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May 3, 1991
Fort St. Vrain
Unit No. 1
P-91152

U. S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, D.C. 20555

Attention: Dr. Seymour H. Weiss, Director
Non-Power Reactor, Decommissioning
and Environmental Project Directorate

Docket No. 50-267

SUBJECT: Natural Gas Collection Pipelines in the Vicinity of Fort St. Vrain

REFERENCES: 1) PSC Letter, Crawford to Weiss, dated March 27, 1991 (P-91111)

2) PSC Letter, Crawford to Weiss, dated April 23, 1991 (P-91139)

Dear Mr. Weiss:

In a phone conversation on April 29, 1991 between Mr. Richard Dudley, Jr. of your staff and PSC's Mr. Michael Holmes, the NRC requested additional information concerning the natural gas issue at Fort St. Vrain (FSV), primarily related to References 1 and 2. The purpose of this letter is to provide the NRC with the requested information.

Attachment 1 includes the NRC questions and PSC's response to each question. Attachment 2 is a document entitled "Natural Gas Explosion Concern at FSV." This document was prepared by a consultant (Mr. Stanley Martin) whose services PSC acquired upon the recommendation of the U.S. Gas Research Institute (GRI) and the Federal Emergency Management Agency (FEMA), who identified Mr. Martin as a leading expert in the area of deflagrations and detonations of unconfined gas vapor clouds, and the structural effects upon target buildings of the deflagrations and detonations. PSC has found Mr. Martin's extensive knowledge in this field to be enlightening and considers that the information in Attachment 2 will prove helpful in resolving the natural gas issue at FSV. Attachment 2 also includes a number of reference documents associated with Mr. Martin's evaluation.

C001 1/1

Attachment 3 is Mr. Martin's resume, documenting his qualifications in this particular field of knowledge.

Should you have any questions concerning this submittal, please contact Mr. M. H. Holmes at (303) 480-6960.

Very truly yours,

A. Clegg Crawford
Vice President
Nuclear Operations

ACC/JRJ:blt
Attachments

cc: Regional Administrator, Region IV

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Responses to NRC Phone Questions

NRC Question - As stated in PSC's letter dated April 23, 1991, concerning this natural gas issue, an overpressure of 0.45 psi at the Reactor Building was calculated to result from postulated detonation of natural gas assumed to be released from rupture of the 4 inch line south of the FSV facility. By doubling this, the NRC arrives at an overpressure of 0.90 psi at the Reactor Building. The question is, what would happen to the blowoff panels, located above the fuel deck, in the event of such an overpressure condition at the Reactor Building?

PSC Response - As discussed in Reference 2 of the cover letter, PSC takes exception to the NRC's doubling the calculated overpressure at the Reactor Building. This "doubling" only applies to actual detonations which produce shock waves with essentially instantaneous rise times to account for the effects of reflected pressure from a wall normal to the incident pressure wave. It is not applicable to pressure waves generated from deflagration of an unconfined natural gas vapor cloud. This is further discussed in Attachment 2, a document prepared for PSC by Mr. Stan Martin, an expert in vapor cloud detonations and deflagrations and associated effects on target structures, referred to PSC by the U.S. Gas Research Institute (GRI) and the Federal Emergency Management Agency (FEMA). In Attachment 2, Mr. Martin provides justification for his contention (and that of virtually all other experts contacted by PSC on this subject) that detonation of an unconfined natural gas vapor cloud will not occur, and discusses effects of deflagration of such a cloud, which is a credible occurrence.

The blowoff panels respond to dynamic pressures, such as would be generated by winds, which give rise to drag forces. As noted in Attachment 2, winds generated by deflagration of an unconfined natural gas vapor cloud could reach speeds equal to the combustion flame propagation speed through the flammable portion of the cloud. Assuming highly turbulent conditions (much higher than would be generated by the assumed 1 meter per second wind speed used to reduce dispersion and maximize the amount of natural gas within a flammable concentration), a combustion flame propagation speed of 30 meters per second would be possible. Thus, wind speeds at the portion of the natural gas cloud at the lower flammable limit (LFL) could reach 30 meters per second (67 miles per hour). Such a wind speed would have no impact on the Reactor Building, or its blowoff panels, designed to blow off at wind speeds greater than 202 mph.

If a detonation were hypothesized to occur, which produced an overpressure shock wave at the Reactor Building of 1.0 psi, the blowoff panels would not be expected to break away from the wind girts which support them. This is demonstrated by the following assessment: The relationship of dynamic pressure (q) to peak side-on overpressure (P) in an ideal air blast is

$$q = \frac{5/2\ (\text{P-squared})}{(7\ \text{times the atmospheric press.}) + P}$$

This is the Rankine - Hugoniot equation for a shock wave, and can be found on page 97 of Glasstone and Dolan, 1977. There is a thumb rule associated with this equation, relating particle velocities (or wind speeds) to peak side-on overpressure in a shock wave, which is used for peak side-on overpressures less than about 10 psi: a 1 psi peak side-on overpressure equates to a 50 feet per second particle velocity, and for each additional psi of peak side-on overpressure, an additional 50 feet per second particle velocity is added. NRC Regulatory Guide 1.91, "Evaluation of Explosions Postulated to Occur on Transportation Routes Near Nuclear Power Plant Sites" - January 1975 presents the following equation for relating dynamic pressures (q) to wind speeds (V):

$$q = 0.002558 \text{ (V-squared)}$$

Where q is the dynamic pressure in pounds per square foot and V is the maximum wind velocity in miles per hour. Based on the Rankine - Hugoniot equation and the above equation relating dynamic pressure to wind speed, the actual dynamic pressure can be calculated and the equivalent wind speed can be determined for a given peak side-on overpressure generated from a hypothetical detonation.

For a 1.0 psi peak side-on overpressure generated from a detonation, the corresponding dynamic pressure would be 0.029 psi. This corresponds to the dynamic stagnation pressure developed by a wind speed of about 40 miles per hour. In order to achieve the dynamic pressure and drag forces associated with a 202 mph wind, and begin to break away blowoff panels, a peak side-on overpressure of approximately 5 psi would have to occur at the Reactor Building. For overpressure of 1.0 psi, or less, PSC considers that the Reactor Building structure would not be damaged. This is consistent with conclusions reached by the NRC in Regulatory Guide 1.91, Rev. 1 (For Comment), dated February 1978, which states

> "A method for establishing the distances referred to above can be based on a level of peak positive incident overpressure... below which no significant damage would be expected. It is the judgement of the NRC staff that, for the structures, systems, and components of concern, this level can be conservatively chosen at 1 psi."

For the maximum 0.45 psi overpressure which was calculated to occur at the Reactor Building in Reference 1, and for double this overpressure, PSC concludes that the Reactor Building blowoff panels would remain in place.

<u>NRC Question</u> - If it is assumed the Reactor Building blowoff panels above the fuel deck were torn off, what effect would this have on the capability to remove decay heat from the fuel in the PCRV and in the fuel storage wells?

PSC Response - The method for decay heat removal of fuel in the core and fuel storage wells, relied upon in the FSV Defueling Safety Analysis Report (incorporated into Sections 3.11 and 14.14 of the Updated FSAR) and Section 4.3 of the FSV Fire Protection Program Plan (FPPP), is one loop of liner cooling. Two redundant liner cooling loops supply both the PCRV and the fuel storage wells. Water can be supplied through these liner cooling coils by System 46 pumps (2 pumps per loop) in the recirculate mode, or by a firewater pump in the once-through mode. For either mode of cooling, the equipment relied upon is classified Safe Shutdown and protected so as to withstand the effects of the Maximum Tornado with wind speeds as high as 300 mph (FSAR Sections 1.4 and 14.1.2). FSAR Section 14.1.2 states that

> "At the 300 mph wind speed, the siding on the auxiliary and confinement buildings, above the refueling floor level, may be carried away, but the basic building structure will not collapse. The confinement and auxiliary buildings are not required for safe shutdown. However, equipment and systems essential to safe shutdown which are located above the refueling floor are protected from tornado missiles by redundancy of the components, with sufficient separation and missile shielding such that a single missile could not involve both components. Equipment and systems essential to safe shutdown which are located below the refueling floor level are protected from tornado missiles by special heavy steel siding on the building."

The PCRV liner cooling water surge tanks and associated piping are located above the refueling floor ("fuel deck"). A concrete missile shield separates these two tanks. Even if both tanks were assumed to be ruptured, PCRV liner cooling and fuel storage well liner cooling could be readily established from either one of the two firewater pumps. Thus, loss of the blowoff panels would not jeopardize the capability to remove decay heat from the fuel, even in the event of 300 mph winds passing through the top of the Reactor Building.

NRC Question - In a previous phone call, PSC stated that cooling could be secured to the fuel for about three weeks, without creating unsafe conditions. Could PSC document the basis for this statement?

PSC Response - Decay heat generation from the fuel is extremely low, due to the permanent reactor shutdown on August 18, 1991. FSV Technical Specification 4.0.4 defines the method used to compute the CALCULATED BULK CORE TEMPERATURE (CBCT). The basis for this specification explains that this calculation assumes all decay heat power generated is retained in the active core, with no heat transfer to the reflector, PCRV internals or primary coolant. Specification 4.0.4 does not permit the CBCT to exceed 760 degrees F, which corresponds to the design maximum core inlet temperature. This limit assures there can be no damage to fuel or PCRV internal components, even in the absence of forced circulation of primary coolant helium.

Based on current decay heat generation, the CBCT would not reach 760 degrees F if all cooling ceased for over 21 days. This is based on the assumption of adiabatic heatup of the fuel. If PSC were to perform an analysis which modeled heat transfer out of the fuel, it is quite likely that it could be shown that forced circulation and PCRV liner cooling could be secured indefinitely and would never need to be restored to prevent unacceptably high fuel temperatures. Due to the substantial heat sink designed in to the fuel storage wells (discussed in FSAR Section 9.1.2), fuel in these wells could easily withstand loss of all cooling for times beyond 21 days without reaching the 750 degree F limit discussed in the basis for LCO 4.7.3, "Fuel Storage Wells."

NRC Question - In PSC's letter dated March 27, 1991, concerning this natural gas issue, a contradiction was noted at the bottom of page 2 of Attachment 2. PSC states the "shut-in valve" located at the wellhead automatically actuates to isolate the producer pipe at the wellhead, in the event of high or low casing pressures. But the next sentences state that pressure switches are set to open the shut-in valves at a pressure of approximately 350 psig and close the shut-in valves at a pressure of approximately 170 psig, for all ten wells that feed the gas collection system in the vicinity of FSV. Can PSC clear this up?

PSC Response - There was a mistake in the first sentence the NRC mentioned. The shut-in valves are automatically opened on high pressure and close on low pressure. They do not isolate the producer pipe at the wellhead on high pressure, as stated, only on low pressure. PSC apologizes for any misunderstanding caused by this mistake.

NRC Question - Since the 6 inch manual isolation valve was closed, which connects the 16 inch line to the 6 inch line, and flow between these two lines is through the 1.5 inch diameter line that bypasses this valve (as discussed in PSC's letter dated March 27, 1991, concerning this natural gas issue), has there been a significant pressure increase in the natural gas collection system in the vicinity of FSV?

PSC Response - Based upon data submitted to PSC by Panhandle Eastern, the owner of this natural gas collection pipeline system, pressures increased from an average pressure of about 130 psig to an average pressure of about 155 psig as the result of closing the 6 inch manual isolation valve and restricting flow to the 1.5 inch bypass line.

NRC Question - What is the design pressure and test pressure of the 6 inch and 4 inch diameter piping in this collection system?

PSC Response - Per discussions with personnel from Panhandle Eastern, all of the 4 inch and 6 inch piping in question has a design pressure of 720 psig and was hydrostatically tested to 1080 psig, one and one-half times the design pressure.

<u>NRC Question</u> - In PSC's letter dated March 27, 1991, concerning this natural gas issue, PSC stated that the 6 inch manual isolation valve (discussed above) would be closed, except during maintenance or surveillance activities when Panhandle Eastern would have the valve "continuously manned by an operator who has been instructed to promptly close the valve in the event a pipeline rupture is observed or suspected." How will this operator know a pipeline rupture has occurred at either Break 1 or Break 2 locations?

<u>PSC Response</u> - An operator stationed at the six inch manual isolation valve would be able to hear and see the effects of a large pipe rupture, such as was postulated to occur at the Break 1 and Break 2 locations discussed in References 1 and 2 of the cover letter. The Break 1 location is approximately 3900 feet from the 6 inch manual isolation valve and the Break 2 location is approximately 4800 feet from the 6 inch manual isolation valve. Gas leaving the pipe at sonic velocity would set up a shock wave that could be heard at much greater distances. The noise produced by gas escaping from a large rupture would be comparable to that produced by a jet engine. The terrain between the postulated rupture locations and the 6 inch manual isolation valve is quite flat, without many trees or structures which could interfere with and significantly attenuate the sound.

In addition to the sound generated from a large pipe rupture, the gas escaping at high pressure from a buried pipe would create a large plume of dust which would be visible from the 6 inch manual isolation valve due to the fact that Break 1 and Break 2 locations are within the line of sight of a person stationed at the 6 inch manual isolation valve. Were the natural gas to ignite, as the result of sparks at the rupture location, it would flare, which would also be visible to a person stationed at the 6 inch manual isolation valve.

In addition, it is probable that the noise produced at the 6 inch manual isolation valve itself, due to a sudden flow reversal and drastic flow increase, would be sufficient to alert the operator stationed at the 6 inch manual isolation valve. However, there is insufficient experience and no means of testing this to arrive at this conclusion with a high degree of certainty.

Based upon hearing a pipe rupture and/or seeing the effects of the pipe rupture, experienced personnel at Panhandle Eastern and Western Gas Supply Company (PSC's natural gas subsidiary) are confident that an operator stationed at the 6 inch manual isolation valve would rapidly become aware of a large pipeline rupture near either the Break 1 or Break 2 location.

P-91152
Attachment 2
May 3, 1991

NATURAL GAS EXPLOSION CONCERN AT FSV

Introductory Remarks

By far, the preponderant majority of cases of accidental or experimental, unconfined vapor-cloud explosions have failed to produce significant airblast effects. Notable exceptions--the Flixborough and Port Hudson events are about the only examples--are often held up to those who would dismiss the prospect lightly, as a reminder that experience shows that the threat of structural damage and/or personal injury/death cannot be ruled out. These events were special, however, because the first involved a massive release of cyclohexane, while the second was propane, and may have involved detonation initiated within a strong walled building. These two examples are therefore not directly appropriate to the circumstances of current consideration, that is, a natural gas release on the open prairie, in the absense of enclosures where strong shocks might be generated (PSC letters to S.H. Weiss, dated 27 March and 23 April 1991). Both experience and theory-based analyses say: unconfined natural-gas clouds in air (lacking some peculiar, extreme, and very special conditions) are not a blast damage/injury threat.

The Concept of TNT Equivalence

For years, attempts have been made to express the hazard of such uncondensed explosives as fuel-gas/air and fuel-gas/oxygen mixtures in terms of the energy release (or yield) equivalent to some standard condensed-phase explosive such as TNT. The concept has some merit, as long as the state of a uniform mixture of the reacting gases is well known, and the explosion-to-target distance is large compared to the size of the cloud (i.e., the target is sufficiently remote that the extended source approximates a point source.) This is usually not the case, nor of practical interest, in accidental gaseous releases into the atmosphere. The amount of gas that may participate in the combustion reaction, soon enough to support a pressure wave, is commonly much less than any calculation of the time-averaged lower-flammability-limit envelope would suggest. Any estimate of yield is, therefore, very sensitive to variations in cloud geometry and eddy fine-structure within the cloud, which in turn depends on wind-speed profiles, gustiness, terrain roughness, etc., that are hardly knowable. Forecasts are quite beyond doing, with any confidence, at the present stage of development of the technology.

Another very important source of variability in gas-phase explosions is the kind of explosion: 1. deflagration;

2. detonation; 3. thermal explosion. In the order given, the explosion energy yields increase from a small fraction of that potentially available (order of 0.01) to a large fraction (approaching 100%). For natural-gas/air, we can eliminate any prospect of a thermal explosion, because alkane hydrocarbons are stable in air at ambient temperatures; and detonations can occur only in very special circumstances, such as in channels with high Reynolds' Numbers or in enclosures with strong walls. In pure methane/air, detonations can be ruled out. Higher hydrocarbons are more subject to detonation (more on this later), unsaturated hydrocarbons, even more, and certain chemical additions to the hydrocarbon structure increase this tendency dramatically. This explains, in part, the differences in experience-based energy yields of explosive vapors and gases. Refer to the table of yield factors (Table B.3) used with FEMA's ARCHIE Code. Alkane hydrocarbons are in the group having Y=0.03. This would be appropriate for deflagration of natural-gas/air. The higher yields are for ethers, nitrated paraffins, olefins, and acetylenics. This is entirely consistent with the findings of Brasie and Simpson(1968). In the incidents they surveyed, including a wide range of hydrocarbon/air explosions, yield values were commonly less than 0.04. Deflagrations having yields as high as 0.1 require mixtures containing the more reactive components, listed above, or special circumstances. Analysts often use this more conservative value to cover any and all eventualities, to be way over on the safe side. It would seem, however, inappropriate to do so here, unless it can be shown that detonations are both possible and probable. This issue is addressed in the following section.

The Possibility of Detonation

There is considerable, quality evidence that detonation cannot be directly initiated in a natural-gas/air mixture with anything less than heroic efforts (e.g., kilograms of high explosive or a strong shock emanating from a pipe; see MIT-GRI LNG Workshop, 1982). Further, there is considerable doubt that, once initiated, a detonation could sustain itself in practical situations of nonuniform mixing. That may have happened at Port Hudson because of special circumstances, but alternative explanations for the damage have been offered. It must be remembered that the Port Hudson event was fueled by propane not natural gas.

The only reason for not categorically denying the possibility of detonation at the FSV site is the presence of higher hydrocarbons in natural gases. (Refer to FSV gas composition in PSC letter, dated 22 February 1991.) Concentrations greater than 15% (by volume) of ethane and/or propane increase the sensitivity to initiation of detonation. Results of all the tests conducted to the 1982 date of the MIT-GRI Workshop, to study the detonability of unconfined vapor clouds, indicated the following:

- No detonations are possible in an unconfined stoichiometric mixture of pure methane vapor and air, even under the initiating influence of 2 kg explosive

- Sustained detonations are possible in unconfined vapor clouds containing stoichiometric fuel air mixtures when the fuel vapor contains methane and propane in the molar ratios of 60/40, 70/30, and 85/15. Above 85% (molar) methane concentrations, no sustained detonations have been observed.

- Propagating detonations (from a pipe) have been sustained in unconfined mixtures of methane/propane/air (stoichiometric) for methane volume fractions of less than 85% in the fuel vapor.

It is evident from these results that relatively small fractions of heavier hydrocarbons, such as ethane and propane, in the fuel vapor increase the propensity for the detonation of unconfined vapor/air mixtures. This phenomenon is of great importance in evaluating the detonability consequences of natural-gas releases in the form of late-time boil-off from LNG, but usually does not apply to releases from pipelines, because gaseous releases are usually not rich in higher hydrocarbons. The sensitivity of the natural gas at the FSV site to the initiation of detonation can be gauged by referring to attached Figure 7 from Bull and Martin (1977), which shows the mass of tetryl required to detonate binary methane/ethane mixtures. A 10-to-20% ethane mixture still needs a kilogram or more of high explosive to detonate.

As a practical matter, as I understand the circumstances of the possible release of natural gas at the FSV site, I conclude that the likelyhood of a detonation is essentially zero.

Flame Generated Pressures

In view of the large uncertainties in any attempt to establish an explosive-energy yield, an arguably better approach to setting an upper bound on airblast pressures from unconfined gas-phase explosions is one based on the theoretical development of Kuhl, Kamel, and Oppenheim (1974; see attached figure.). A flame propagating through a premixed gas of uniform composition and properties pushes unburned gas ahead of its flame front, causing the pressure to rise. In the free field, the flame propagates in three dimensions as a sphere. The compression is less than it would be if the flame were constrained by a nonyielding surface (e.g., the ground or a wall) to propagate with only two degrees of freedom, and still less than situations in which expansion is constrained to just one dimension. In any case, if the flame has a fixed speed--neither accelerating nor decelerating--it will maintain a fixed pressure rise

in the unburned gas it pushes ahead. Unless the speed of the flame front is up around 40 m/s, the overpressure just ahead of the flame cannot exceed one atmosphere (14.7 psig). To shock up and (possibly) detonate requires much higher speeds. The required "run-up speed" for natural gas in air is not known, but certainly approaches--and may exceed--Mach 1 (Lee, 1977), that is, about 330 m/s, which is patently unattainable in the open. Typical burning speeds for methane are 7 m/s, in quiescent conditions. Turbulence may increase that by a factor of four (to, say, 30 m/s; see Kanury, 1975, pp. 303,304).

Thus, the upper bound of overpressure (for pure methane), at the flame front, would be 0.4 atmospheres (about 6 psig). At the target distance (taken to be 930 ft), this falls to about 0.035 atmospheres, or 0.5 psig. It must be noted that, in order to estimate the falloff of pressure with distance, it is again necessary to use an energy-yield factor to compute a "scaled distance" or a nondimensionalized "reduced distance." Here, we have used the ultraconservative value of 0.1. A calculation using the more realistic yield of 0.03 would, of course, result in smaller overpressures. In either case, estimates of dynamic (i.e., wind) pressure would be inconsequential.

It is important to note that this air blast will not "shock up"--that is, the pressure wave will have a finite rise time, and it is, therefore, inappropriate to use a doubling rule for reflected pressure loading of walls. Burning speeds would need to exceed 230 m/s to develop any significant shocking of the pressure wave (Lee, 1977). The pressure rise time will be comparable to the time taken by the flame to transit the near-stoichiometric (and richer) portion of the cloud. If this were on the order of 100 ft, the rise time could be a second or two long.

Structural Loading and Response

Actually, side-on overpressures seem to have little or nothing to do with structural response in this case. I am not familiar with the building or buildings that might be subjected to blast loading, but I suspect it is (or they are) more likely to respond to drag loading than to diffraction (or crush) loading*. If the rise time is long compared to diffraction times and clearing times (and for leaky structures, long compared to inside-to-outside pressure equalization times), then there would be little net force acting on a wall except for dynamic (i.e., drag) forces. An air-tight box *would* be subjected to crushing forces, but such structures are inherently strong--even within the

* For a fuller development of the mechanisms of airblast loading and responses of structures (and definitions of such terms as *drag*, *diffraction*, and *clearing times*), refer to Glasstone and Dolan, 1977.)

cloud, no pressures capable of crushing damage would be expected. The pressure-pulse duration (and the accompanying drag-phase flow) is undoubtedly long compared to the natural period (roughly 1/2 sec.) of the Turbine/Reactor Building Complex as described in PSC letter, dated 23 April. Pressure durations from uncondensed explosives are 1 to 2 orders of magnitude longer than ideal explosions (see Bodurtha, 1980, p. 108); therefore, the dynamic pressure pulse can be compared to a wind gust. Accordingly, it is appropriate to consider the wind force of the dynamic pressure wave to be the principal mode for mechanical damage, and to compare its magnitude to the design value.

In ideal blast waves with a true shock front, peak dynamic pressures can be appreciable in magnitude compared to peak (side-on) overpressures. For example, a 4 psi peak (side-on) overpressure is accompanied by 0.4 psi (60 psf) peak dynamic pressure. That represents a particle velocity of 200 ft/s or 136 mph. A 6-psi overpressure is accompanied by 0.8 psi dynamic pressure, corresponding to a 260 ft/s particle velocity, representing a 177 mph wind gust. A useful rule-of-thumb: The particle velocity associated with a 1-psi overpressure is about 50 ft/s, and increase (or decreases) in linear proportion to the overpressure. Thus, a 300-mph air blast (440-ft/s particle velocity) accompanies a peak overpressure of 8.8 psi.

Alkane/air deflagrative explosions, by contrast, do not generate shocks. Clearly, therefore, the peak particle velocity driven by the explosion cannot exceed the flame speed driving it. As a result, flame speeds in quiescent, premixed methane/air mixtures would be incapable of driving wind gusts above 16 to 18 mph <u>at the edge of the exploding cloud</u>! I have no evidence showing that this conclusion would not apply to the FSV gas as well. Allowing a factor of four for turbulence, the limit would still be a factor of 4 to 5 below the designed wind force for the Reactor Building, and would rapidly dissipate with distance from the explosion. This is consistent with my previous statement that the independently computed dynamic pressure is inconsequential.

<u>Conclusions</u>

These are my basic conclusions:

1. The likelyhood of a detonation is negligibly small, if not zero.

2. The air blast from a deflagrative explosion would exhibit a weak pressure pulse having a long rise time compared to any characteristic building-response time. Thus, the response would be entirely like a response to natural wind forces.

3. Responses to side-on overpressures, if any, would be limited to window/door/light-panel breakage or deformation, but (except for glass window breakage) this is expected only from overly conservative estimates of yield.

4. Dynamic pressures would be inconsequential relative to the 300-mph design.

Stanley B. Martin
2 May 1991

[signature]

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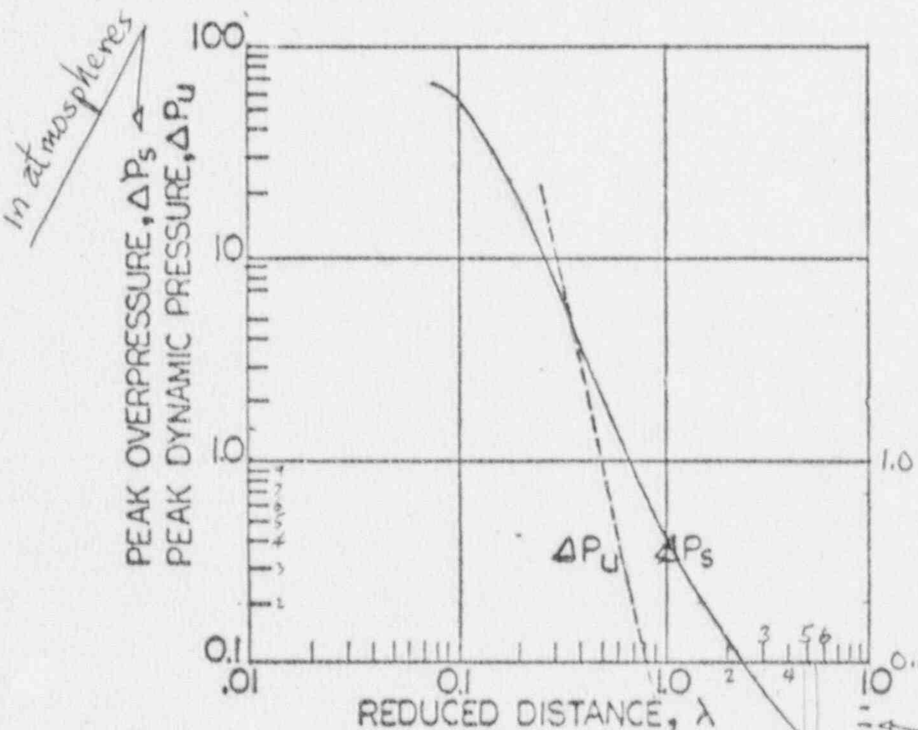
IDEAL BLAST WAVE CALCULATIONS

Brode (1955) solved the gas dynamics equations for spherical blast waves from point sources, and this solution has been used by Allan and Athens* to predict the effects of vapor cloud explosions on structures. Brode's solutions can only be used for far field blast effects of vapor cloud explosions since a vapor cloud is not well represented by a point source. However, estimated overpressures and durations at a distance of several cloud diameters are good enough for most purposes, the uncertainty of other factors in estimating explosive yields causing greater deviations.

Allen and Athens provided plots based on Brode's solutions to determine the peak (side-on) overpressure and peak ~~static and~~ dynamic pressures, the duration of the positive pressure phase, and the ~~static~~ over-pressure and dynamic pressure impulses at any distance from the center of explosion. The plots are reproduced in Figures 2 through 4 and can be used to estimate blast wave characteristics once the energy yield is known.



R is actual distance from center of explosion

$$\Delta P = \Pi - 1 = \frac{P}{P_0} - 1$$

$$\lambda = \frac{R}{a} \quad a^3 = \frac{E_{tot}}{P_0}$$

for large V

$$\lambda = \frac{(R^3+V)^{1/3}}{a}$$

FIGURE 2

Peak overpressure and peak dynamic pressure vs reduced distance.

in closer to the cloud (of volume = V) use:

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*Allan, D.S. and Athens, P., "Influence of Explosions on Design," CEP Technical Manual, Loss Prevention Vol. 2, AIChE, New York, 1968.

My calculation of the Reduced Distance, λ, follows:

Assume 2500 kg of CH_4

$$\begin{array}{l} \times\ 13.3 \times 10^3 \text{ Kcal / Kg } CH_4 \\ \hline 33250 \times 10^3 \text{ kcal heat released on combustion} \end{array}$$

(or 33.25×10^6 Kcal)

Using the yield that might pertain to cloud detonation ($\epsilon = 0.1$)

3.325×10^6 Kcal drives the "ideal" blast wave.

Converting to joules --

$$\begin{array}{l} 3.325 \times 10^6 \text{ kcal} \\ \times\ 4.19 \times 10^3 \text{ J/kcal} \\ \hline E_{tot} = 1.392 \times 10^{10} \text{ J} \end{array}$$

$P_o = 1$ atm $= 101325$ N/m^2 (ie, Pascals)

So $$a = \left(\frac{1.392 \times 10^{10} \text{ J}}{101325 \text{ N/m}^2}\right)^{1/3} = \underline{\underline{51.6 \text{ m}}}$$

Take $R = 280$ m ; $R^3 = 21952000$

The initial volume of the cloud

$$V_o = \frac{2500 \text{ Kg } CH_4}{0.66635 \text{ Kg/m}^3} = 3752 \text{ cu meters}$$

Assume the final exploded volume is a hemisphere with radius increased by factor of 1.8 by expansion:

$$V = (1.8)^3 V_o = 5.832\ V_o = 21882 \text{ cu meters}$$

Then $$\lambda = \frac{(R^3 + V)^{1/3}}{a} = \frac{(21952000 + 21882)^{1/3}}{51.6} = \frac{280.09 \text{ m}}{51.6 \text{ m}} = \underline{\underline{5.43}}$$

Using this value of λ, the extrapolated $\Delta P_s \cong 0.035$ atm $\cong 0.5$ psi

The dynamic pressure would be some two orders of magnitude smaller.

(end)

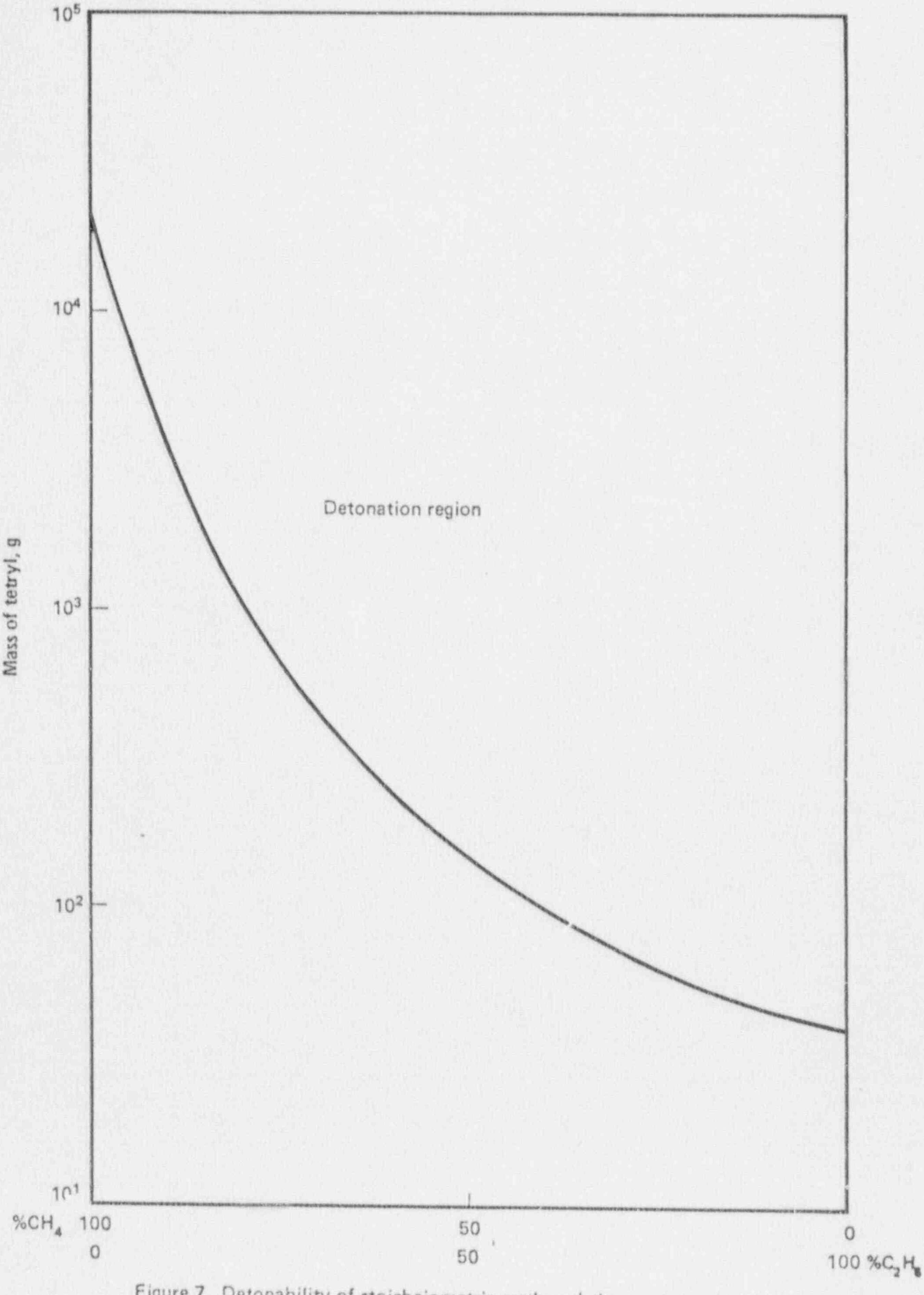
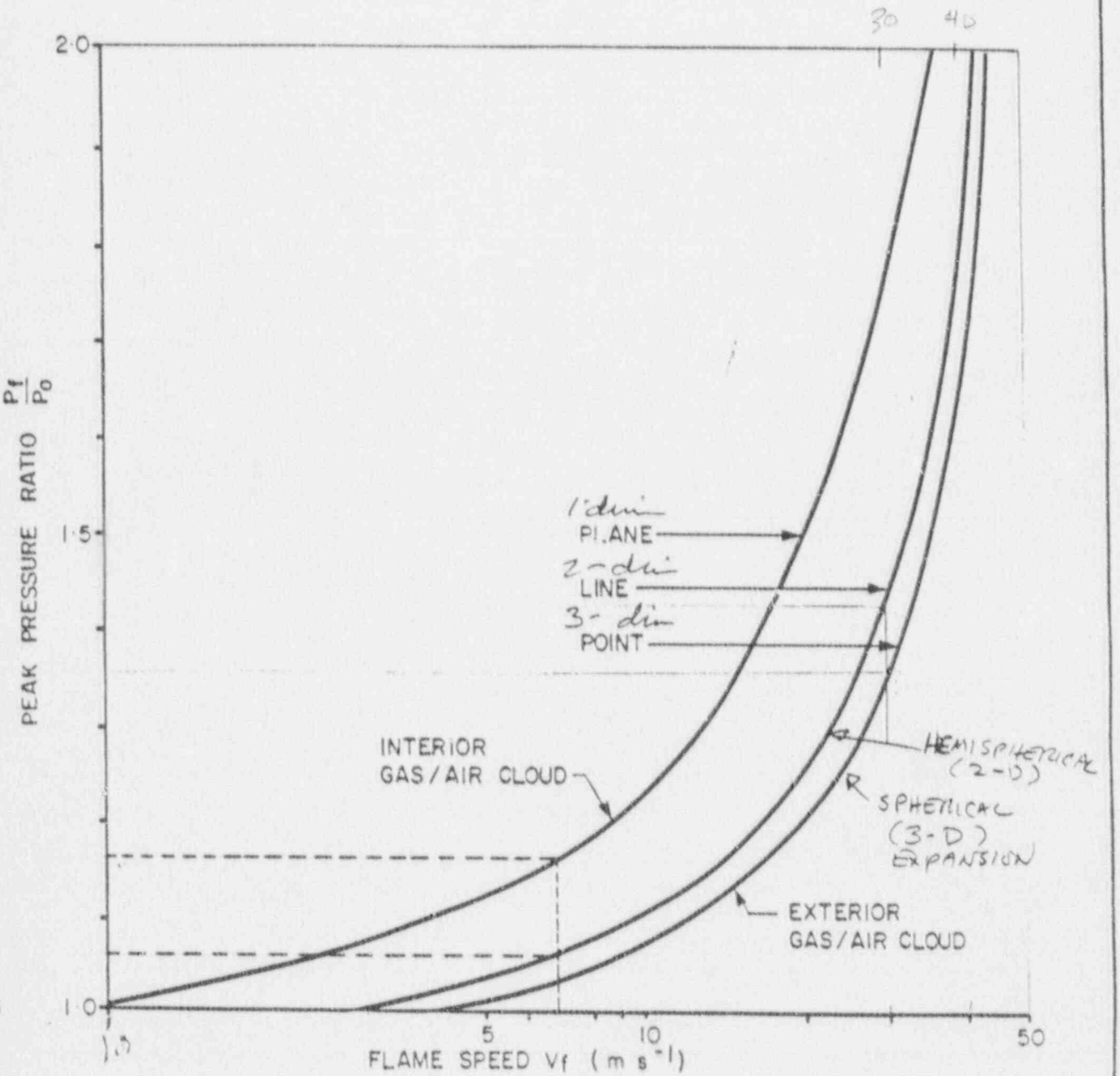


Figure 7. Detonability of stoicheiometric methane/ethane mixtures with air



A FUNCTION OF BURNING RATE FOR DEFLAGRATION EXPLOSIONS IN A UNCONFINED VAPOUR CLOUD

CLIENT

Kanury, A.M (1975)

This equation shows that an increase in the flame speed would result in a higher space heating rate. Rendering the flames turbulent, the flame speed may be increased far beyond the fundamental (i.e., *laminar*) flame speed. Added to this, the flame surface area is greatly increased by turbulence as it multilates, folds and often breaks up the flame front. The result is a greatly exaggerated space heating rate.

The effect of turbulence on flame propagation was discovered quite accidentally. Experiments using tube method indicated that the "fundamental" flame speed measured in tubes of larger diameters is larger. This was later realized to be a consequence of turbulence which increases with an increase in tube size. Note here must be made, however, that once turbulence is triggered on, what indeed we measure is no longer the "fundamental flame speed" whose definition requires the flame to be laminar. While the fundamental flame speed is a characteristic property of the reacting mixture alone, the turbulent flame speed (hereafter called burning speed, in order to distinguish it) depends upon the dimensions of the tube as well. Transport of heat and mass in laminar flames occurs by molecular diffusion phenomena. In turbulent flames, however, eddy mixing which is a function of geometry contributes to this transport.

Referring to Chapter 3, turbulence is characterized by the eddy size—large or small scale—and the mixing length. The eddy diffusivity ε is a measure of the mutual interaction among the eddies in the same manner as the kinematic viscosity ν is a measure of the molecular interactions. ε is known to be approximately proportional to the Reynolds number in tube flow. (Refer to Chapter 7.) Transition from laminar to turbulence is expected in tube flow if Reynolds number ($\equiv \rho u d/\mu$) is greater than 2,300. Thus, flow in a tube becomes turbulent if the tube size or the flow rate is increased.

Figure 8.24 shows Damkohler's (Bunsen burner) measurements of flame speed at various Reynolds numbers. He found that the flame speed is (a) independent of Reynolds number when $Re < 2{,}300$, (b) proportional to the square root of Reynolds number in the range $2{,}300 \lesssim Re \lesssim 6{,}000$ and (c) proportional to the Reynolds number if $Re \gtrsim 6{,}000$. Obviously, only item (a) above obeys our definition of the *fundamental* flame speed; items (b) and (c) are influenced by turbulence and hence the measured flame speeds depend on geometry and flow. Denoting the turbulent flame speed by the symbol S_T, Damkohler explains his measurements as following.

(a) *Small Scale Turbulence*

In the range $2{,}300 \lesssim Re \lesssim 6{,}000$, turbulence is of fine scale; that is, the eddy size and mixing length are much smaller than the flame front thickness. The

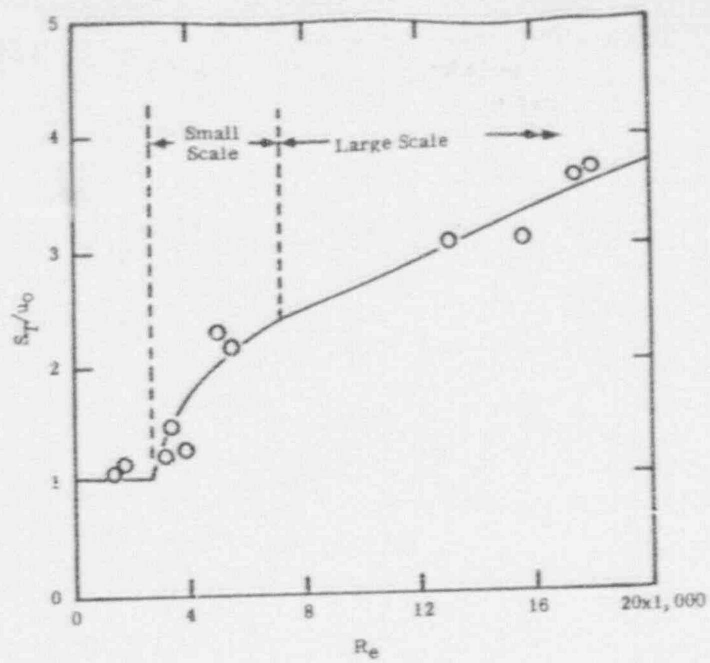


Figure 8.24 Effects of Reynolds number on the flame speed (from G. Damkohler, *Zeit. Electrochem.*, **46**, p. 601, (1940))

effect of these fine scale eddies is to enhance the intensity of transport processes within the combustion wave. Under these circumstances, transport of heat and species is proportional to the eddy diffusivity ε rather than the molecular diffusivity D_i (or $K/\rho_s C$). Equations 8.15 and 8.16 indicate that the flame speed is directly proportional to $\sqrt{K/\rho_s C}$ or $\sqrt{D_i}$. Hence it is logical to expect the burning speed, of a small scale turbulent flame, to be proportional to $\sqrt{\varepsilon}$. Thus

$$\frac{S_T}{u_0} = \left(\frac{\varepsilon}{K/\rho_s C}\right)^{1/2} \approx \left(\frac{\varepsilon}{D_i}\right)^{1/2} \approx \left(\frac{\varepsilon}{\nu}\right)^{1/2}$$

From Section 7.6, $\varepsilon/\nu \approx 0.01$ Re for flow in a tube. Therefore,

$$\frac{S_T}{u_0} \approx 0.1\,\mathrm{Re}^{1/2} \tag{8.18}$$

This equation indeed predicts the trend of Damkohler's small scale burning speed measurements.

(b) *Large Scale Turbulence*

When Re $\gtrsim$ 6,000 the turbulent eddies are large, of dimensions comparable with the tube diameter, much larger than the laminar flame front thickness. These eddies do not increase the diffusivities as the small scale eddies do, but they distort the otherwise smooth "laminar" flame front as shown in Figure 8.25. The influence of these folds in the flame front is to *increase the flame front area* per unit cross section of the tube. As a consequence, the apparent flame speed is increased without any change in the instantaneous local flame structure itself. Damkohler estimated to show that the increase

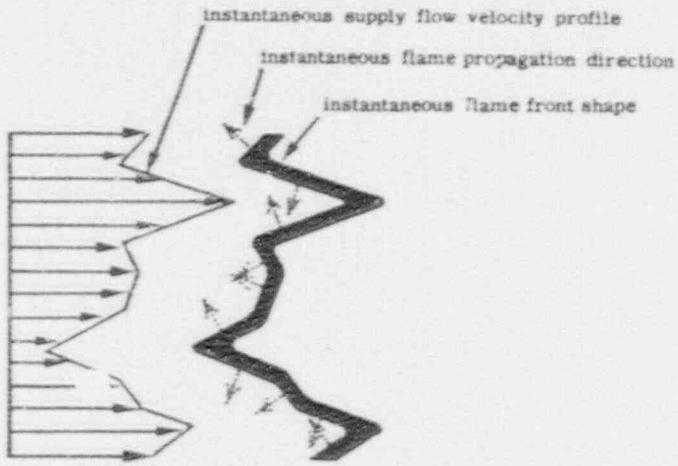


Figure 8.25 An exaggerated view of the turbulent flame front

in surface area is proportional to the characteristic wrinkle (fold) size which is proportional to the magnitude of velocity fluctuation (i.e., of turbulence intensity). Since ε is proportional to the product of intensity and mixing length and since $\varepsilon/\nu \approx 0.01$ Re,

$$\frac{S_T}{u_0} \propto \text{area} \propto \text{fluctuation} \propto \varepsilon \propto \text{Re} \tag{8.19}$$

This explanation describes Damkohler's large scale burning speeds quite satisfactorily.

It is possible to conceive that at very high Reynolds numbers the turbulence may get so intense that the wrinkles and folds in the flame front ultimately end up breaking the front. The resultant "pieces" (islets or lumps) of flame may now jump ahead of the mean flame location into the fresh gas and conversely, lumps of the fresh gas may jump into the flame. This situation is extremely complex and at present our understanding of it is too sketchy.

8.8 Flame Stabilization

In order to accomplish large thrusts in a turbojet or a ramjet engine, the supply velocity of the reactant mixture is desired to be extremely high; it is not unusual for this velocity to be as high as ten times the maximum possible turbulent flame speed of a given mixture. Experience shows that the flame is blown away when the supply velocity exceeds the flame speed. The maximum supply velocity with which fresh mixture may be brought to the flame front without blowing it away is known as *blow-off velocity*. This important limiting velocity depends upon a host of factors which includes the nature of the fuel and oxidant, their ratio, mixture temperature, combustion chamber pressure, turbulence in the approach stream, burner geometry, burner wall roughness temperature, etc.

(a) *Stability of a Bunsen Flame*

Figure 8.8 indicated the mechanism which determines the shape of a Bunsen flame. Based upon this simple mechanism we can explain the phenomena of blow-off and flash-back. Figure 8.26 shows flame speed and normal component of the supply velocity u_{sn} in four different situations. Only the region

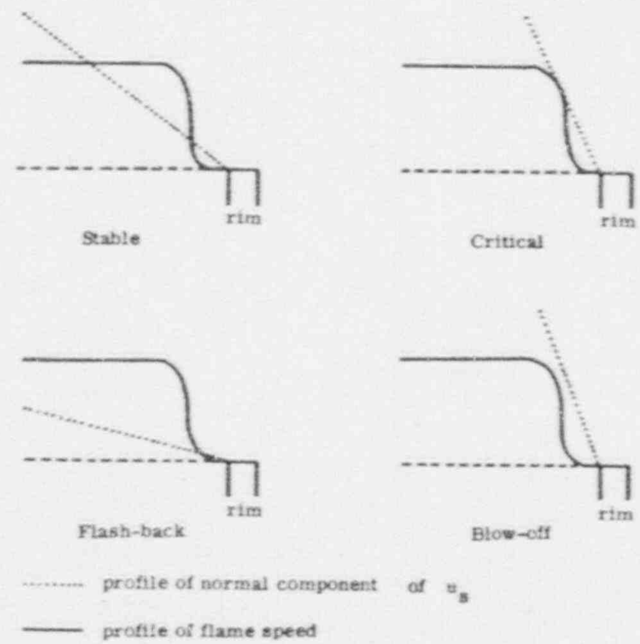


Figure 8.26 Stability of a flame front near a wall

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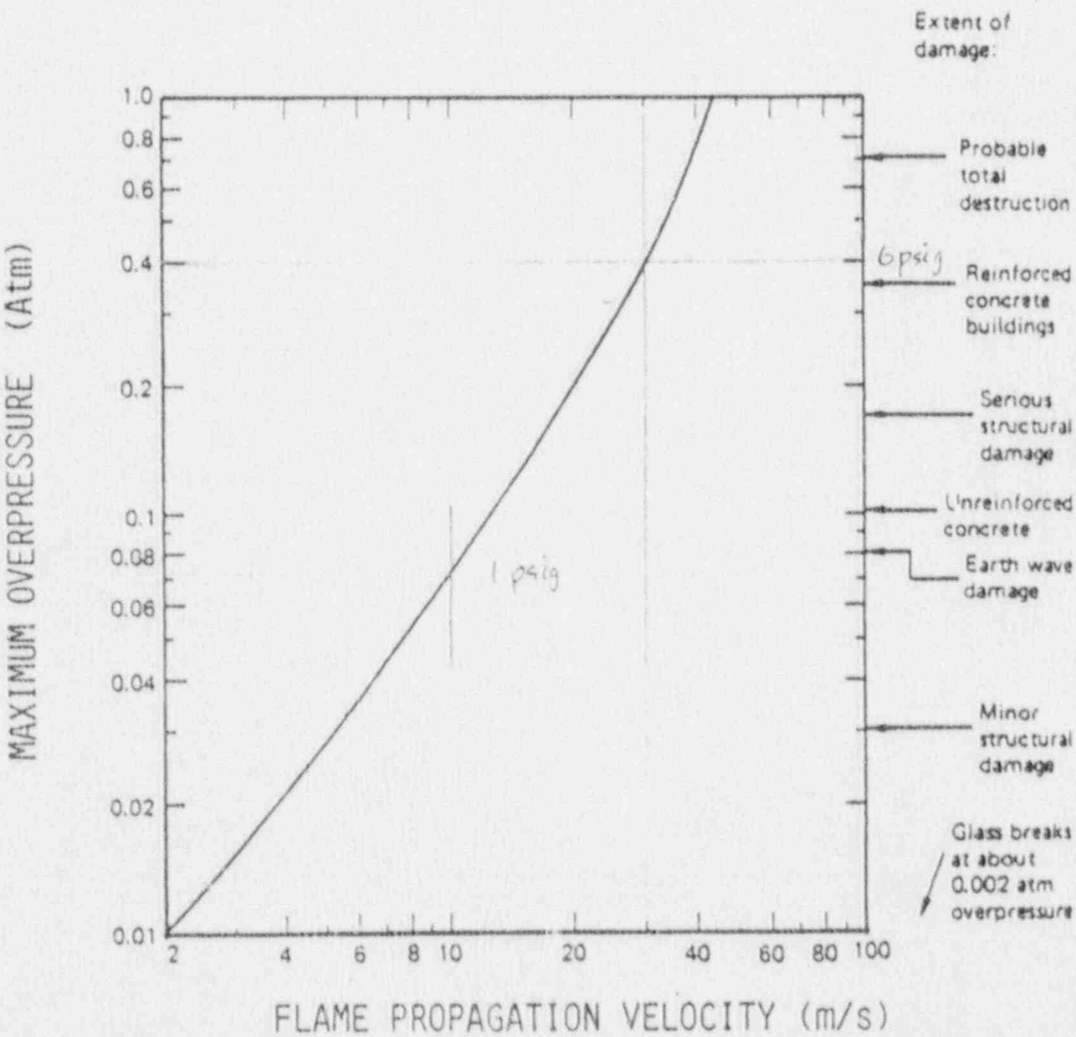

Figure III-8: Maximum Overpressures Developed at Various Flame Speeds in a Vapor Cloud

ratio, and cloud temperature are a few. I will discuss only the first three.

Laboratory experiments at McGill University, LLNL, and elsewhere have shown that flame speeds can increase under the influence of partial confinement and turbulence. Figure III-15 shows the results of these experiments. These data show that flame speeds can increase dramatically, but confinement seems to have much more influence than turbulence.

In the 40 m^3 vapor burns we conducted at NWC, flame speed was one variable we paid close attention to. Table III-10 shows the boundary conditions of each of the vapor burn tests. Times given are all measured from the beginning of the spill. Four techniques were used to measure flame speed: (1) high speed optical cameras; (2) side-on infrared imagery; (3) overhead infrared imagery; and (4) in-situ vapor burn sensors. All data has not been analyzed as yet and therefore the results I will give are preliminary.

In the Coyote 3, 5, 6, and 7 experiments, good flame velocity measurements in the downwind direction were obtained from the side-on infrared cameras. The wind speeds in these four experiments were 5.8, 10.0, 4.6, and 6.0 m/sec. The average downwind flame velocities were 12.6, 16.4, 11.9, and 18.9 m/sec respectively. If we subtract the wind velocity from these numbers, we obtain flame velocities relative to the air of 6.8, 6.4, 7.3, and 12.9 m/sec. That is, the velocities were all around 7 m/sec, except for the last experiment, when it was almost twice that. It must be noted that the field of view of the infrared imager differed from experiment to experiment, so we should not yet draw general conclusions. In the only flame pressure measurement we performed, the results from Coyote 6 showed pressures of about one millibar.

The overhead IR imagery on Coyote 6 and Coyote 7 allows us to follow the flame front in both the upwind and the downwind directions. We see the data plotted in Figure III-16. Velocities appear to be very high near the

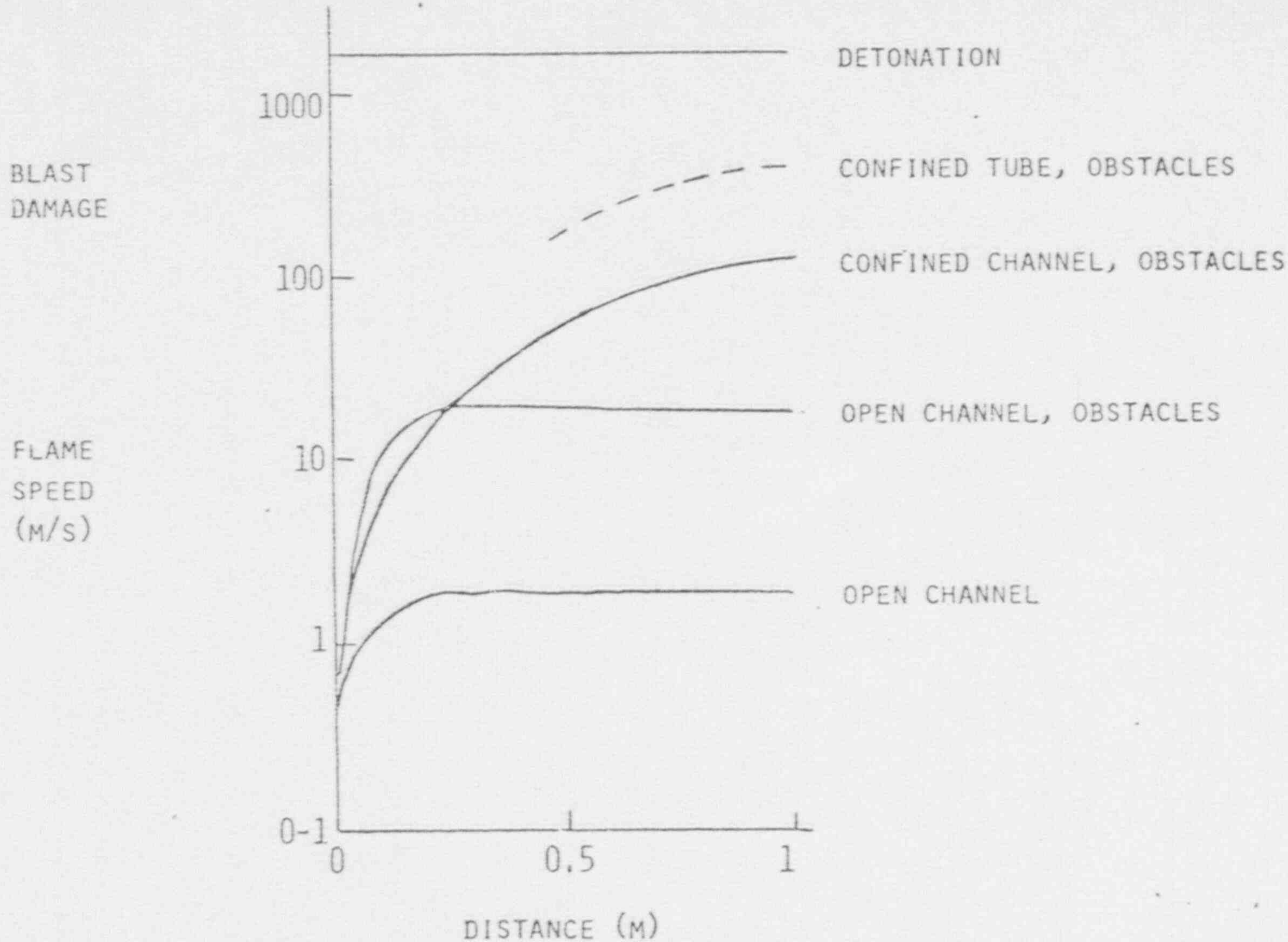

Figure III-15: Effect of Confinement and Obstacles on Vapor Fire Flame Speed

Table III-10: Summary of the Lawrence Livermore National Laboratories' Vapor Burn Tests

Coyote Test Number	Date	Material Spilled (% CH_4)	Spill Date (m^3/min)	Spill Duration (min)	Wind Speed (m/s)	Ignition Source	Ignition Time (min)
2	8/20/81	70	16	0.5	5.9	FLARE	1.2
3	9/02/81	79	14	1.1	5.8	FLARE	1.7
5	10/07/81	75	17	1.6	10.0	FLARE	2.0
6	10/27/81	82	17	1.4	4.8	FLARE	1.9
7	11/12/81	99.5	14	1.9	6.0	JET	2.4

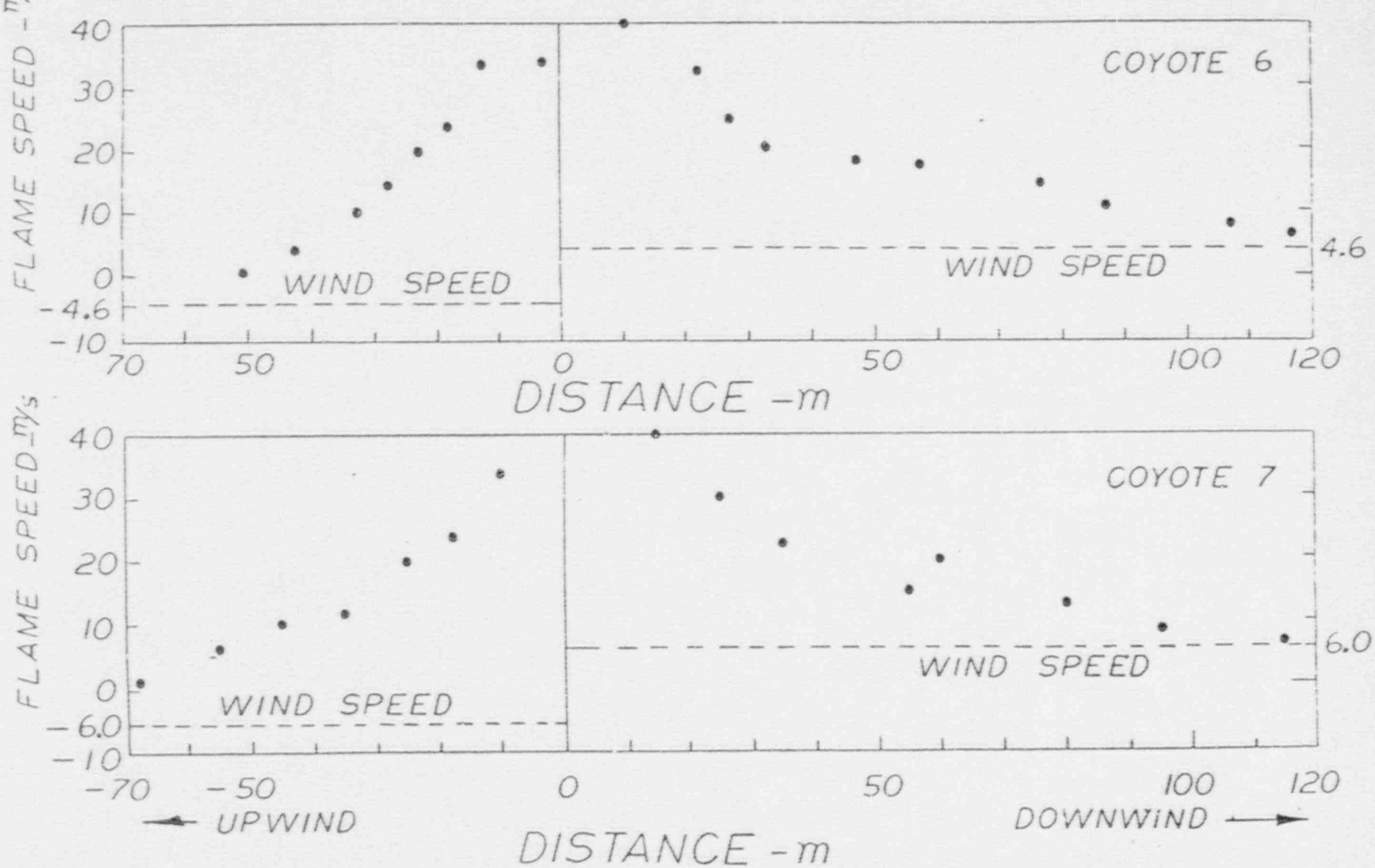

Figure III-16: Variation of Flame Velocity Upwind and Downwind of Ignition Point with Time

ignition source (whether it is a jet or a flare) and to fall off rapidly as the flame moves away from the source in either direction.

While it is too early to draw very broad conclusions about flame speeds two things are clear. We saw much larger flame speeds than did the British at Maplin Sands and our velocities were not at all constant throughout the cloud.

Several questions important to determining possible overpressure damage from flame acceleration remain unanswered. How much confinement and turbulence is necessary to produce damaging flame speeds? Are there realistic cloud sources and geometries that will result in fast flames? Will a fast flame slow down after leaving the source region? How does flame velocity change with cloud size?

d. Thermal Damage

Thermal damage from a fire can be estimated given the area engulfed in flame, the intensity and spectrum of the emitted thermal radiation, and the side-on area of the flame and its speed. Others have addressed issues surrounding the emission of thermal radiation. I will address the shape of the fire.

The fire's shape (i.e., the horizontal area engulfed in flame and width seen side-on) will be determined by the relative values of flame speed, wind velocity, buouancy, and inertia. The balance among these forces may change as a function of cloud size. The pre-ignition 5% concentration contour has usually been used as the horizontal fire area. To see if this is true for clouds produced by 40 m^3 spills on water, we measured the spatial concentration history of the clouds in the Coyote vapor burns up to ignition. We will then compare the total burn area as measured in the overhead infrared imagery to the total area within the pre-ignition 5% contour. The short video clips you see show representative data. It

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EXPLOSION OF UNCONFINED CLOUDS OF NATURAL GAS

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Paper to be presented at the American Gas Association
Transmission Conference St. Louis May 1977

SUMMARY

This work deals principally with explosions and detonations in unconfined natural gas clouds. It reviews the work of others and notes their conclusions that deflagration to detonation transition is unlikely. The particular systems studied and reported concern direct initiation of hydrocarbon/oxygen/nitrogen mixtures and it is noted that initiation of spherical detonation of methane/air mixtures requires about 22 kilograms of Tetryl or its equivalent. Other heavier hydrocarbons are more readily detonable and hence practical natural gases may be expected to exhibit less stable characteristics than pure methane. Nevertheless initiation by the equivalent of about 1 kilogram of Tetryl would be required for most natural gases and with this in mind it is extremely doubtful whether detonation within the confines of buildings represents a sufficiently energetic source to initiate detonation within an unconfined gas cloud.

Thus within the present state of our knowledge it seems that by all mechanisms detonation of unconfined natural gas clouds is extremely unlikely. However, it is not possible to say at this present juncture that detonation cannot occur.

More attention is required to studies of initiation and propagation of detonation in practical unhomogenous gas clouds. Similarly a better modelling is required of the blast potential of other than clouds of artificial geometric shape.

1. INTRODUCTION

It is not the author's intent to present a detailed scientific account of the various circumstances in which natural gas may be made to explode, but rather to state the issues simply attempting to summarise current thinking and to point out areas where presently knowledge is inadequate.

The term "explosion" is generally used for any gaseous expansion which gives rise to audible noise. Hence it may be made by, for instance, LNG spilled on to water, which in some cases with high ethane content gives rise to vapour explosions, or by uncontrolled combustion of flammable gas/air mixture in confined surroundings. These two types of occurrence have been widely studied and it is not the intent to deal with them here, rather this paper will deal with explosive combustion of unconfined clouds of natural gas which might follow leakage from a damaged pipeline or accident involving a spill of LNG.

We have studied the subject of explosions very much with LNG storage, shipment and handling in mind, since the Shell group of companies has for some time participated in LNG trading and wishes to develop it at a time when good supplies of clean gaseous energy are particularly required in many industrialised countries. The reasons for investigation into this subject are, firstly, a need to quantify the extent of hazard following a specified incident and gain some better impression as to the chance of it occurring and, secondly, by study of the mechanisms involved, hopefully to be able to reduce both the chance of an accident occurring and its magnitude should it occur.

Two major incidents are uppermost in many peoples' minds and these are a major collision or grounding involving substantial damage to an LNG carrier and a major accident in an LNG storage installation. One set of "ground rules" for size of disaster to be considered in the former was formulated by the US Coastguard. This requires consideration of one cargo hold lost instantaneously. For land storage the NFPA 59A regulation sets the maximum credible accident as the complete failure of the largest through wall connection to a storage vessel. In this case modern high bunded storage configurations employing insulating concretes and, if necessary, fire fighting foams can reduce vapour evolvements and disperse it in flammable concentrations within the property limits. Clearly it would be desirable to move the product to an undamaged storage vessel if this were available, but if this were not so it would be tempting to consider a suggestion put forward by Sliepcevich (1) to deliberately fire the spill if this could be done with safety. The idea of firing a spill before a large hazardous vapour cloud has time to develop is even more tempting in the case of major damage to an LNG carrier, as here no means has yet been developed of limiting the speed of formation of the cloud. However, there are obvious problems which have yet to be overcome concerning the safe evacuation of the carrier crew and also the crew of any other vessel involved in the collision. Further it must be realised that the time available before mixing produces a dangerous cloud is very short, typically a few minutes, and thereafter this method could precipitate an accident.

We have all read accounts in which the explosive potential of a complete LNG cargo is compared to that of a large high explosive bomb

or even nuclear warhead. Such statements are usually based on calculation of the gross thermal equivalent of the LNG which is then related to the heat release of some quantity of high explosive. This seems to be about as appropriate as grossing up the calorific content of all the natural gas used in the United States annually and on this basis arguing that natural gas usage should be prohibited since it is equivalent to 10,000 megatons of high explosive. Here the argument is clearly taken to extreme, but it does emphasise the point that the gas must be available in the right place at the right time, and mixed with the correct amount of air for an explosion to occur. As will be seen later these conditions do not apply to all the gas involved in a spillage. The next point concerns the speed at which the energy is released, and here we do not intend to dwell on the blast equivalent of gas clouds and TNT explosions, but the issue is largely the mode of burning - will it deflagrate or detonate?

2. DEFLAGRATION

The gas clouds evolved from LNG spills are far from homogenous (see Figure 1). There are many models available for the calculation of the amount of gas in any cloud lying between stated concentrations in air. Shell has developed its own models which are applicable both for gaseous releases as from a pipeline leakage [2,3] or from a pool source [4] and, as a model shows clearly, at any given time only a fraction of the gas is mixed in flammable proportions with air.

Most models give a time average picture and opinions are very much varied as to the likely extent of the variation in peak-to-average gas concentrations at any given point. This is almost certainly a factor of spill size and of the distance of the point in question from the spill source. Figure 2 shows the fluctuations recorded on a highly sensitive instrument in a small gas spill. From the experimental work which we have done, it is clear that dependant largely on the size of the spill, in some circumstances the gravity spreading effects are dominant whereas in others the atmospheric turbulence plays a more significant role.

In calculations regarding major spills, we generally assume that the time average half-LEL contour defines the limit of flammable gas travel. Of course the upper flammable limit contour in no way represents a boundary upon the gas which enters into deflagration. If it were to do so pool fires could not result. The convection currents set up once a flame is burning are sufficient to promote mixing of air with pockets of rich gas so enveloping virtually the whole over-rich portion of the cloud.

Regarding flame speeds, in the small scale LNG spills which we and other experimenters have used involving quantities of a few cubic metres spilled on land or water, the gas has always burned quietly and undramatically despite the varied atmospheric conditions. Not infrequently in small spills the gas fails to light-back to the pool source, either because it fails to ignite or local burn-out occurs.

Although we do not plan to carry out tests at high wind speeds, it sometimes happens that wind develops during test and in these

circumstances we have noted that light-back to the source can occur at gust speeds of about 20 m.p.h. So clearly turbulent conditions prevail and it seems not unreasonable to predict that flame speeds of up to 10 metres per second are possible.

In this connection it is interesting to note the results obtained by others with well mixed methane/air systems in stoichiometric proportions. Lind and Strehlow(5) reported flame speeds of up to 5.8 metres per second horizontally and 7.3 metres per second vertically. We are aware that other workers are presently active, notably those at the Midland Research Station of the British Gas Corporation, and we understand in their comparatively large scale tests, flame speeds of less than 10 metres per second were recorded.

For evidence of higher flame speeds, it is necessary to turn to other workers using more reactive systems. Dorge and Wagner (6) examined acetylene : air combustion. Using a 0.2 metre sided cube, they noted flame speeds of up to 20 metres per second when the mixture was ignited with a weak spark under conditions where high turbulence was generated by use of spherical nets. However the maximum peak over-pressure revealed was 0.2 atmospheres and flame acceleration was not sustained.

Kuhl, Kamel and Oppenheim have given us a model relating flame speed to over-pressure (Figure 3). From this it is clear that pressures at the flame front of methane/air systems are likely to be less than 0.1 atmospheres, with scarcely detectable blast pressures. It is indeed unfortunate that almost without exception experimenters investigating spherical flames have used equipment which is much too insensitive to record the small over-pressures which are generated, and so have missed the opportunity of validating the prediction of the model.

Munday (7) has fitted the damage caused within the cloud to an appropriate flame speed and matched the impulses to the TNT decay curves to align with damage in the far field. Using this or similar methods he and other workers have assigned flame speeds of up to 50 metres per second to violent explsions such as those at Flixborough - which of course involved a cyclohexane.

A survey by Strehlow and Baker (8) of large scale natural gas escapes which was subsequently ignited has shown no evidence of high flame speeds.

3. DETONATION

Thus so far in deliberate tests, or in small scale accidents involving unconfined natural gas clouds, these have burned quietly. However, it is possible to postulate that in very large clouds more violent thermal stirring would occur and hence more vigorous combustion would follow - although the mode by which very high flame speeds would result is far from evident. The real issue is will detonation of a free cloud occur? Conceivably it might follow deflagration or be directly caused by a more energetic sources, such as an explosion.

3.1 Deflagration to Detonation Transition

As has already been mentioned those workers who have investigated

the former mode have come up with very unexciting conclusions. Wagner (9) observed acceleration in propane/air mixtures, but this was not sustained when the turbulence was removed. Boni, Chapman and Cook (10) have reviewed the six distinct processes which Lind and Strehlow have suggested might result in a deflagration to detonation transition and conclude that the presence of a turbulent boundary layer or Rayleigh Taylor instability of the flame front, and buoyancy induced acceleration of large flames are very unlikely mechanisms: neither do they think likely flame acceleration due to other turbulent processes of a fluid mechanical origin. This view is shared by Lee (11) who points out that the turbulent flame speed required for self initiation of fuel/air mixtures is about 230 metres per second compared with laminar flame speeds for most hydrocarbon/air mixtures of the order of 0.5 metres per second.

These workers then, conclude that weak initiation may not be possible. Certainly in order to achieve it, an extremely folded flame front would be required and Lee doubts if this folded structure can be maintained long enough for detonation to occur.

Of the 108 incidents reported by Strehlow and Baker, only one - that at Port Hudson, involving propane, resulted in damage which was considered to be consistent with detonation having occurred. In view of the amount of evidence which has since been accumulated, it seems possible that such damage could be resulted from some lower flame speed followed by focusing of the blast effect.

The workers from Science Applications Inc. have concluded that for deflagration to detonation transition to occur the only plausible mode would involve an explosion within some confined space which would progress to detonation within that space and which then might propagate into the cloud.

3.2 Direct Initiation

So far in discussing deflagration to detonation transition, reference has been made to studies performed by a number of other workers. At Thornton Research Centre most attention has been directed to the alternative mode of detonation initiation - that of propagation from a shock wave established by use of an explosive charge. The first series of experiments has been reported elsewhere (12), but since new data will be presented in this paper, it is appropriate to briefly describe the experimental arrangements.

Well stirred stoichiometric mixtures of methane and oxygen were used with various amounts of nitrogen as dilutant, and detonation was initiated by electrically firing selected amounts of Tetryl explosive. The gaseous mixtures were contained in polythene bags, fabricated from 130 micron polythene sheet of specific weight 130 gm^{-2} and were of uninflated size 1.80m. x 1.80m. or 3.05m. x 1.52m. The gases themselves were of more than 99% purity, no hydrocarbons other than methane were detected and the principal impurity in the methane was nitrogen.

The gases were simultaneously admitted to the test bags in predetermined proportions using integrating gas meters, rotameters and a mixer/flame trap assembly. Thus on entering the bag the gases were saturated with water at ambient temperature. Figure 4 shows a laboratory mock-up of the polythene bag as it was suspended in the bomb chamber at ERDA, Waltham Abbey, (which was made available to us by the Ministry of Defence). A member of their staff assisted in some of the experiments.

The progress of the detonation wave was monitored by use of a microwave Doppler unit operating at 10.687 GHz. This was coupled to a pyramidal brass launching and receiving horn operating to an aperture of 146 mm x 118 mm and again of 16 dB. The horn was fitted with a PTE plug and flexible wave guide coupling to give a measure of protection to the microwave Doppler module. An array of piezoelectric air blast gauges were set on the same (horizontal) plane as the microwave Doppler unit. The gauges were positioned at distances 0.6 m, 1.2 m and 1.6 m from the explosive initiator corresponding to distance of about 1.1, 1.8 and 1.2 m. from the centre of the bag.

At the time the work was planned, the experiments of Kogarko(13) were known and so there was some hope that the full amount of nitrogen could be added to represent methane/air mixtures. However, it soon transpired that more energetic sources were required than had been predicted by Kogarko. Closer examination of Kogarko's experiment revealed that his measurements of detonation velocity were made from time of transit between two piezo gauges set at radii so close to the initiator charge that the latter contributed 22% and 8% of the total wave energy. The experiment was therefore not suitable for determining whether or not the wave was self-sustained as a detonation; the fact that the time of transit velocity recorded was very much below C-J indicates that in all probability it was not. This does serve to underline the importance of ensuring that the experimental path length is sufficient that the wave observed is quite free from effects of the initiator source. For a spherical wave this obviously implies liberation of large quantities of energy. As our experiments were limited by the amount of Tetryl and fuel which it was thought safe to use within the facilities, a technique of "end initiation" shown in Figure 4 was adopted. This allowed a much greater experimental path for any given gas volume and comparative tests with a centrally initiated detonation showed that the position of the initiator had no effect on the measured critical nitrogen content, or the pressure and velocity of the detonation waves.

The experimental method was to use five charges of known weight and size and to determine the limiting nitrogen concentration for detonation to just be sustained. The results are given graphically in Figure 5. As has been intimated earlier, it was not possible to experiment directly with methane/air systems due to the limitations of the experimental arrangements. Limiting nitrogen : methane ratio at which detonation occurred with our largest explosive charge was about 5.5 : 1. The experimental velocity measurements for all of the mixtures accorded well with the calculated C-J values.

Within the experimental range the log of the initiator charge mass to limiting nitrogen concentration relationship is linear and there seems to be no reason from chemical kinetics or thermodynamic considerations why there should be a sudden departure from this. Figure 5 also shows the results in which the bridge wire detonator was used alone as an initiating source. From the characteristics of the blast wave, it appears that this is equivalent to a charge of 0.25 grams of Tetryl. However, the rate of energy deposition is not necessarily the same as for a Tetryl charge. For these reasons the results of the detonator used alone have not been included in calculating the regression line shown on Figure 5.

As the figure clearly shows, the projection of the straight line relationship indicates that more than 20 kilograms of Tetryl would be required to initiate a spherical detonation in a stoichiometric mixture of methane/air. The work also points to the long path length (11 m.) which would be required in any experimental verification of the extrapolation.

In more recent work the amounts of tetryl required for initiation of detonation in stoichiometric mixtures of other hydrocarbon fuels with air have been directly determined using the same experimental method, and these are shown in Figure 6. The extreme stability of methane in comparison with these other hydrocarbons is clearly demonstrated as might be expected from a compound with its particular atomic structure and relative inertness as exemplified by a high minimum auto-ignition temperature and high octane number. The amount of Tetryl required to initiate detonation of methane is more than two orders of magnitude greater than that for the other saturated paraffin hydrocarbons and more than three orders of magnitude greater than that for ethylene.

Inevitably such a result must raise questions about the probable behaviour of natural gas as opposed to pure methane. Natural gas is of course not a single substance which may be defined chemically, but commonly contains varying amounts of higher hydrocarbons than methane according to its origin and the treatment to which it has been subjected. It might be supposed that these smaller amounts of higher hydrocarbons would effectively "seed" the detonation and hence promote detonation in the whole gas.

The Thornton team has therefore carried out a few supplementary experiments, which are still continuing, on simulated natural gas mixtures. In Figure 7 the figures for methane/ethane mixtures have been shown which would appear to confirm this supposition. It is intended to extend this work into mixtures containing hydrocarbons other than ethane, but from the evidence produced in Figure 6 there is little reason to suppose that, for instance, propane will behave in manners significantly different to ethane and hence the data presented on Figure 7 may be considered to a first approximation as methane admixed with such higher hydrocarbons as are likely to occur in natural gas.

At this stage it is appropriate to return to the question left unanswered at the beginning of this section; namely the possibility of detonations, originating in confined spaces, propagating into

free clouds of natural gas and hence initiating detonation therein. From the data presented in Figure 7 it is clear that an explosive source equivalent to at least 1 kilogram of Tetryl would be required to initiate such a detonation in most natural gases. At this present juncture it seems to be generally accepted that the critical conditions for the initiation of a detonation cannot be wholly defined by critical energy considerations alone nor even by some refinement which considers the application of power density to unit volume. With such reservations in mind and accepting the imperfection of our understanding, it appears that any explosion within a confined space, which might be relieved by the destruction of windows or even of the building itself, is most unlikely to provide the energetic source required.

It is conceivable, however, that detonation in more confined surroundings which could generate higher pressures as, for example, in processing plant, could lead to the sufficiently energetic sources to trigger detonations in free gas clouds.

In the previous section when considering deflagration, reference was made to the highly structured nature of unconfined gas clouds as exemplified in Figures 1 and 2. Certainly not all the gas lies within the flammable limits and the proportion which does is a function of time. When dealing with detonation, however, we are not concerned with gas within the flammable limits, but rather with gas within a narrower band. Only gas lying within these detonation limits will contribute to detonation since the time scale of events is insufficient to permit spectral changes.

Again, due to the limits imposed by the test equipment, it has not been possible to determine the amount of initiator required to promote direct detonation over a range of concentrations of methane in air. However, this has been done for ethane/air and the results are illustrated in Figure 8. There is no reason to suppose that the shape of curve would be markedly different considering methane/air and for normal natural gases it may well be argued that the higher hydrocarbons effectively determine the sensitivity to detonation. From the ethane/air curve the heavy dependance upon stoichiometry will be seen and it will be noted that the amount of initiator required varies by almost two orders of magnitude according to stoichiometry. Thus considerable amounts of energy will be required to initiate detonation in gas mixtures lying at the extremes of the detonable limits.

With these considerations in mind, there is clearly some uncertainty as to the amount of gas in any unconfined gas cloud which will contribute to detonation. In any one selected area only the amount of gas lying within the detonable limits will contribute. The question is, however, can such detonations propagate through discontinuities to other areas lying between these same detonation limits and cause sympathetic explosion.

A subsidiary question which arises is therefore "If these discontinuities cause the wave to decay, to what level can it decay before it is no longer able to re-establish itself, when it once again encounters a detonable mixture? In this context

measurements were also made with critical initiation of ethylene/air which like those of Brossard and Edwards on acetylene/oxygen/nitrogen and propane/oxygen/nitrogen systems, respectively, indicate that there exists under conditions just critical for initiation, a region after the major decay of the very intense shock from the initiator where the average velocity of the wave is below the steady state Chapman-Jouguet value. These results are illustrated in Figure 9 where it may be seen that the reaction front velocity falls to a minimum of approximately one-third of the Chapman-Jouguet value before attaining a steady state velocity similar to that projected by the Chapman-Jouguet calculations. From this work it therefore appears that knowledge of the behaviour of a detonation under conditions marginal to its propagation coupled with better information concerning the instantaneous concentration of fuel in air within a gas cloud will define whether propagation of detonation through a spillage cloud is possible, and under what range of conditions the possibility could exist. It will also help to indicate the proportion of the fuel likely to be detonated and the nature and extent of the blast wave produced by the detonation.

4. DAMAGE POTENTIAL

The concept of a TNT equivalent of a gas explosion has in the past been useful as it gives some impression of equivalence. It is generally accepted, however, that this model must be used with considerable reserve, particularly when applied to the near field.

In practice as has been seen from Figures 1 and 2, the unconfined gas clouds originating from LNG spills are inhomogeneous disc-like in appearance, viz they are thin compared to their diameter. Some models treat these as well mixed hemispherical clouds for mathematical convenience. In practice the energy liberated in the wave will parallel the inhomogeneities. Further, there is bound to be considerable interference from waves leaving the thin disc and, therefore, present analysis of the blast effects within the cloud and in the far field are sadly very deficient.

5. REMEDIAL ACTION

Although this work has been proceeding for a period of about two years there is clearly much still to be done and our understanding of the mechanisms involved is very imperfect. It has already been seen that large gas clouds are very lumpy and badly mixed and there is some question as to whether detonation can proceed throughout the whole mass gas lying within the detonation limits. This, therefore, suggests that if some mechanism can be found to break up the gas it may be possible to use such discontinuities to reduce the blast effect caused should a detonation ensue.

From Figure 6 it is apparent that the tendency of gases to detonate is a strong function of their chemical reactivity. It is well known that the methyl halides act as combustion suppressants by inhibition of the chemical kinetic properties. It was therefore hoped that they would be effective in suppressing detonation. The very limited amount of work which has been carried out to date in this area has proved disappointing. These methyl halides have acted in the same way as any

inert material such as nitrogen and therefore we must return to more fundamental studies and look elsewhere for solutions. It remains our hope however that some substance may be found which will prove an effective detonation suppressant and which may be safely and quickly spread on any major gas spillage.

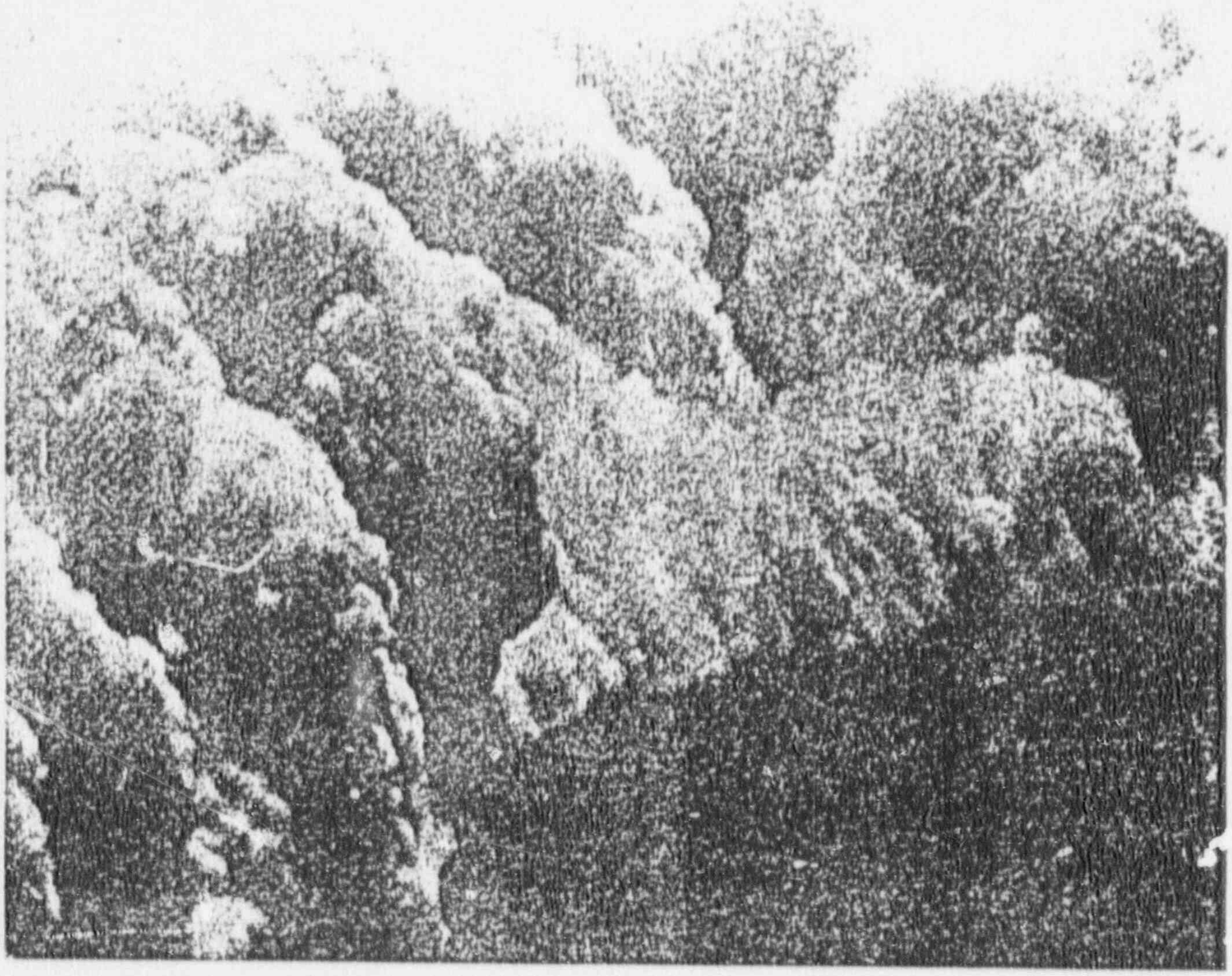

Figure 1. Gadilla Jettisoning Trials: Portion of gas cloud

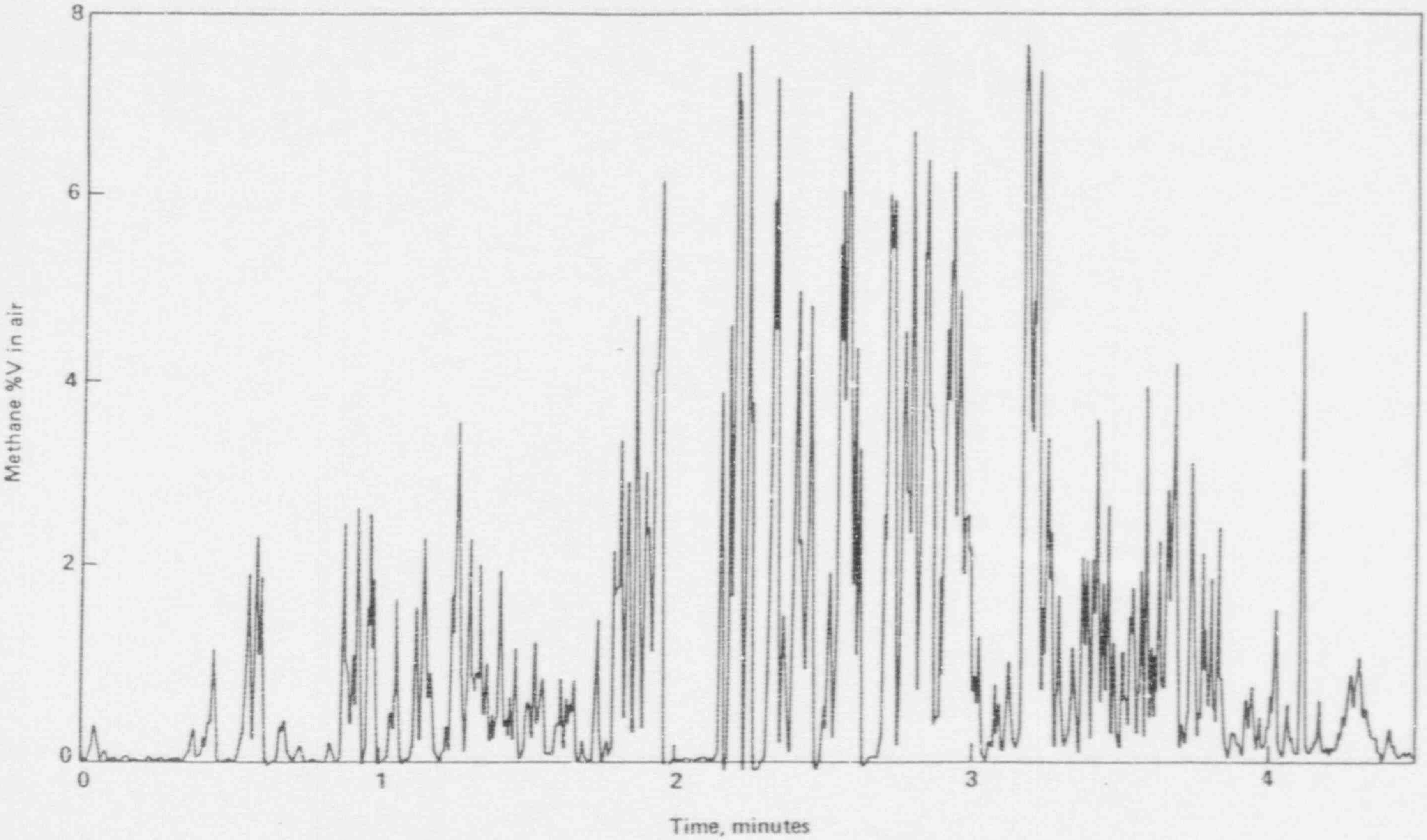

Figure 2. Methane concentration at single sample point in small spillage cloud

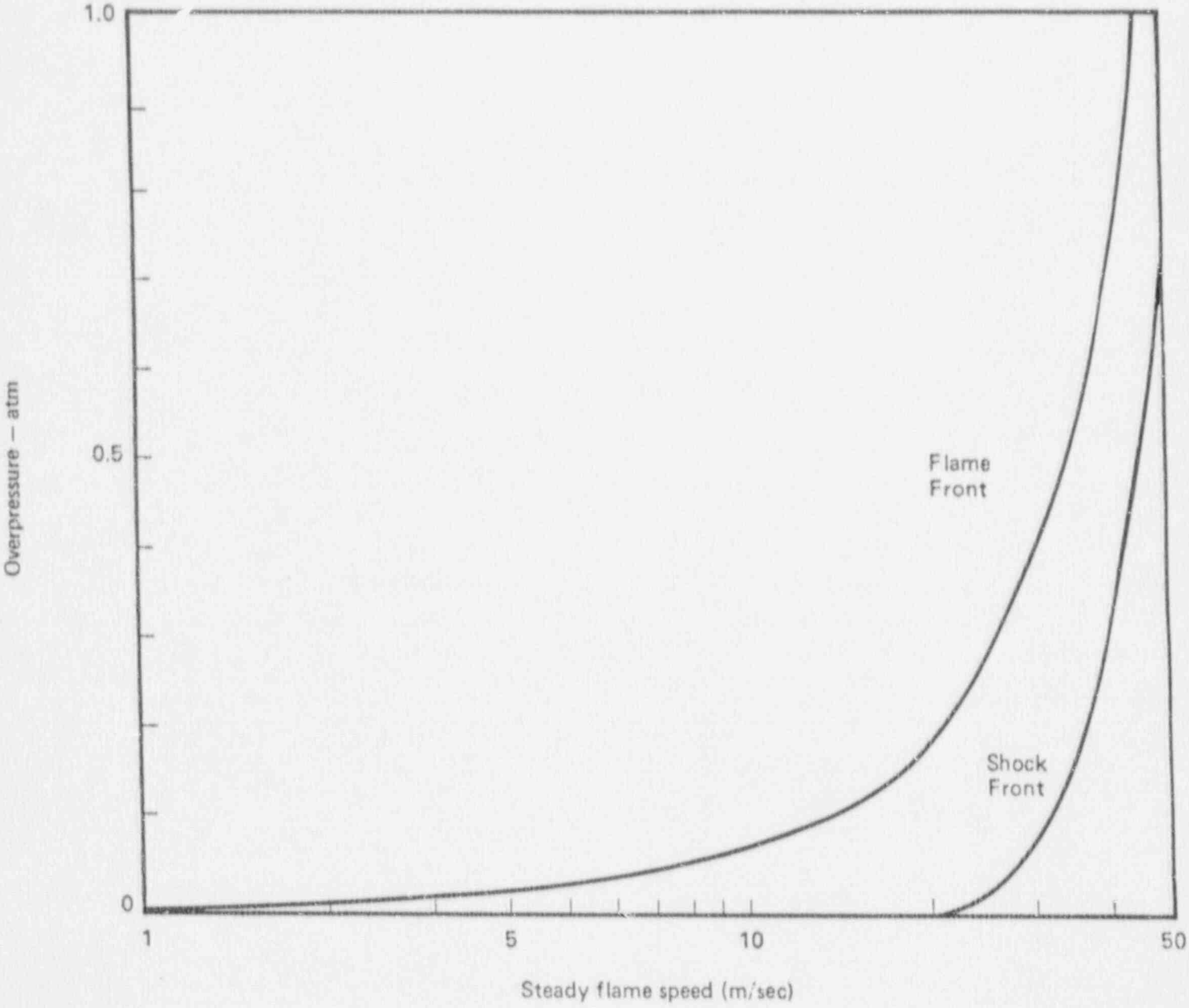

Figure 3. Flame and shock overpressure as a function of burning speed for a spherical flame (Oppenheim)

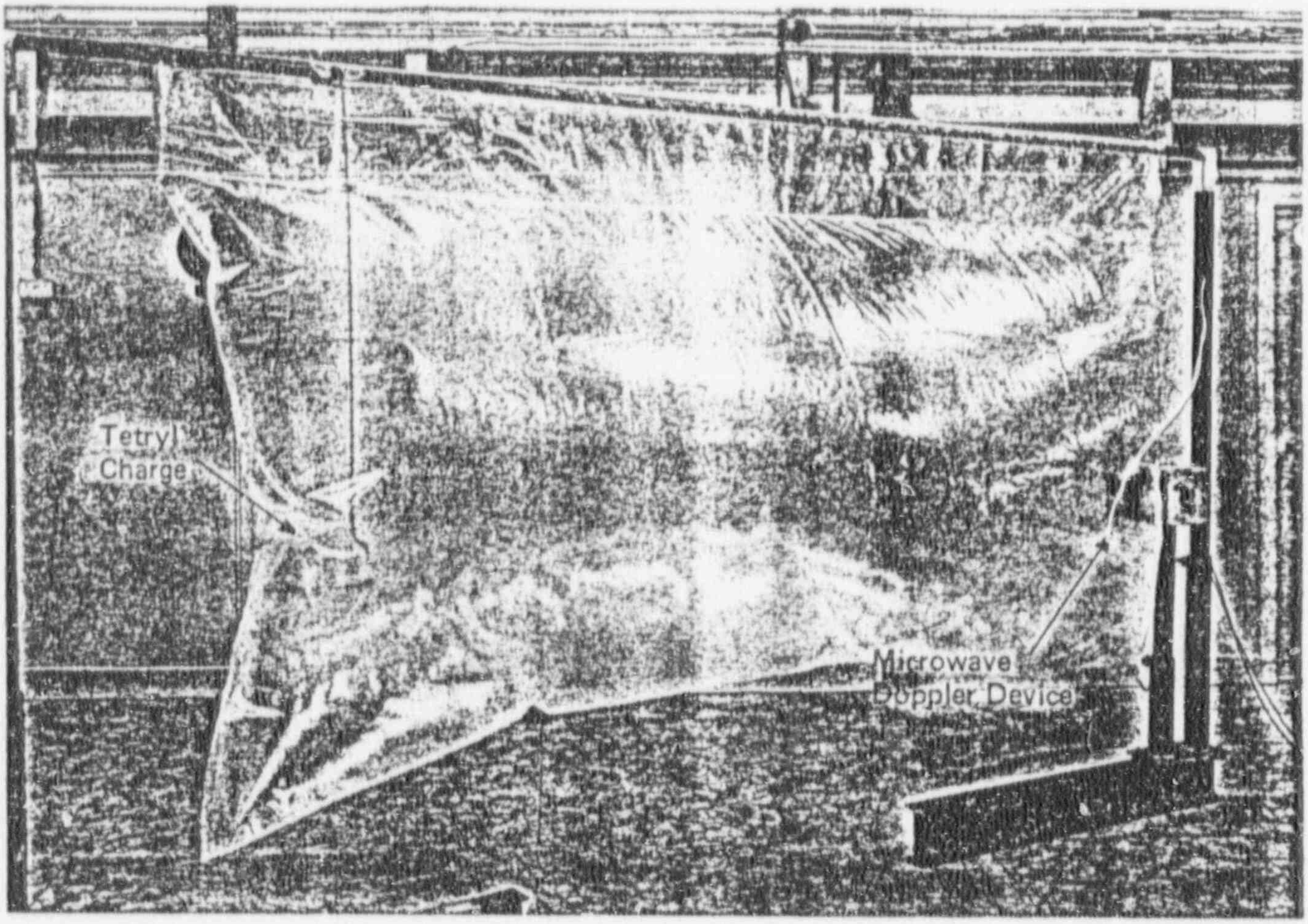

Figure 4. Test arrangement for direct initiation detonation trials

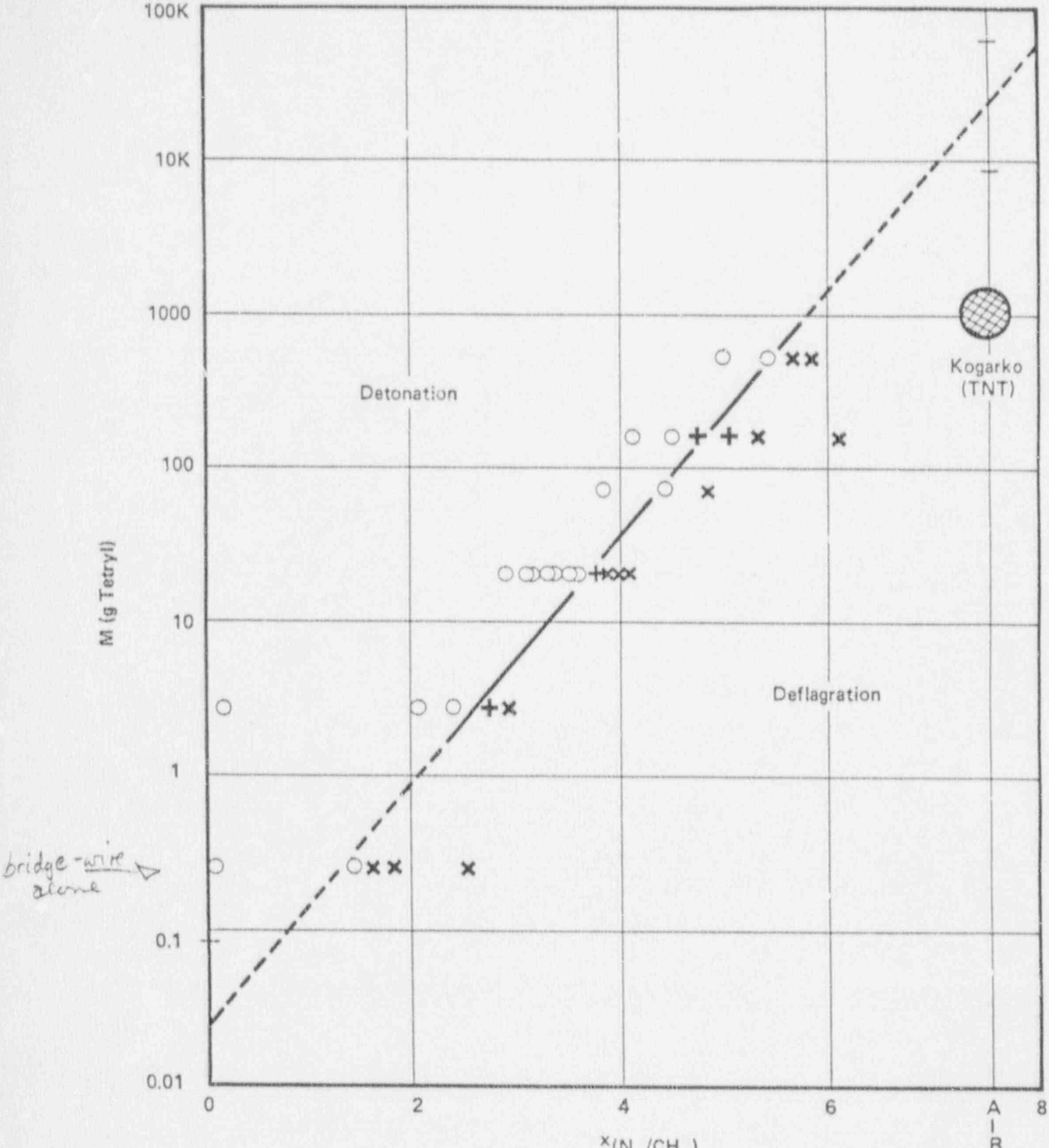

Figure 5. Detonability limit of $CH_4 + 2O_2 + xN_2$ in the (x,M) plane

○detonation established (microwave and pressure); ✖ detonation failed; ✚ pressure records indicate detonation, but microwave interferograms do not, 95% confidence limits to regression extrapolation

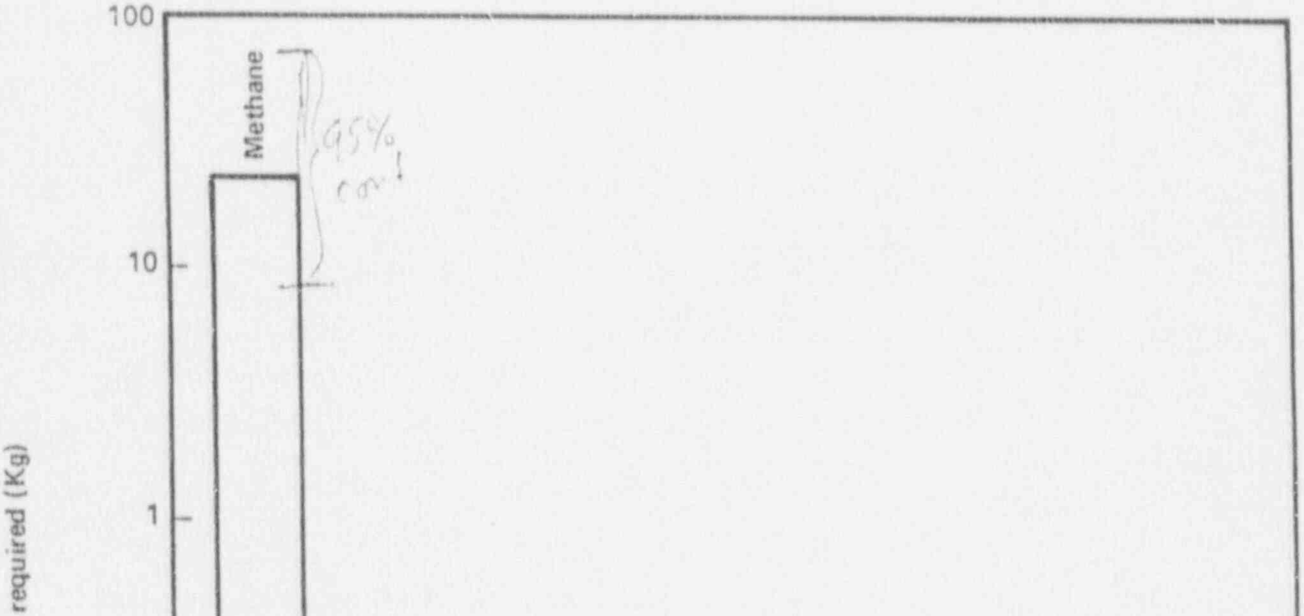

Figure 6. Relative detonabilities of Fuel/Air mixtures

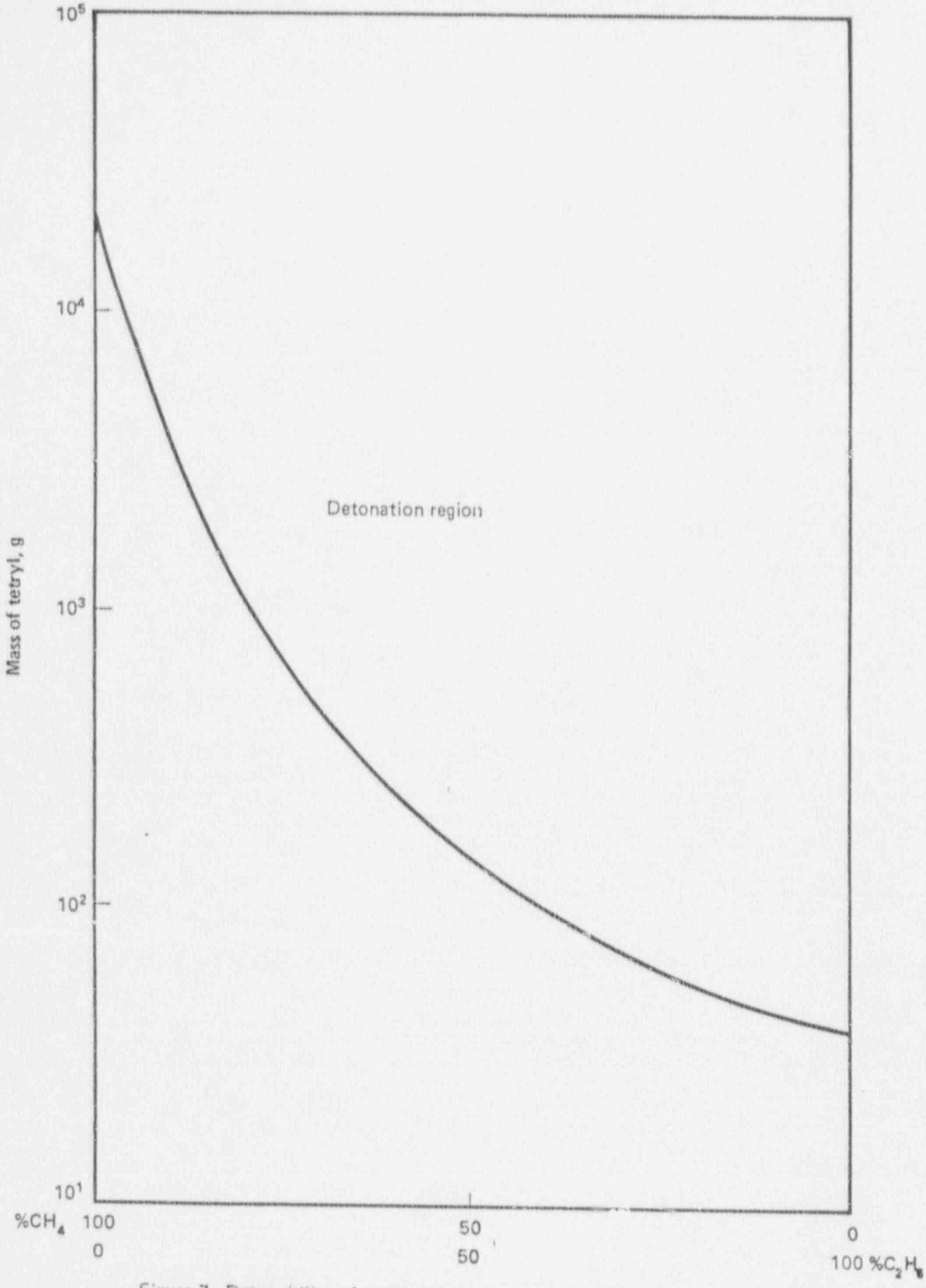

Figure 7. Detonability of stoicheiometric methane/ethane mixtures with air

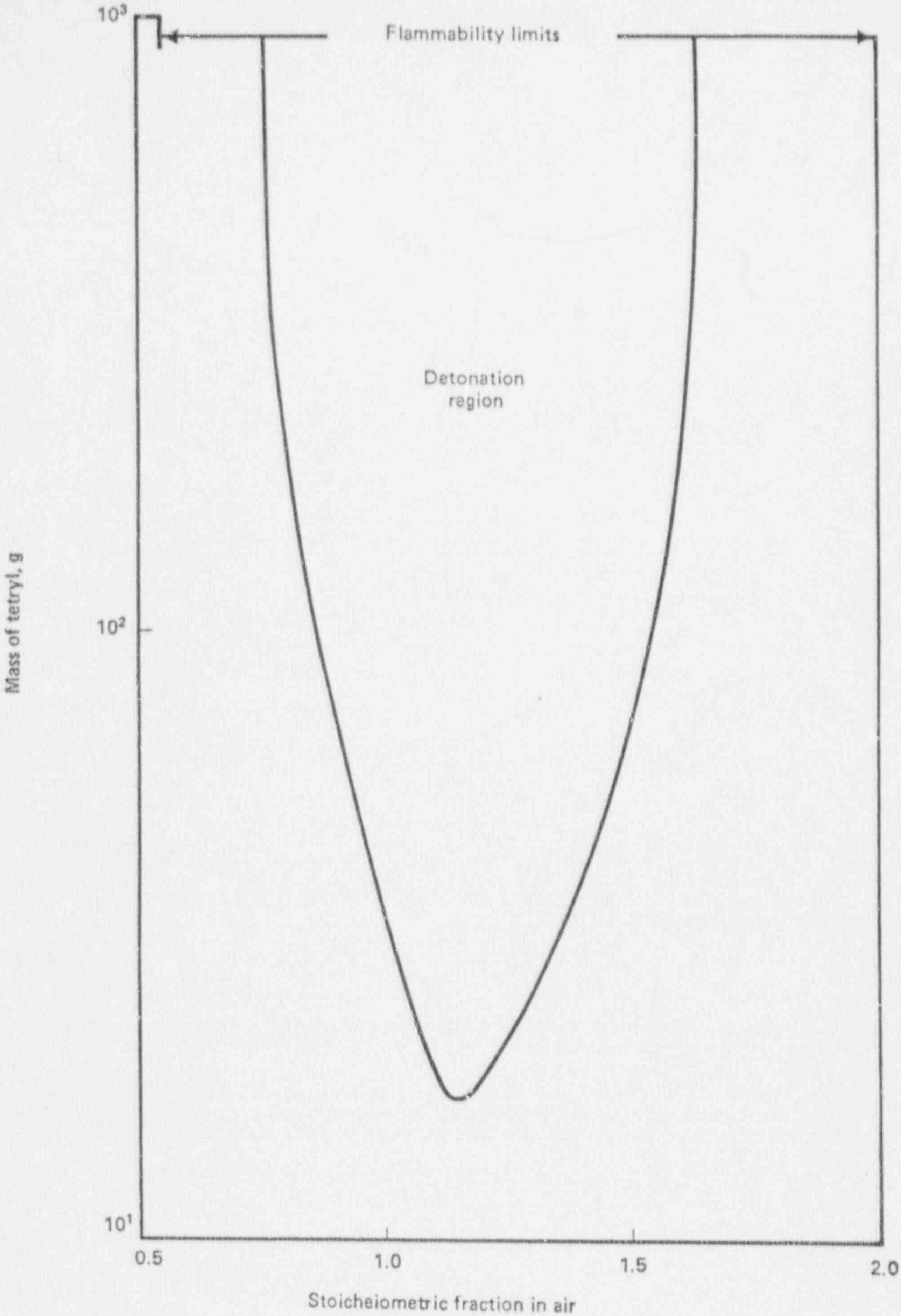

Figure 8. Ethane/air detonability

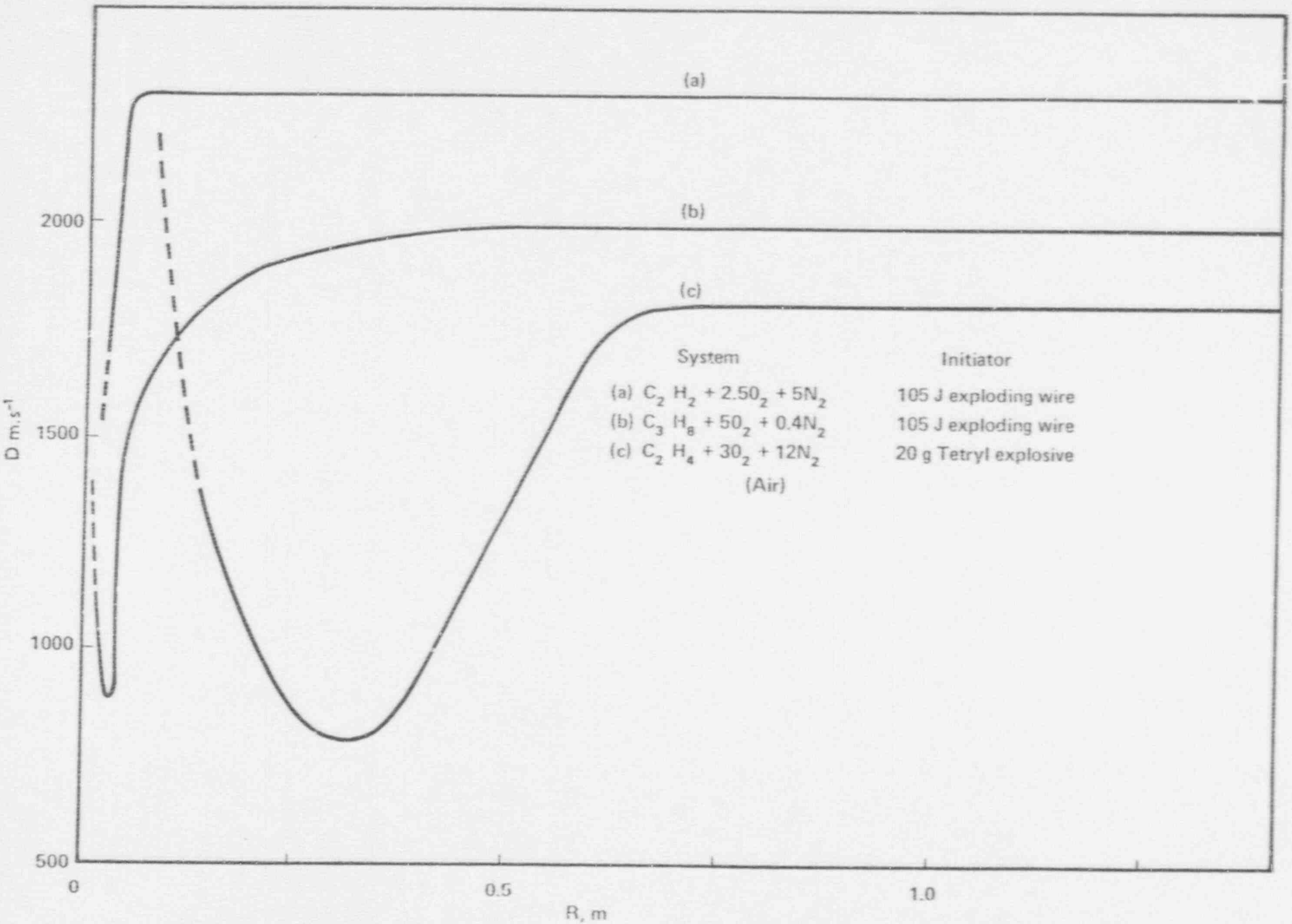

Figure 9. Reaction front velocity/radius plots for critical initiation of spherical detonations

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From Glasstone and Dolan - 1977

3.50 Somewhat related to the condition of the surface are the effects of objects and material picked up by the blast wave. Damage may be caused by missles such as rocks, boulders, and pebbles, as well as by smaller particles such as sand and dust. This particulate matter carried along by the blast wave does not necessarily affect the overpressures at the shock front. In dusty areas, however, the blast wave may pick up enough dust to increase the dynamic pressure over the values corresponding to the overpressure in an ideal blast wave. There may also be an increase in the velocity of air particles in the wave due to precursor action. Consequently, the effect on structures which are damaged mainly by dynamic pressure will be correspondingly increased, especially in regions where the precursor is strong.

GROUND SHOCK FROM AIR BLAST

3.51 Another aspect of the blast wave problem is the possible effect of an air burst on underground structures as a result of the transfer of some of the blast wave energy into the ground. A minor oscillation of the surface is experienced and a ground shock is produced. The strength of this shock at any point is determined by the overpressure in the blast wave immediately above it. For large overpressures with long positive-phase duration, the shock will penetrate some distance into the ground, but blast waves which are weaker and of shorter duration are attenuated more rapidly. The major principal stress in the soil will be nearly vertical and about equal in magnitude to the air blast overpressure. These matters will be treated in more detail in Chapter VI.

3.52 For a high air burst, the blast overpressures are expected to be relatively small at ground level; the effects of ground shock induced by air blast will then be negligible. But if the overpressure at the surface is large, there may be damage to buried structures. However, even if the structure is strong enough to withstand the effect of the ground shock, the sharp jolt resulting from the impact of the shock wave can cause injury to occupants and damage to loose equipment. In areas where the air blast pressure is high, certain public utilities, such as sewer pipes and drains made of relatively rigid materials and located at shallow depths, may be damaged by earth movement, but relatively flexible metal pipe will not normally be affected. For a surface burst in which cratering occurs, the situation is quite different, as will be seen in Chapter VI.

TECHNICAL ASPECTS OF BLAST WAVE PHENOMENA[*]

PROPERTIES OF THE IDEAL BLAST WAVE

3.53 The characteristics of the blast wave have been discussed in a qualitative manner in the earlier parts of this chapter, and the remaining sections will be devoted mainly to a consideration of some of the quantitative aspects of blast wave phenomena in air. The basic relationships among the properties of a blast wave having a sharp front at which there

[*]The remaining sections of this chapter may be omitted without loss of continuity.

is a sudden pressure discontinuity, i.e., a true (or ideal) shock front, are derived from the Rankine-Hugoniot conditions based on the conservation of mass, energy, and momentum at the shock front. These conditions, together with the equation of state for air, permit the derivation of the required relations involving the shock velocity, the particle (or wind) velocity, the overpressure, the dynamic pressure, and the density of the air behind the ideal shock front.

3.54 The blast wave properties in the region of regular reflection are somewhat complex and depend on the angle of incidence of the wave with the ground and the overpressure. For a contact surface burst, when there is but a single hemispherical (merged) wave, as stated in § 3.34, and in the Mach region below the triple point path for an air burst, the various blast wave characteristics at the shock front are uniquely related by the Rankine-Hugoniot equations. It is for these conditions, in which there is a single shock front, that the following results are applicable.

3.55 The shock velocity, U, is expressed by

$$U = c_0\left(1 + \frac{\gamma + 1}{2\gamma} \cdot \frac{p}{P_0}\right)^{1/2},$$

where c_0 is the ambient speed of sound (ahead of the shock front), p is the peak overpressure (behind the shock front), P_0 is the ambient pressure (ahead of the shock), and γ is the ratio of the specific heats of the medium, i.e., air. If γ is taken as 1.4, which is the value at moderate temperatures, the equation for the shock velocity becomes

$$U = c_0\left(1 + \frac{6p}{7P_0}\right)^{1/2}.$$

The particle velocity (or peak wind velocity behind the shock front), u, is given by

$$u = \frac{c_0 p}{\gamma P_0}\left(1 + \frac{\gamma + 1}{2\gamma} \cdot \frac{p}{P_0}\right)^{-1/2},$$

so that for air

$$u = \frac{5p}{7P_0} \cdot \frac{c_0}{(1 + 6p/7P_0)^{1/2}}.$$

The density, ρ, of the air behind the shock front is related to the ambient density, ρ_0, by

$$\frac{\rho}{\rho_0} = \frac{2\gamma P_0 + (\gamma + 1)p}{2\gamma P_0 + (\gamma - 1)p}$$

$$= \frac{7 + 6p/P_0}{7 + p/P_0}.$$

The dynamic pressure, q, is defined by

$$q = \tfrac{1}{2}\rho u^2,$$

so that it is actually the kinetic energy per unit volume of air immediately behind the shock front; this quantity has the same dimensions as pressure. Introduction of the Rankine-Hugoniot equations for ρ and u given above leads to the relation

$$q = \frac{p^2}{2\gamma P_0 + (\gamma - 1)p}$$

$$= \frac{5}{2} \cdot \frac{p^2}{7P_0 + p} \qquad (3.55.1)$$

between the peak dynamic pressure in air and the peak overpressure and ambient pressure. The variations of shock velocity, particle (or peak wind) velocity, and peak dynamic pressure with the peak overpressure at sea level, as derived from the foregoing equations, are shown graphically in Fig. 3.55.

Stan Martin & Associates

STANLEY B. MARTIN

Consultant, Petrochemical Fires and Explosions

SPECIALIZED PROFESSIONAL COMPETENCE

Research and applications of research to engineering problems in a broad field of fire and explosion protection. Analysis of vapor evolution and dispersion, both underwater and in the atmosphere; evaluation of growth and decay of explosion-limit envelopes with time in a variety of wind fields, detonation potential, consequences of boiling-liquid-expanding-vapor explosions (BLEVEs), airblast overpressures and thermal radiation fields resulting from both confined and unconfined explosions, damage-causing and life-threatening effects of explosions and subsequent fires; development of concepts for prevention and mitigation.

EXPERIENCE

Length: Over 30 years of relevant experience.

Affiliations: Stan Martin & Associates, Proprietor and Principal Investigator (since 1982)
Los Alamos Technical Associates, Senior Scientist (part time, since 1982)
SRI International (formerly Stanford Research Institute), Director, Fire Research Department (1969-1982)
URS Research Co., Manager, Fire Research Group (1965-1969)
U.S. Naval Radiological Defense Laboratory, Research Scientist (1950-1965)

Related Experience: Broad-ranging research and problem-solving applications in fire and explosion hazards (see general resume)

Experience Specific to Petrochemical Fires and Explosions: While at SRI, Mr. Martin investigated the risks and damage potential of releases of LNG and LPG in maritime accidents (see: "Cost Effectiveness of Marine Fire Protection Programs," Final Report to U.S. Dept. of Commerce, Maritime Administration, November, 1978). He managed and actively participated in several experimental programs in which fire-fighting effectiveness of various agents and techniques were evaluted in situations involving petroleum-fueled fires (see, for example: "Extinguishants for Aircraft Fire

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Fighting: Auxiliary Fire Suppressants," International Seminar on Aircraft Rescue and Fire Fighting, Geneva, Switzerland, 13-17 September 1976).

Since 1982, Mr. Martin has devoted a major part of his project activities to accidents involving fires and/or explosions fueled with petroleum products. For Varian Associates (Palo Alto), Mr. Martin personally assessed the potential for damage/injury caused by accidental leakage of on-site storage of liquified propane. He assisted Dames & Moore (San Francisco) in an analysis of the risks of damaging fires and explosions from the accidental release of various petroleum products in a Persian Gulf scenario.

For Mobil Oil Co.(Exploration Norway), he assisted Sierra Consultants International (San Francisco) in a detailed study of possible consequences of failure of the planned sea-bed, natural-gas pipeline from the Statfjord Field in the North Sea, and more recently in a comprehensive fire/explosion safety study of Canada's Hibernia Field development. Also for Mobil (Chemical Company, Phosphorous Division), he analytically recreated a runaway aerothermo-chemical-mechanical scenario that resulted in a damaging explosion at a trimethylphosphite plant.

Mr. Martin assisted Environmental Research and Technology, Inc., in the preparation of an environmental impact statement for a proposed shipping terminal in the Santa Barbara area, by forecasting airblast overpressure contours associated with a hypothetical supertanker explosion, and thermal radiation safe-standoff distances for large petroleum fires.

These studies have generated several novel software programs for reliable and convenient machine computation of the fire/explosion hazards accompanying petroleum and petrochemical accidents. Most of these studies have included recommending cost/effective fire protection concepts and state-of-the-art systems for fire suppression and damage limitation.

STAN MARTIN & ASSOCIATES

Consultants in Fire and Explosion Safety

CALCULATION OF MAGNITUDE
AND
CONSEQUENCES
OF
LARGE VAPOR-PHASE EXPLOSIONS

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Codes for Industrial Accident Risk and Consequence Analyses

by

Stanley B. Martin
of
Stan Martin & Associates

Presented to:

Eleventh International Conference on Fire Safety

January 13 to 17, 1986

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STAN MARTIN & ASSOCIATES

Consultants in Fire and Explosion Safety

NARRATIVE

During the past two decades, or so, my colleagues and I have been engaged in experimental studies and large-scale field-test measurements of fire and explosion phenomena. Some of these have a direct bearing on industrial and transportation accidents; others, while less obviously relevant, have given results that are nonetheless helpful in anticipating the consequences of such accidents and suggesting the need for safety measures. More recently, Stan Martin & Associates has had frequent occasion to apply this technology to industrial safety planning, some of it aimed at the anticipation of life- and property-threatening consequences of unlikely (yet possible and even credible) large releases of hydrocarbon fluids. An analytical methodology has evolved, which I will describe and illustrate.

While the applications addressed thus far have been mainly blowouts of wellheads, high-pressure pipelines, and pre-refinery process equipment, much of the analytical development is also applicable to a variety of accidents involving the release of flammable gases, liquids, and/or two-phase fluids. Computer codes have naturally accompanied these developments, particularly in those situations of repetitive, labor intensive calculations. This development is summarized in the attachment. To date, however, these individual coding efforts have not been pulled together into a general utility, user-friendly package, despite the prospects for its widespread use.

The physical understanding that serves as a foundation for this analytical methodology seems to be pretty well in hand. There are, however, some still unresolved issues, which I have attempted to bring out in my talk. One of these is the onset of instability in pool fires as size increases and fuel supply limits the per-unit-area burning rate. Another is deflagration airblast from unconfined clouds of gases/vapors, and how the resulting overpressures depend on ambient air motion and the site of flame initiation. Full confidence in analytical forecasts must await a satisfactory resolution of such incompletely understood issues. Low-budget experimentation could lead to the resolution of the instability question, especially if it were coordinated with analytical modeling. The second issue may not yield significantly without a costly series of large-scale tests.

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STAN MARTIN & ASSOCIATES

Consultants in Fire and Explosion Safety

CODES DEVELOPED FOR INDUSTRIAL
ACCIDENT RISK AND CONSEQUENCE ANALYSIS

The analytical methodology applied by Stan Martin & Assocs. to the evaluation of fire and explosion hazards of accidental discharges o' flammable fluids from pressurized process equipment and transport lines and carriers makes use of several computer codes of our own development. Examples follow:

- mechanics of subsea releases of pressurized gases and/or miscible two-phase fluids, including plume flow and separation at the sea surface. This was written as a key-stroke program for the HP-41C. Since then, the equations have been rewritten for improved generality and convenience. They have yet to be programmed in machine language, however.

- atmospheric dispersion of cryogenic fluid spills and high-rate releases of neutral-density gases (IBM BASICA). Version CONCALC2 treats dispersion from a point source at the atmospheric boundary; CONCALC3 treats unbounded cases. Wind variables are speed and fou- gustiness categories.

- explosion potential of unconfined gas clouds and explosive mixtures in weak-walled enclosures; estimates far-field overpressures and their decay with distance from explosion center. (IBM BASICA -- filename, EXPLOP.BAS)

- radiant heat levels from a fire plume (as a plane, rectangular source); calculates safe standoff distances, given endurable fluxes as input. (IBM BASICA -- filename, RADHEAT.BAS)

- rates of gas discharge from pressurized pipelines and reservoirs; flow may be either sonic or friction limited. (Fortran 4 -- filename, PIPE.FOR ; IBM BASICA -- filename, PIPELEAK.BAS)

These codes have been successfully employed in several industrial accident-consequence analyses. In a recent study,

four codes were linked to accomplish the following:

1. Estimate the steady mass flow and nozzle velocity of pressurized gas issuing from holes of specified size.

2. Interrelate momentum dissipation by air entrainment with composition and velocity change, along the length of the jet of gas issuing from the hole, from its supersonic origin to the region where its directed flow effectively melds into the wind field. This result is used to decide how much of a role jet mixing plays in the formation of explosible mixtures.

3. Describe the size, downwind extent, and explosion potential of the steady plume formed by processes of wind shear.

4. Estimate the airblast overpressure field that might reasonably result from the deflagrative explosion of the described plume.

The estimates of discharge mechanics are based on the well known equation for adiabatic, isentropic expansion of a gas (ideal) through an orifice with pressure drop sufficient to ensure at least sonic flow. The second analysis uses results of the theory of jets developed by A. M. Kanury and presented in his book: "Introduction to Combustion Phenomena," Gordon & Breach Science Publishers, New York, 1975, pp 217-267.

The analysis of atmospheric dispersion is based on the bimodal gaussian model of Pasquil as subsequently applied by Burgess et al.(15th Combustion Symposium, 1974). Overpressure estimates follow developments of Brode, Porzel, and others for situations of noncondensed explosives. The efficiency factor is judgemental, but based on guidance derived from reviews of accidents (e.g., Brasie, W.C., and Simpson, D.W., AIChE, Loss Prevention, Vol. 2, 91-102 (1968)].

More recently, boiling-liquid, expanding-vapor explosions (BLEVEs) have been reviewed, and a theoretical basis for code algorithms was developed to permit estimating the airblast overpressure field around such accidents. This has not as yet been translated to software.

Modifications have been made to the radiant-heat model for hydrocarbon-pool fires to increase its versatility and realism. The flame column is now modeled as a cylindrical radiator that bends in response to the ambient wind. Thus the hazard added by an unfavorably directed wind may be evaluated. Target points may be selected at elevated locations. (IBM BASICA -- filename, FLAME2.BAS) Further modifications to make the code more "user friendly" are in progress.

10 December 1985

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