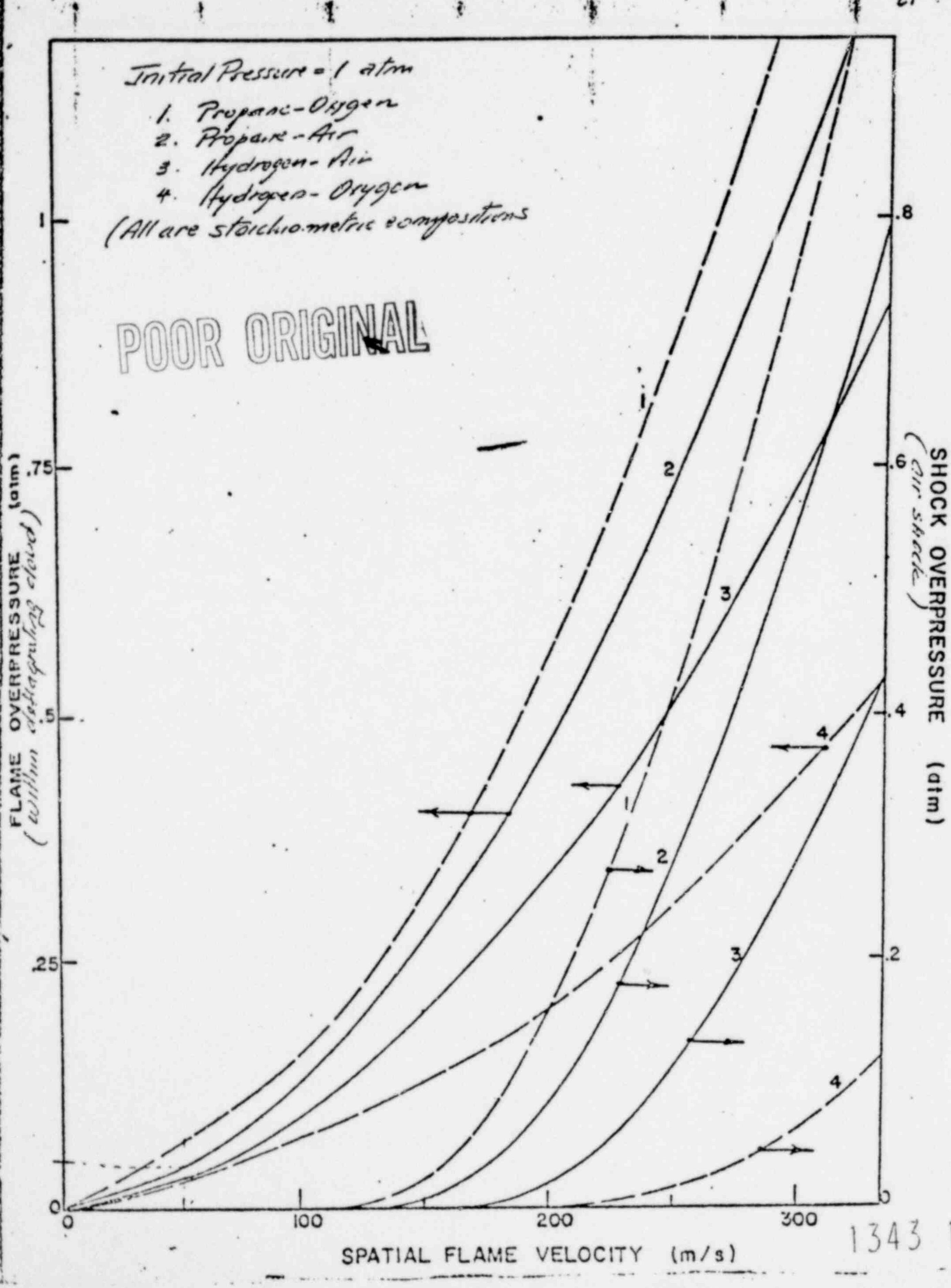
The effect of oxygen richness is not surprising since lack of inerts such as nitrogen has the effect of raising the Hugoniot curve for complete reaction to higher values. For instance the C-J detonation point for a stoichiometric propane oxygen mixture would correspond to overpressure almost exactly double that occurring for the detonation of propane-air mixtures, with detonation velocities thirty percent higher. Similarly the C-J deflagration velocities for oxygen rich mixtures is expected to be higher than that for propane-air mixtures.

Hence C-J deflagrations of any kind exhibit velocities in excess of 1300 fps. The fact that no such spatial burning velocity has been observed confirms that C-J deflagrations do not occur, but that only weak deflagrations, i.e. basically constant pressure burning,occur.

For these kinds of deflagrations, the precompression sent into the unburned medium and surrounding air is in the nature of basically an acoustic wave, which does not steepen into an air shock unless spatial flame velocities of 300 fps or more are achieved, as shown in the attached figure taken from reference 1.

Reference 6- NUREG/CR -0075 "Accidental Vapor Phase Explosions on Transportation Routes Near Nuclear Power Plants", April 1977.

Reference 5- Lind, C. D. and R. A. Strehlow, 4th, International Symposium on Transport of Hazardous Cargoes by Sea and Inland Waterways, Jacksonville, Florida (1975)


Initial Pressure = 1 atm
1. Propane-Oxygen
2. Propane-Air
3. Hydrogen-Air
4. Hydrogen-Oxygen
(All are stoichiometric compositions
POOR ORIGINAL
FLAME OVERPRESSURE (atm)
(within deflagrating cloud)
SHOCK OVERPRESSURE (atm)
(air shock)
SPATIAL FLAME VELOCITY (m/s)
0
100
200
300
.25
.5
.75
1
.2
.4
.6
.8
1
2
3
4

Likewise there is no overpressure of great significance within the deflagrating cloud. For typical spatial burning velocities of 30 fps or less, overpressures of about 1 psi will occur just ahead of the flame front. Hence it is concluded that blast damages are insignificant for deflagrative burning of propane air clouds either near or far from the cloud. Hence for a deflagration the possible damage is limited to temperature.

In a detonationevent after passage of the initial detonation blast, the compressed products expand. Under the assumption that this expansion is isentropic, the final volume will be approximately 9.7 times initial volume (assuming K= 1.25),(for an oxygen rich detonation these rates would be more than double). This expansion in turn can generate a second shock in the air ahead of the expanding products of the detonation, which follows the initial shock caused by the hydrodynamic coupling of the detonation wave and the air.

This second shock is one order of magnitude smaller than the first air shock (see reference 7) and exhibits the same decay with distance from the center of detonation as the first and much stronger shock.

Since the Waterford plant has been shown to withstand the first shock overpressures, it is also safe against the weaker second shock caused by the expanding detonation products.

During the preceding it has been tacitly assumed that the flammable cloud is entirely formed of a stoichiometric mixture of propane and air (or oxygen). This was of course the case for all experiments conducted (see references 2,3,6,7). In fact the computed propane air clouds as shown in figures 2.2-8 and 2.2-9 exhibit a range of mixtures which are only stoichiometric in a region which at ground level is centered from 1300 ft to 3500 ft from the origin of the cloud. At closer distances to the origin of the cloud ground level concentrations are overrich, farther away they are leaner than stoichiometric

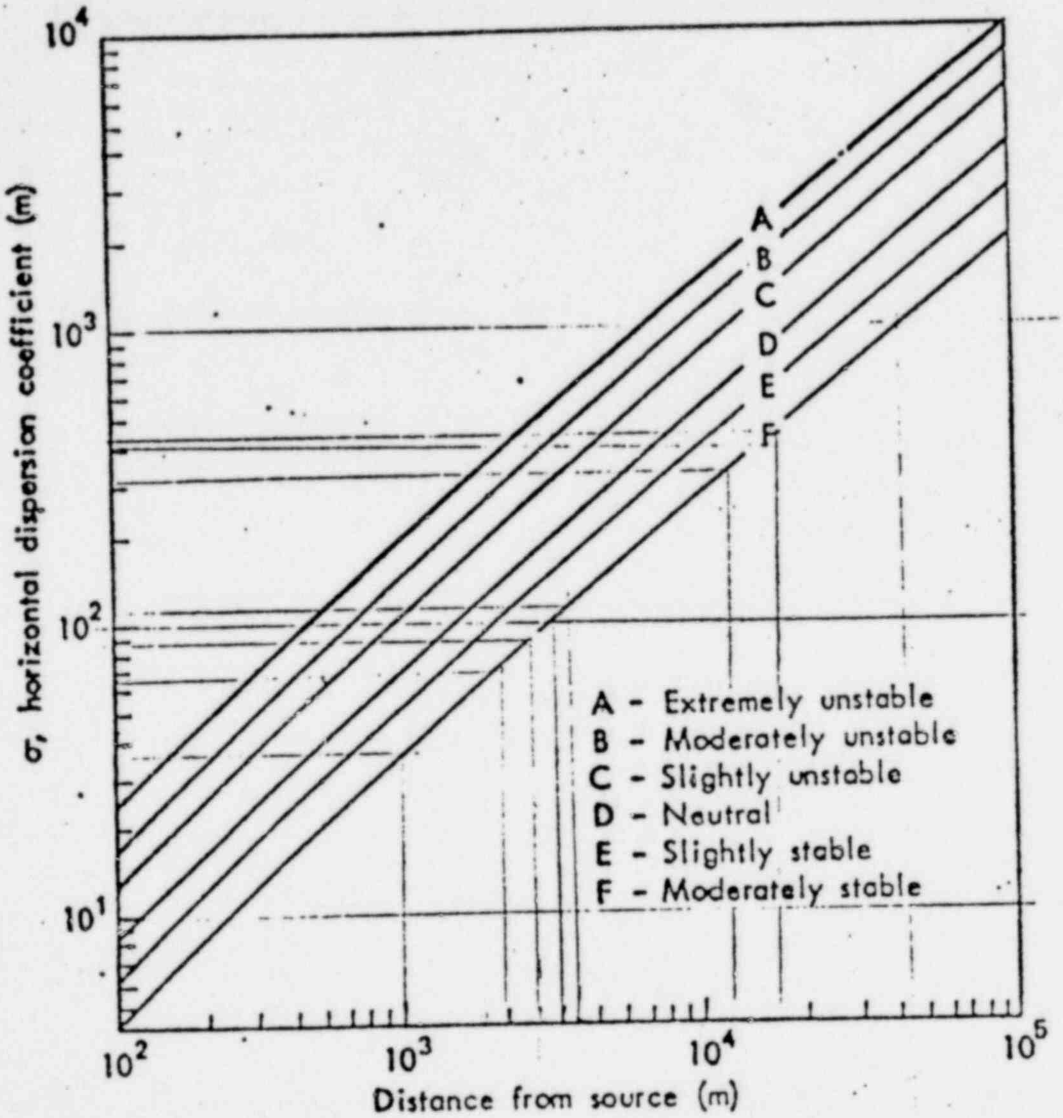


Fig. 4—Lateral diffusion, σ_y, versus downwind distance from source for Pasquill's turbulence types (Source: Ref. 25)

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Since the propane plume downwind of the 1000 ft^3/sec source is shown to present the greatest hazard to the plant, Figure 2.2-9 has been modified to reflect the larger span of mixture concentrations within which a deflagration can occur. Whereas the detonable limits for propane air mixtures are 7.0 and 2.8 percent by volume of propane, the limits of deflagrations are 9.5 and 2.2 percent.

In addition an overconservatism was discovered in the values of σy and σy used in assembling the information of Figure 2.2-9. Smaller values of σy has been used than published in the literature for distances downwind exceeding 2500 ft.

With the corrected Table 2.2-21 and Figure 2.2-9, the lower limits of flammability and detonability are reached at 5020 and 4298 ft respectively. Similarly the upper and lower detonability limits are reached at 2178 ft and 2575 ft from the break.

The volume of flammable mixture contained within the vapor cloud is computed to be 1.95×10^7 ft^3, whereas the detonable volume is only 1.15×10^7 ft^3.

Hence 40% of the total flammable volume has concentrations below 2.8%, or below 0.67 times the stoichiometric concentration of 4.12%.

The expansion of a mixture of less than 67% stoichiometric concentration (as well as that of concentrations above 120-130% of stoichiometric mixtures is at least 30% less than the expansion of stoichiometric mixtures. This results basically from the lower flame temperature. The expansion given in Figure 1 at point B is thus applicable only to stoichiometric concentrations. Therefore the final volume of the deflagrated vapor cloud can be conservatively estimated by expanding the volume of 2.8% or larger propane concentration to a final volume 8 times larger, and the volume of lower concentration to a volume 5.5 times larger. The resultant final volume would be $1.35 \times 10^8 ft^3$.

Assuming that the original cloud can be represented as a hemi-ellipsoid of 4564 ft, 143 ft, and 28.6 ft dimensions in the downwind, crosswind and vertical direction, centered at 2734 ft from the break, and that the deflagration is either centered at that point or the final dimension of the product cloud downward will be 6717 ft from the break.

The closest distance from the 8" pipeline to a safety structure in Waterford 3 is 7350 ft. Hence it is concluded that the deflagration of the "worst" cloud ensuing from a catastrophic break in such line poses no hazard to the plant.