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BLAST EFFECT FROM A PANCAKE SHAPED FUEL DROP—AIR CLOUD DETONATION (THEORY AND EXPERIMENT)

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Summary

The tendency of fuel—air clouds to assume a pancake shape on the ground, due to buoyancy effects, significantly increases the ground area affected by subsequent detonation. Blast from a cloud with this configuration was theoretically evaluated using an analysis of planar detonation with side relief due to Sichel and the HEMP hydrocode. Theoretical results compare satisfactorily with pressure data obtained from detonation of a large (~ 50 m diameter) hydrocarbon fuel-air cloud.

Introduction

Explosive fuel—air clouds produced during transportation accidents are likely to have the form of a pancake in contact with the ground. This configuration effectively maximizes the blast damage for a given amount of explosion energy by keeping the energy release near the ground. Sichel [1] has carried out an analysis of planar detonation with side relief to calculate the pressure history on the ground during detonation of a cloud with small height to diameter ratio. This analysis applies where effects of curvature of the detonation front are negligible. Although Sichel indicates that the pressure behind the detonation front decreases quite rapidly, a finite core pressure is maintained throughout the detonation process. Thus, the positive phase duration near the center of the cloud is extremely long, even though the pressure is relatively low.

To gauge the overall blast effect from such a pancake shaped cloud, the HEMP [2] computer code was used to simulate centrally initiated detonation in a cloud with height to diameter ratio 0.03572. HEMP is a two-dimensional, lagrangean hydrodynamic computer code developed at Lawrence Livermore Laboratory, suitable for calculating the hydrodynamics of detonation processes. The results of this calculation, along with Sichel's analysis, are compared with pressure data measured in the detonation of a large, pancake shaped fuel—air cloud of comparable thickness and small height to diameter ratio. Reasonable agreement between calculations and experiment are indicated. The

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overall size of the blast effect being considered is demonstrated by comparison with blast parameters for a 100 ton TNT hemisphere detonated on the ground.

Calculation

The cloud configuration was taken to be a thin disk, 4.57 meters thick by 128 meters diameter, in contact with a perfectly reflecting surface (Fig. 1).

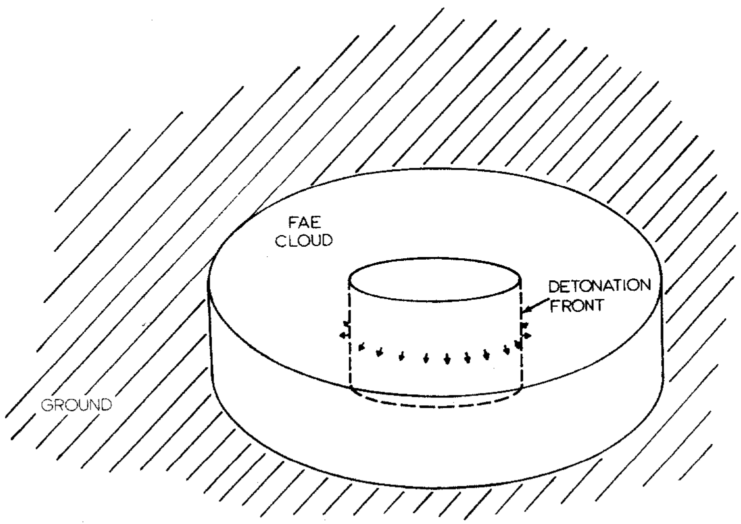

Fig. 1. Schematic diagram of the HEMP calculation configuration.

Initiation was assumed to occur on the axis of symmetry at the reflecting surface. The HEMP computer code requires the effective explosion energy to be assigned to each computational cell prior to detonation. This energy is then added to the flow through the energy equation in small increments commencing when the detonation front passes by the cell. Perfect gas behaviour was assumed. Initially, the internal energy of the gases, relative to their original pressure and specific volume is

$$\frac{E_0}{P_0 V_0} = \frac{1}{\gamma_0 - 1}$$

The "chemical energy" to be added to explosive cells was calculated from the formula appropriate to a C—J detonation in a perfect gas [3]:

$$\frac{Q}{P_0 V_0} = \frac{(\gamma_2 + 1)\dfrac{P_{CJ}}{P_0} + \frac{1}{2}\left(\dfrac{\gamma_2 + 1}{\gamma_2 - 1}\right)\left(\dfrac{P_{CJ}}{P_0}\right) - \frac{1}{2}}{(\gamma_2 + 1)\left(\dfrac{P_{CJ}}{P_0}\right) - 1} - \frac{\gamma_0}{\gamma_0 - 1}.$$

For this calculation, the C—J detonation pressure for a stoichiometric kerosene—air mixture, $C_{11.6}H_{23.2}$ (liquid) + 17.4 O_2 + 69.6 N_2 at standard conditions ($P_0 = 1.0132 \times 10^6$ pascals, V_0 (air) = 784.6 cm^3/g) was calculated using the TIGER thermodynamic equilibrium code [4]. The calculated detonation pressure (P_{CJ}/P_0) is 18.08 and the adiabatic exponent for the products of combustion is $\gamma_2 = 1.254$. This mixture is 6.08% kerosene by weight, so the cloud being considered in the computation represents 3937 kg (5 tons) of kerosene. Assuming the initial adiabatic exponent for the cloud and surrounding air to be

$$\gamma_{air} = \gamma_{cloud} = 1.377,$$

the "chemical energy" from the above formula is

$$\frac{(Q)}{E_0} = 12.787.$$

Associated values for the detonation properties can be calculated using formulae from [3]:

$$D/\sqrt{P_0 V_0} = \sqrt{(\gamma_2 + 1)(P_{CJ}/P_0)-1} = 6.3042 \text{ (C—J detonation velocity)}$$

$$V_{CJ}/V_0 = \left(\gamma_2 \frac{P_{CJ}}{P_0}\right) \Big/ \left((\gamma_2+1)\frac{P_{CJ}}{P_0} - 1\right) = 0.5702 \text{ (C—J specific volume).}$$

Initial specific volume of the cloud is $V_{cloud} = 0.94\ V_0$ (because of the weight of fuel), and the cloud thickness to radius ratio = 0.07144.

Calculation results

A relatively large cell size was required to make this computation tractable. Effects of having a smeared out combustion region are quite noticeable, resulting in the calculated detonation pressure being less than it theoretically should be. However, this difficulty does not greatly affect the calculated impulse.

Since the cloud is thin, pressure relief from the upper surface decreases the pressure behind the detonation from what it would otherwise be, but the "core" of explosion products remains at approximately 2.5 atmospheres until the entire cloud is consumed. Thus, the detonation quickly develops a "steady state" configuration as it moves radially outwards, so that the part of the pressure profile with $P > 2.5$ does not depend on radius, except close to the outer edge. Calculated pressures are shown in Fig. 2 for both the R = 44.8 meter and R = 51.2 meter positions. Results are essentially identical at the two locations over the time frame indicated. Note that time is measured relative to time of arrival of the detonation.

Sichel [1] has published an analytic solution for a planar detonation with side relief, and a schematic diagram of the problem is shown in Fig. 3. The detonation should approach this configuration at larger radii where curvature of the detonation front is insignificant. Sichel's theoretical pressure profile is

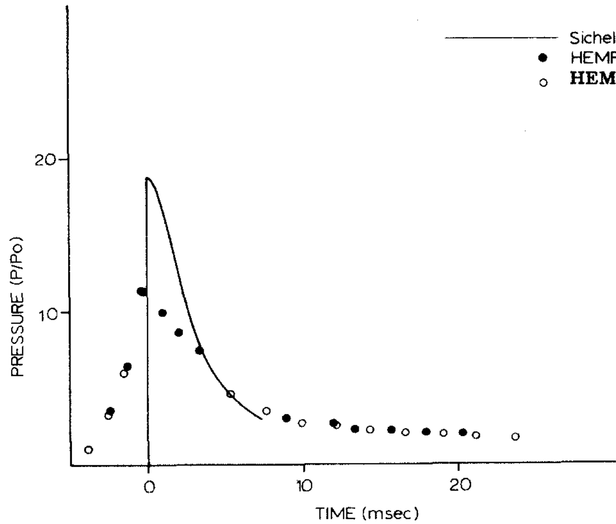

Fig. 2. Analytical pressure histories.

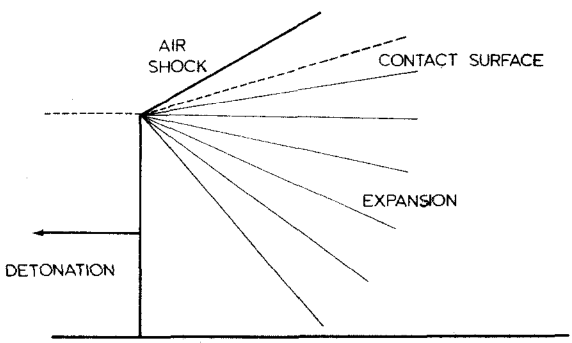

Fig. 3. Schematic diagram of configuration for Sichel's theory.

shown by the solid line in Fig. 2. The dilatory effect of smearing out the energy release zone over several cells in the calculation is plainly evident.

Calculated impulse at R = 51.2 meters is shown in Fig. 4 along with the impulse from Sichel's theory. Once again, the effect of broadening the pressure pulse can be seen. However, both calculations agree satisfactorily beyond 2 msec after detonation arrival.

Peak overpressure versus radius for the fuel—air cloud is shown by the solid line in Fig. 5. The overpressure value indicated inside the cloud is based on the theoretical C—J detonation pressure. Shock pressure decays very rapidly beyond the edge of the cloud. Shown (dashed line) for comparison is the peak overpressure from centrally initiated detonation of a 91919.1 kg TNT hemisphere on the ground taken from Kingery [5]. Despite the fact that there is twenty times more weight of TNT than fuel, there exists a large region

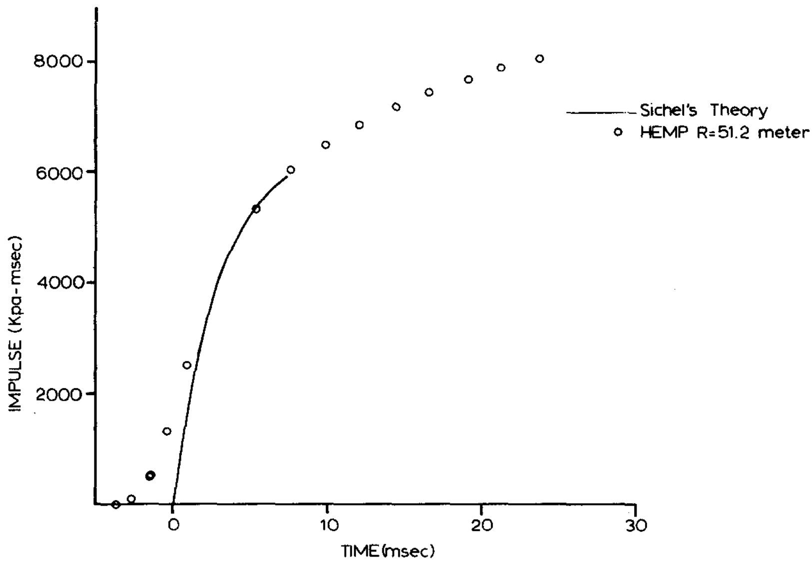

Fig. 4. Analytical impulse histories.

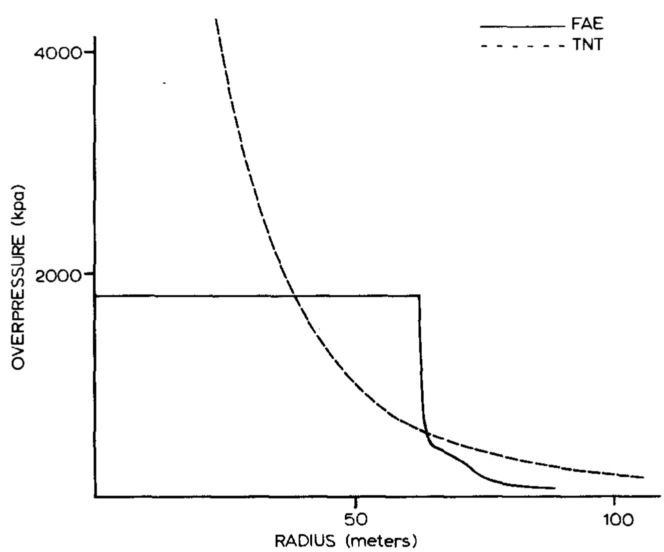

Fig. 5. Calculated overpressure versus radius for FAE and TNT.

where the fuel—air cloud produces higher overpressures. The total energy released by the TNT is 9.62×10^7 kcal compared to 4.8×10^7 kcal for the fuel—air cloud. Calculated total impulse versus radius is shown in Fig. 6 along with the impulse from the TNT hemisphere. They are comparable over the region covered by the fuel—air cloud.

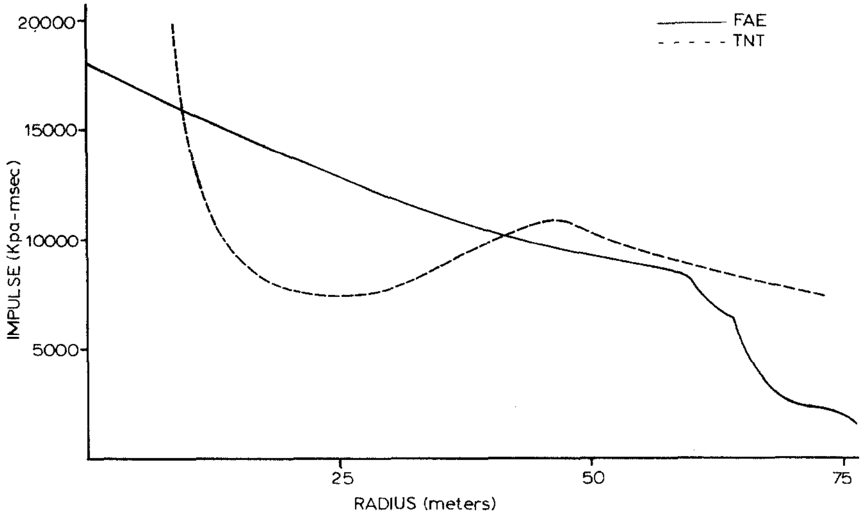

Fig. 6. Calculated impulse versus radius for FAE and TNT.

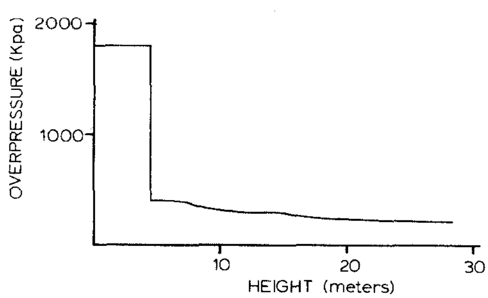

Fig. 7. Calculated overpressure versus height for FAE.

Figure 7 shows the calculated peak overpressure versus height above the cloud at the R = 51.2 meter position. The peak pressure between 0 and 4.57 meters is simply the detonation pressure. However, the peak pressure has a discontinuous jump at 4.57 meters, down to the pressure produced in the air originally along the top of the cloud by the oblique shock attached to the detonation. Beyond this discontinuous drop, the shock pressure decay with increasing height is very slow, since the detonation product gases expand upward producing a "piston effect" on the upward propagating shock wave. At a height of 6 cloud thicknesses above the cloud, the shock pressure is still within 70% of its value at the top of the cloud.

Experiment

A large fuel drop—air cloud was detonated to generate data on the effects of such an explosion. This cloud did not duplicate the height to diameter ratio assumed in the calculation, being nominally 70 meters in diameter and about 5.8 meters thick; however, the height to diameter ratio was sufficiently small that pressure measurements at positions well within the cloud could be expected to correspond to the results of Figs. 2 and 4. The cloud consisted of a hydrocarbon fuel (mostly heptane) aerosol with stoichiometric C—J detonation properties similar to those assumed in the calculation. A sketch of the experimental cloud is shown in Fig. 8. It was generated from four liquid fuel dispensers and appeared relatively homogeneous except for the regions near the sources indicated in the sketch. Detonation was initiated at the two sites indicated by diamonds in the sketch. This meant that the two resulting detonation waves collided near the center of the cloud. The position of the two fronts just prior to collision is indicated by the dotted lines superposed

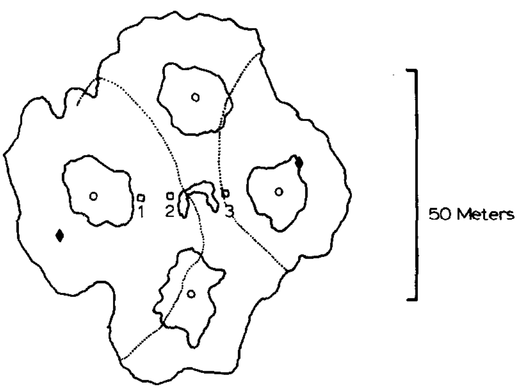

Fig. 8. Overhead view of experimental FAE cloud.

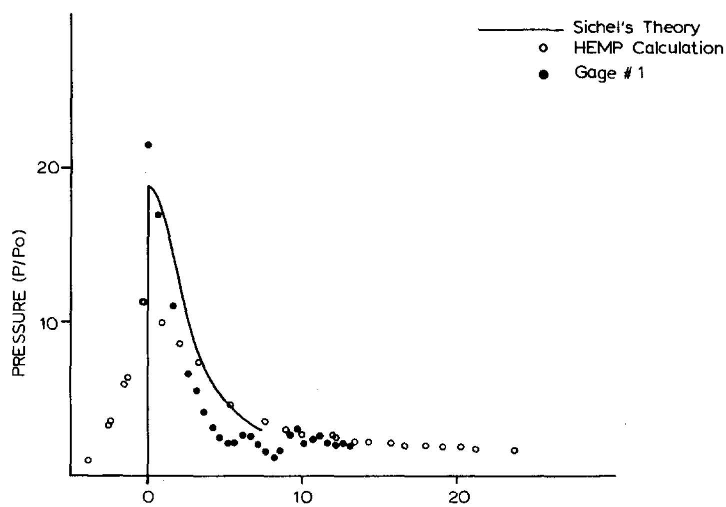

Fig. 9. Pressure history at gauge 1.

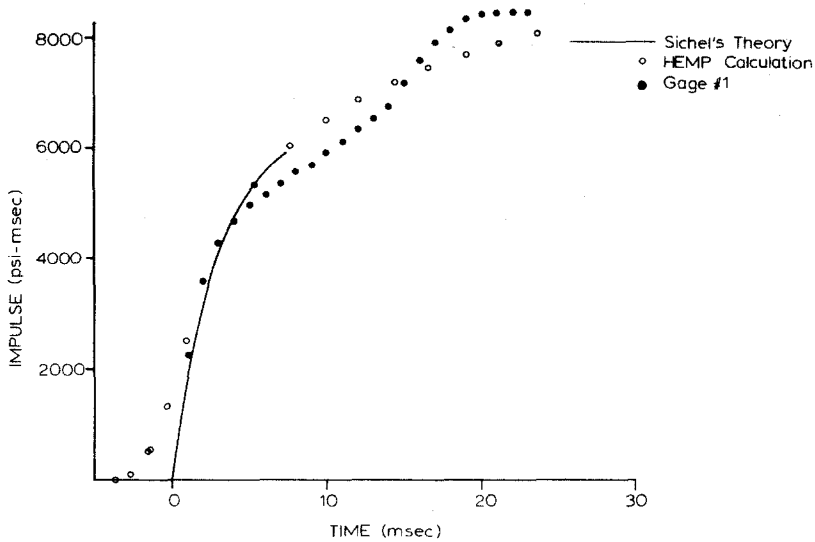

Fig. 10. Impulse history at gauge 1.

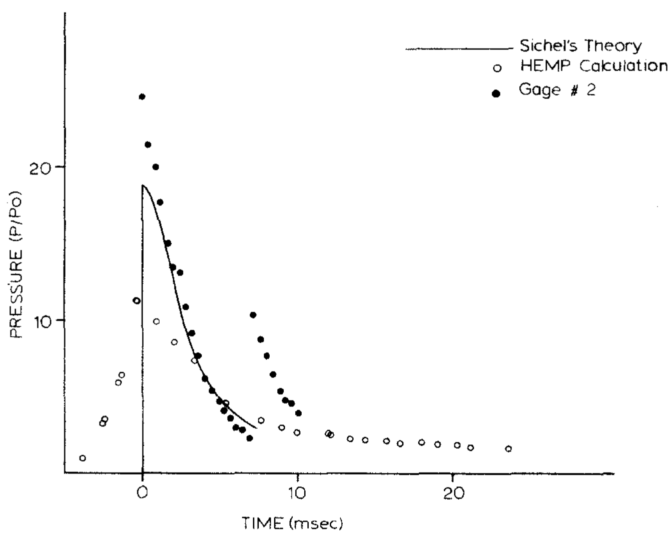

Fig. 11. Pressure history at gauge 2.

on the sketch. Pressure was measured at the three locations indicated by squares. Resulting data are shown in Figs. 9–14, with the previous theoretical values superimposed (solid line and open dots).

A gauges 1 and 3, the peak pressure was close to the theoretical value, but the pressure decayed more rapidly than predicted. Thus, the measured impulse eventually falls slightly below the predicted value, except at late times, when

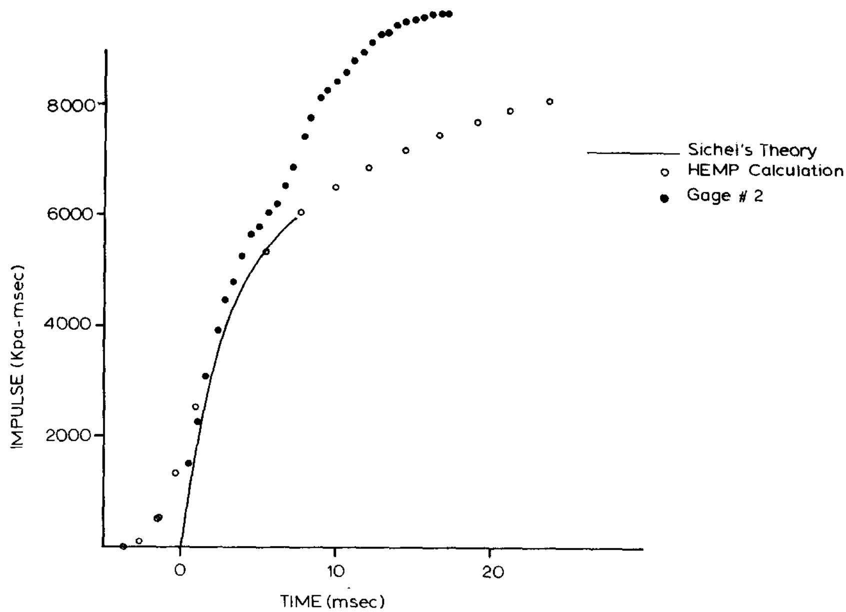

Fig. 12. Impulse history at gauge 2.

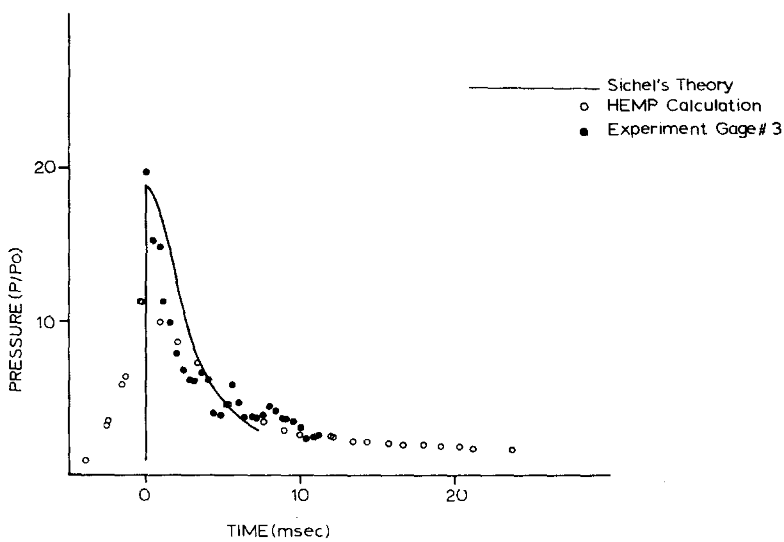

Fig. 13. Pressure history at gauge 3.

the effect of the detonation collision is felt in the data. Gauge 2 measured noticeably higher peak pressure than predicted, but the pulse length agrees well with theory when the secondary shock wave generated by the detonation collision is disregarded (the reflected wave is the secondary pressure spike in

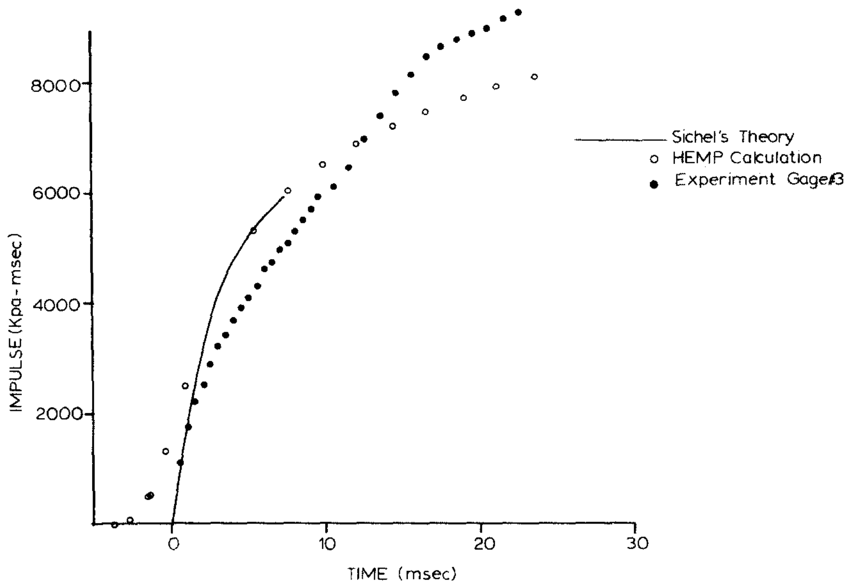

Fig. 14. Impulse history at gauge 3.

fig. 11). The impulse measured by this gauge agrees well with predicted values, until the arrival of the reflected wave.

Conclusion

It has been appreciated for some time that heats of combustion of fuels are generally much larger than heats of explosion of condensed explosives, and that this makes available large blast effects from fuel–air explosives. In addition, the tendency for fuel–air clouds to form pancake shapes and creep along the ground can significantly enhance the range of their blast effect. Thus, while the heat of combustion of kerosene (as used in the computation) of 10.59 kcal/g is 9.8 times the heat of explosion of TNT, the pancake shape of the fuel cloud gives a blast effect on the ground comparable to 20 times the fuel weight in TNT. The cloud shape effectively keeps the force of the explosion near the ground. Hazard assessments should include this factor in determining safe distance requirements when handling large quantities of fuel.

Acknowledgement

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