Secondary Fragments from Accidental Explosions in Above Ground Ammunition Storage Houses at High Loading Densities

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Summary

The DPM program was planned to improve methodologies to predict the debris throw in case of an accidental explosion in aboveground storage houses at high loading densities. The program consists of four phases, each including tests and analytics. Phase I of the DPM program was planned in detail.

Phase I of the DPM program is an experimental program. A square concrete slab 1m   1 m 0.1 m, with static reinforcement will be the test object. A cubicle with an inner-volume V = 1 m^3 is the basic test-arrangement. Three different configurations will be tested. A spherical charge of W = 25 kg of HE will be detonated in the center of the cubicle. The loading density is W / V = 25 kg/m^3. A total number of 36 experiments is planned in the DPM Phase I program.

Phase I of the DPM program was planned to answers the questions:
Does venting have an effect on the failure mode?
Does venting have an effect on the initial debris velocity?
How to get data to run DISPRE for high loading situations?

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1. Introduction

The Klotz-Club asked for an improvement of methodologies to predict the debris throw in case of an accidental explosion in aboveground storage houses at high loading densities. The debris from concrete structures was termed "secondary fragments". Early 1980'th the empirical DEN [Debris Energy and Number] methodology was developed by the Ernst-Mach-Institute (EMI) for this case of loading. However, the data base was small and did not allow for a verification of the code.

In the meanwhile the Klotz Club has available the DISPRE code for low loading densities. DISPRE is appropriate to be developed to high loading situations. In order to run DISPRE the close-in shock load as well as the correlations with the failure mode and the initial debris parameters must be investigated.

The loading density in kilogram of HE that is stored per cubicmeter volume in a structure is widely used to describe the loading situation in an ammunition storage house. At high loading density the standoff between the charge and some components of the structure will be small. Those components are loaded by the close-in composite shock from the detonation products. For wall thickness of practical interest this type of loading results in catastrophic failure. Concrete walls are fragmented into a large number of small pieces of debris.

An experimental program was planned to investigate close-in shock loading situations. The program will be done at the Meppen Testsite WTD 91 in Germany. It was termed **DPM** **D**ebris **P**roject **M**eppen. Phase I of the DPM program is an experimental program with concrete slabs as test objects. Phase II and Phase III are test with Generic Structures. Phase I of the DPM program was planned in detail.

Th*e following parameters must be available from experiments to run DISPRE:*
- total destroyed mass of a component
- average debris mass
- debris launch velocity
- initial angles at which debris leave
- effective drag area of debris
- debris drag coefficient

The method to get the input data for DISPRE is:
- determine the internal load for each component of the structure
- determine the failure mode for each component from the correlation of the failure mode with the internal load.
- determine the initial velocity of debris from the correlation with the internal load.

Angles at which debris leave, debris trajectories and the debris terminal ballistics (tertiary fragmentation, ricochet and rolling) will not be discussed in this presentation.

2. Close-in and Far-range Loading Situations

It is not arbitrary to differentiate high and low loading situations!
- Close-in loading corresponds to composite blast from the detonation products.
- Far-range loading corresponds to airblast.

Figure 1: Diagrams of *blast parameters* indicate a critical range for standoff 0.25 $R/W^{1/3}$ 1 (scaled distance in m/kg$^{1/3}$), where the initial shock phase changes from close-in to far-range in a short distance. The reflected peak overpressure is reduced by a factor of 20. The reflected shock impulse is reduced by a factor of 10. This results in a reduction by a factor of 100 in kinetic energy that is imparted to a component. The shock duration is extended by a factor of 10 (from 0.2 to 2 ms/kg$^{1/3)}$. The energy per unit time (power) that is available in the component is reduced by a factor of 1000 from close-in to far-range. Exactly this critical range of standoff distances is important in the DPM program!

The wall thickness (mass per unit area) of the reinforced concrete slabs is the second parameter to determine the failure mode. At identical internal loading a thin wall is fragmented and thrown away at high velocity; a medium wall breakes into large pieces that start at low velocity; a thick wall remains intact and stays in place.

It is proposed to differentiate 3 regimes of *Loading Situations:*

High Loading Situation.
- Close-in composite blast loading
- Scaled standoff   0.25 m/kg$^{1/3}$ (about 5 charge radii)
- Scaled wall thickness   0.04 m/kg$^{1/3}$
- Reflected peak overpressure   100 000 kPa
- Scaled Shock Impulse (per unit area)   5 000 Pa s/kg$^{1/3}$
- Power (per unit volume of concrete)   2500 MW/m^3
- Catastrophic Failure, Fragmentation
- Large number of small pieces of debris
- High initial velocity (order 100 m/s)
- Loading density   8 kg/m^3 (cubicle)

Medium Loading Situation.
- Composite and airblast shock loading, quasistatic loading
- Large and small pieces of debris
- Low and high initial velocities

Low Loading Situation.
- Far-range airblast and quasistatic loading
- Scaled standoff   1 m/kg$^{1/3}$ (charge to wall)
- Scaled wall thickness   0.04 m/kg$^{1/3}$
- Reflected peak overpressure   5 000 kPa
- Scaled Shock Impulse (per unit area)   500 Pa s/kg$^{1/3}$

- Power (per unit volume of concrete)   2.5 MW/m^3
- Basic structural integrity maintained
- Initial shock phase of minor importance
- Internal gas pressure causes rupture
- Tearing-off large pieces
- Small number of large pieces
- Low initial velocity (order of 10 m/s)
- Loading density   0.5 kg/m^3 (cubicle)

3. Close-in Loading on Internal Surfaces

The loading on the internal surface of each component of a structure must be determined in order to get the failure mode as well as the acceleration of debris. The *standoff* between the detonating charge and the component is the most important parameter to determine the failure mode in case of high loading situations.

The standoff determines the primary shock that does not depend on the structural geometry and not on the failure mode of the component. The further pressure-time history, reflections as well as the quasistatic pressure, depend on the structural geometry and on the failure mode of the component.

In order to discuss the internal shock loading close-in of the DPM Phase I test arrangement EMI made a 2-D precalculation with the SHARC code. The calculated primary shock is in agreement with the prediction from empirical data.

Figure 2 shows Pressure vs. Time diagrams. The overpressure in bar at the test slab vs. time in ms at the distance R = 0.5 m from the HE charge W = 25 kg is shown.

Figure 2.1: The primary shockfront arrives at time $t_a = 0.08$ ms after detonation at the wall. The average front velocity from initiation is v   6000 m/s. The peak overpressure is Pr = 250 000 kPa (2500 bar).

The shaded area under the double peak will be termed *"primary composite shock"*. It can be approximated by a rectangle 220 000 kPa high and 0.016 ms (16 microsecond) wide. An impulse $I_r = 3500$ Pa s is applied per unit area (m$^{2)}$ of the component. An energy per unit time (power) is imparted into the testplate by the *"composite shock"* $P_c = 15.6 \quad 10^6$ kW/m^3 (1560 MW/m$^{3)}$. Lateron it will be recommended to correlate the failure mode with P_c.

An approximately triangular pressure decay from 150 000 kPa to 200 kPa in t = 0.28 ms follows. This is not what usually is termed a quasistatic pressure decay! A total impulse of I = 21000 + 3500 = 24500 Pa s is transmitted to the testplate in t = 0.37 ms. Lateron it will be recommended to correlate the initial debris velocity with the *"primary shock impulse"*.

Figure 2.2 shows SHARC pressure-time histories in vented and unvented test arrangements. The composite shock as well as the primary shock impulse are identical. If it is true that the primary composite shock causes the failure mode, then the average debris mass will be identical in both arrangements.

Figure 2.3 shows SHARC pressure-time histories in the center and near the rim of the test plate. The duration of the composite shock (16 microseconds) is identical at both locations. The average pressure is reduced by a factor of 2 from the center to the rim. The energy per unit volume, that is transmitted from the composite shock near the rim, is reduced by a factor of 4.

EMI proposes to determine the internal load on components for close-in situations from the pressure-time history that is numerically calculated by SHARC , AUTODYNE or BLASTX.

4. Correlation of Failure Mode with Loading

A parameter must be selected that characterizes the failure mode. This failure mode parameter must be correlated with a parameter that characterizes both the internal load and the component type.

The average debris mass characterizes the failure mode of concrete walls. The average debris mass must be based directly on the experimental debris recovery data.

The failure mode (average debris mass) does not correlate with the applied impulse as this does not take the component type into consideration. To break a concrete plate to debris the *resistance* of the material strength must be overcome. In dynamic situations *power* is the physical parameter that describes how much resistance can be overcome. A certain amount of stress energy per unit time (and per unit volume) must be available to overcome the material strength! The energy per unit time P depends on both the shock load and the component type.

EMI proposes to correlate *the failure mode (average debris mass)* with *the energy per unit time* (power) that was imparted to the component by *the “composite shock". The shock is numerically calculated by SHARC , AUTODYNE or BLASTX.*

The debris evaluation of the 1982 DEN tests supportes that the shock determines the failure mode at close-in loading.

5. Correlation of Initial Debris Parameters with Loading

The debris initial velocity must be correlated with a parameter that characterizes both the internal load as well as the component type. The kinetic energy that is transmitted to the component depends on both the applied impulse (per unit area) and on the mass (per unit area).

To correlate the initial debris velocity with the internal load at close-in loading situations the impulse-momentum relation is used. The method assumes that the portion of the energy that is used to cause the failure of the component is negligible.

It must be investigated how much impulse contributes to the acceleration of debris at high loading situations. It is not clear if the primary shock alone causes all acceleration or if early reflected shocks contribute.

In the Phase I DPM experiments the vent cover mass is small and the component will be fragmented very fast. The vent area is identical with the component area. The quasistatic and the gas pressure phase is eliminated and does not contribute to the debris acceleration.

Direct measurement of early reflected shocks at the component is not possible. The component was fragmented before reflected shocks arrive. High speed photography of the debris velocity will be used to find out how much impulse was applied.

EMI proposes to correlate *the initial debris velocity* with *the kinetic energy* that was imparted to the component from *the "primary shock impulse"*. The shock loading is numerically calculated by SHARC, AUTODYNE or BLASTX.

The high-speed film evaluation of the 1982 DEN tests supportes that the primary shock impulse determines the acceleration of debris at close-in loading.

6. Characterization of the DPM Program

The program Phase I; II and III that will be done at the Meppen Testsite WTD 91 in Germany (Wehrtechnische Dienststelle der Bundeswehr) was termed: **DPM** **D**ebris **P**roject **M**eppen.

DPM 94 Phase I	Experimental Program with Plates, Identify valid testing procedures Establish possibilities for instrumentation Make available input data for DISPRE Increase the data base
DPM 95 Phase II	Test Program with 3-D Generic Structures Effects of loading density Check and improve DISPRE
DPM 96 Phase III	Test Program with 3-D Generic Structures: Effects of wall thickness Effect of Reinforcement Effects of Earth-Cover
DPM 97 Phase IV	Test Program with Full Scale Structures Verification of DISPRE

7. Phase I of the DPM Program

Phase I of the DPM program is an experimental program to find answers to four questions:

- Does venting have an effect on the failure mode?
- Does venting have an effect on the initial debris velocity?
- How to get data to run DISPRE for high loading situations?
- Which instrumentation must be used in Phase II and III of the DPM program?

A total number of 36 experiments is planned in the DPM Phase I program.

7.1 Experimental Arrangement and Test Site

Figure 3 shows schematically the DPM Phase I test arrangement.

A square concrete plate 1m   1 m   0.1 m, with static reinforcement will be the test object during all Phase I tests.

A cubicle with an inner-volume V = 1 m^3 is the basic test-arrangement.

A spherical charge of W = 25 kg HE will be detonated in the center of the cubicle.

The loading density is W / V = 25 kg/m^3.

The scaled standoff between the charge and the plate center is $Z_{min} = 0.17\ m/kg^{1/3}$ and between the charge and the corners of the cubicle is $Z_{max} = 0.3\ m/kg^{1/3}$.

Three configurations will be tested:

- the non-reacting, **u**nvented arrangement (U)
- the "**f**ully" vented arrangement (F)
- the reacting, **d**elayed vented arrangement (D)

The unvented arrangement will be constructed of thick steelplates at the floor and at 4 sides of the cubicle. Fully vented means a structure with wide openings. Delayed venting will happen in an arrangement that is constructed of identical concrete plates at 5 sides of the cubicle. All 5 plates will be destroyed.

Experiments will be done with the test-plate:

- in a **v**ertical position (V)   (simulating a roof component)
- in a **h**orizontal (H) position (simulating a side-wall component)

The test-plate in the vertical configuration will be flat with the ground surface, the cubicle in a pit. The vertical position has some experimental advantage in filming the launch process and collecting the debris. The debris will be spread over a relatively small area, the recovery rate will be high. All debris hits the ground at vertical trajectories. The tertiary fragmentation and rolling of debris can be better controled.

To make the results comparable to 3-D tests with respect to the number of debris, mass distribution and distances of throw a horizontal arrangement will be used. The cubicle will be above ground.

EMI proposes to use a large concrete platform 100 m x 150 m, called "Startbahn" for the experiments (Pioniersprengplatz Sprakel der WTD 91 in Meppen, Germany). All the debris from Phase I experiments can be collected at the platform .

The main advantage is, that identical conditions can be reproduced for each experiment.The platform can be cleaned before each experiment. Collection squares can be marked and numbered at the platform. The collection of debris by sweeping the marked squares is much easier than the debris collection in the field. A higher recovery rate is expected.

In case it proves to be disadvantageous that the debris hit the hard concrete platform (tertiary fragmentation) there can be spread out a layer of sand or other soft material.

7.2 Instrumentation and Data Evaluation

The main effort in the instrumentation and data evaluation of DPM Phase I will be:
- high speded photography and video
- extensive debris recovery and debris evaluation.

It must be taken into consideration for the data evaluation of Phase I that the failure mode as well as the initial velocity of debris will be different in different parts of the testplate! The standoff between the charge and the plate center is $R_{min} = 0.5$ m; between the charge and the corner of the cubicle is $R_{max} = 0.87$ m. This corresponds to scaled standoffs $Z_{min} = 0.17$ m/kg$^{1/3}$ and $Z_{max} = 0.3$ m/kg$^{1/3}$. It was estimated that the initial velocity will be $v_{max} = 200$ m/s in the center of the plate and $v_{min} = 120$ m/s in the corners.

7.2.1 Internal Loading

Internal loading must be available at the zones of components that are at different standoff from the charge.It is extremely difficult to measure directly the internal loading from close-in composite blast *at the components*. Blast pressure gages are sensitive to the flash of detonation, to the electromagnetic pulse and to the extremly high acceleration (100 000 g). Gages will be destroyed if the component breaks into small pieces of debris. *EMI does not recommend to measure directly pressure-time histories at the components close-in!*

It was discussed in the Close-in Loading section that the internal close-in shock load will be calculated by SHARC, AUTODYNE or BLASTX.

7.2.2 Failure mode

The a*verage debris mass* and the *total mass of the destroyed portion of the component* determine an exponential distribution of debris masses.

The average debrid mass will be evaluated from the debris recovery program. The total mass corresponds at high loading situations to the total mass of the component.

The debris collection will be much easier at the platform than on unsurfaced ground. The recovery rate will be relatively high. The procedure of debris collection and evaluation was developed in the DEN program and will be taken over for the DPM PhaseI experiments.

7.2.3 Debris Initial Parameters

High-speed film and video *will be included in all of the experiments.* 200 to 500 fps will be needed.Yardsticks for length and angles will be included to allow film evaluation. The high-speed photography will be evaluated for debris velocities and the initial angles at which debris leave.

Normal speed film and video will be used to survey the experiments, to estimate maximum height of debris and total flight-time.

Accelerometer measurements are *not* recommended for the Phase I tests. No accelerometer is known that can resolve the extremely high acceleration during the shock loading phase (whilst acceleration during the quasistatic and the gas pressure phase can be measured). It is unclear at which place the accelerometer must be mounted if the test object breakes into small pieces.

Accuracy and precision of data. It will be discussed throughout the program which accuracy and precision for the parameters must be reached.

Optional measurements

Direct measurement of acceleration.

Internal pressure-time history at the floor plate

Radar measurement of debris velocity

8. Generic Structure Tests, DPM Phase II and Phase III

The Klotz Club has defined "Generic Structures" that are typical for above ground storage houses in the different countries according to the overall size, the floor plan, the wall thickness etc. Generic Structures will be tested in Phase II and Phase III of the DPM program. As they have a rectangular floor plan and the charge will be placed in the center of the floor, t*he different walls are at different distances from the charge.*

It was discussed that the shock load on components changes dramatically from composite blast close-in to airblast far- range in a small distance. Exactly in this critical range of standoff distances are the different components of the Generic Structures arranged. The impulsive shock load at the different walls varies by a factor of 10. The shock duration at the nearest component (segment in the lower center of a sidewall) is shorter by a factor of 10 compared to the most distant component (in the corner of the endwall). The kinetic energy, that is imparted into the different components (same wall thickness) varies by a factor of 100. The initial velocity at different components varies by a factor of 10. The available power (per unit volume of wall material) in different components of the structure varies by a factor of 1000!

As a result, everything will happen in the components of the Generic Structures. From fracturing into small pieces in the center of the sidewall to elastic deformation in parts of the endwall. All sizes of debris will be produced from dust to large fragments of wall panels. The different debris start at much different initial velocities.

The debris that is collected in a claim in a certain direction and distance may originate from different sections of a sidewall, the roof, the floorplate or the crater. The dispersion of debris in the *Generic Structures Tests* is such complicated, that no survey of the result will be possible as long as no prediction is available.

DISPRE must be developed until the internal loading at the different components can be predicted. The failure modes of the different components as well as the initial parameters of the debris can be determined. The comparison of prediction with test result will allow a survey. The Generic Structures Tests will help to improve the methodology.

FIGURE 1.

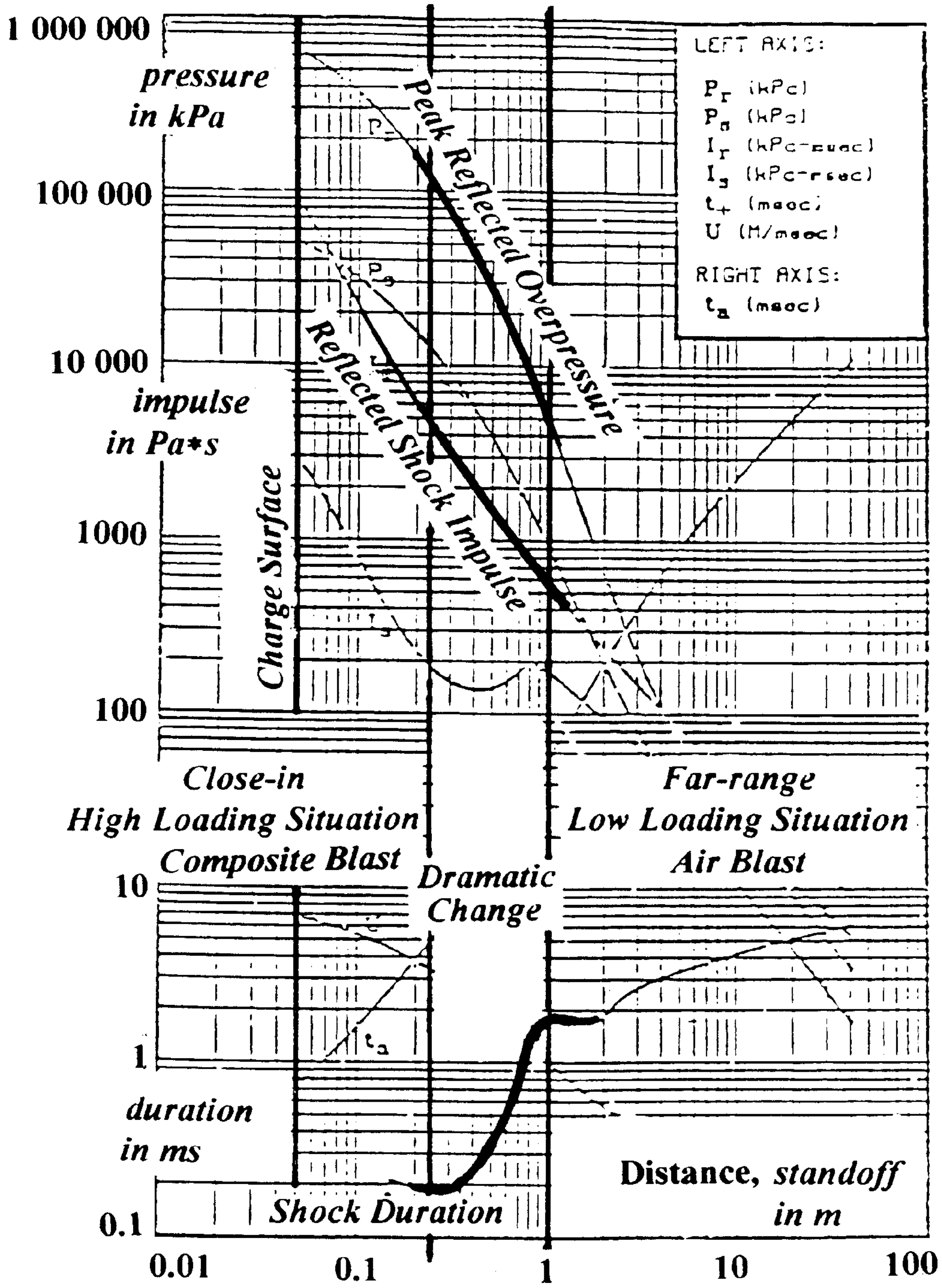
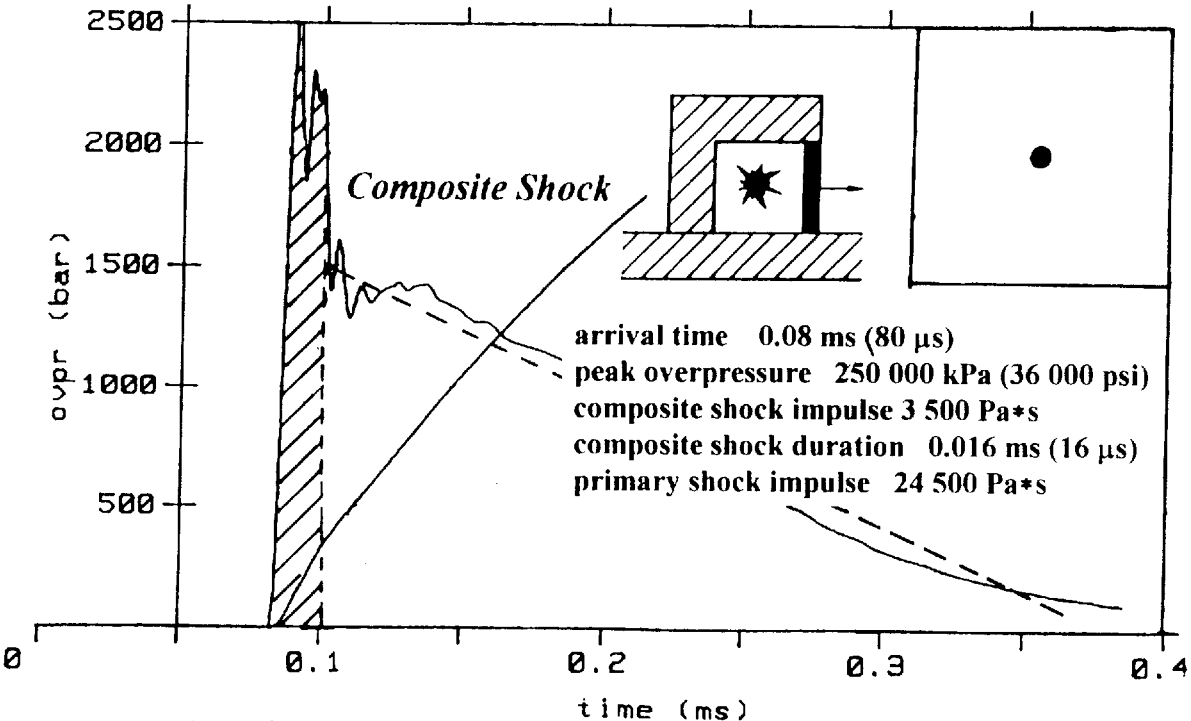


Figure 1 Airblast Parameters vs. Distance for a 1 Kilogram TNT Spherical Air Burst Technical Report ARBRL-TR-02555 Charles N. Kingery, Gerald Bulmash April 1984

FIGURE 2.1



arrival time 0.08 ms (80 µs)
peak overpressure 250 000 kPa (36 000 psi)
composite shock impulse 3 500 Pa*s
composite shock duration 0.016 ms (16 µs)
primary shock impulse 24 500 Pa*s

Figure 2.1
SHARC 2-D 25 kg Pentolite Spherical Explosion R = 0.5 m
Close-in *Composite Shock* Loading **DPM Phase I Test Arrangement**

FIGURE 2.2

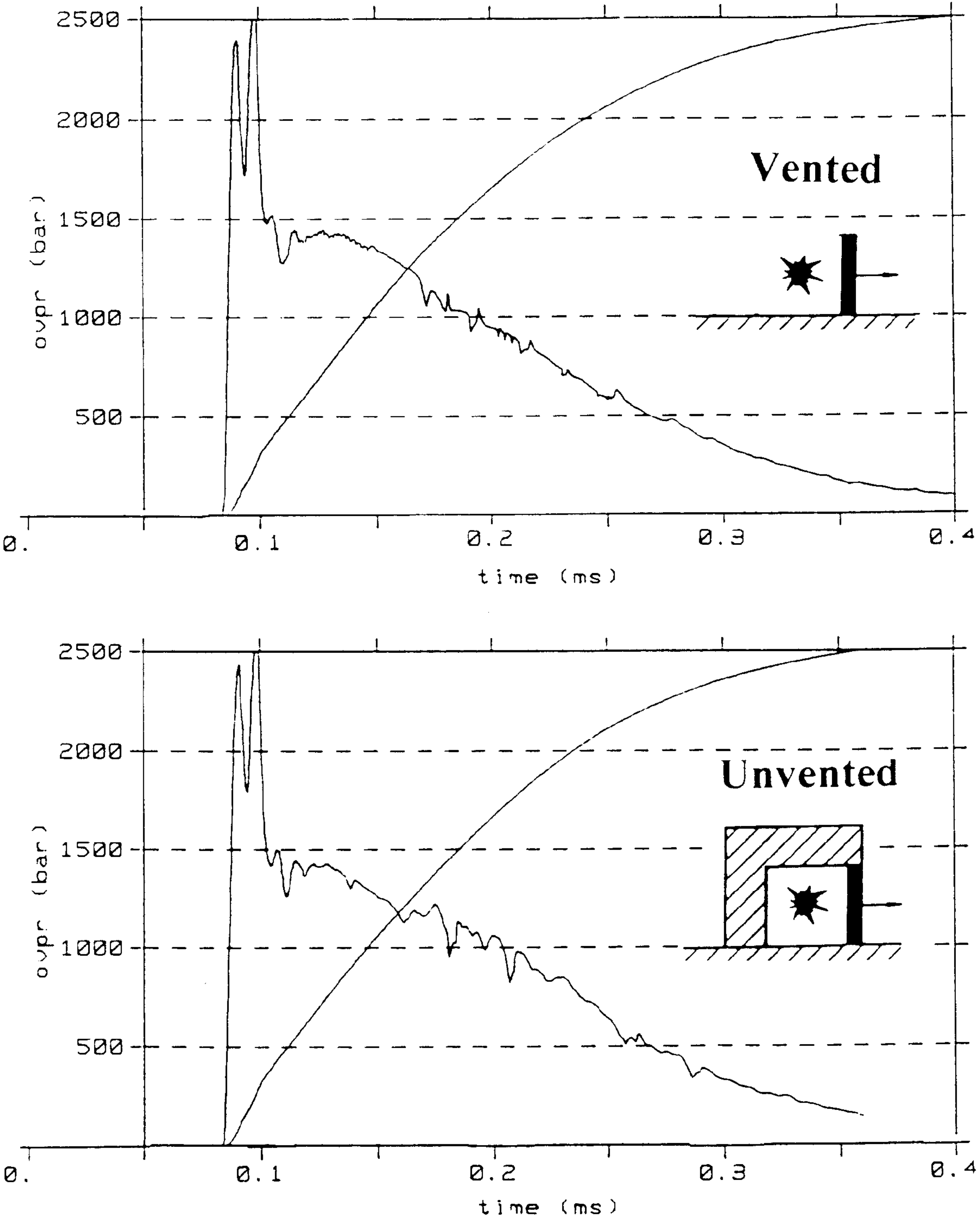
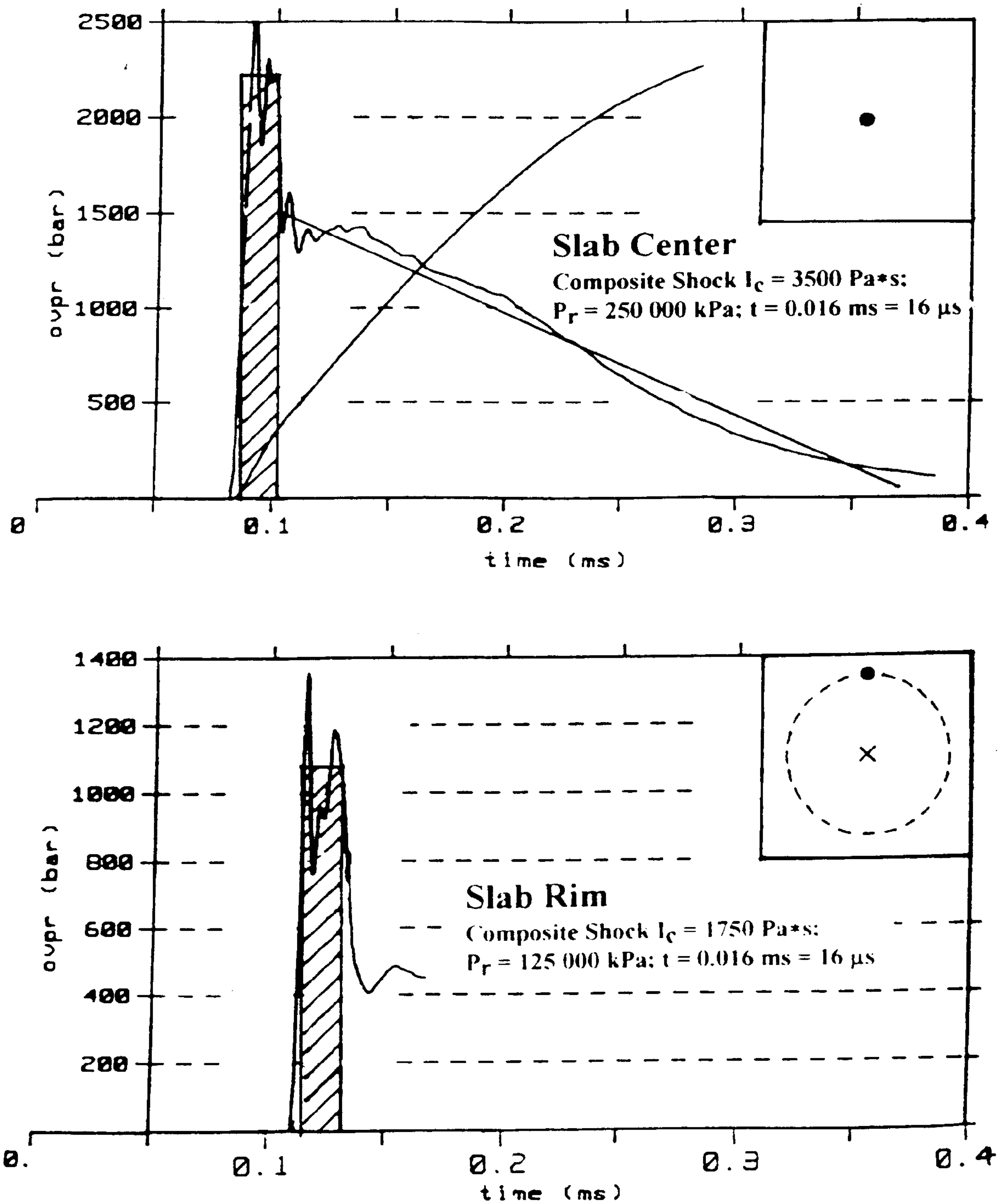


Figure 2.2
SHARC 2-D 25 kg Pentolite Spherical Explosion R = 0.5 m
Unvented and Vented Configurations.
Identical Pressure-Time Histories for Close-in Composite Loading.

FIGURE 2.3



Slab Center

Composite Shock I_c = 3500 Pa*s;
P_r = 250 000 kPa; t = 0.016 ms = 16 µs

Slab Rim

Composite Shock I_c = 1750 Pa*s;
P_r = 125 000 kPa; t = 0.016 ms = 16 µs

Figure 2.3
SHARC 2-D 25 kg Pentolite Spherical Explosion R = 0.5 m
Composite Shock reduced by a factor of 2 from the center to the rim

FIGURE 3.

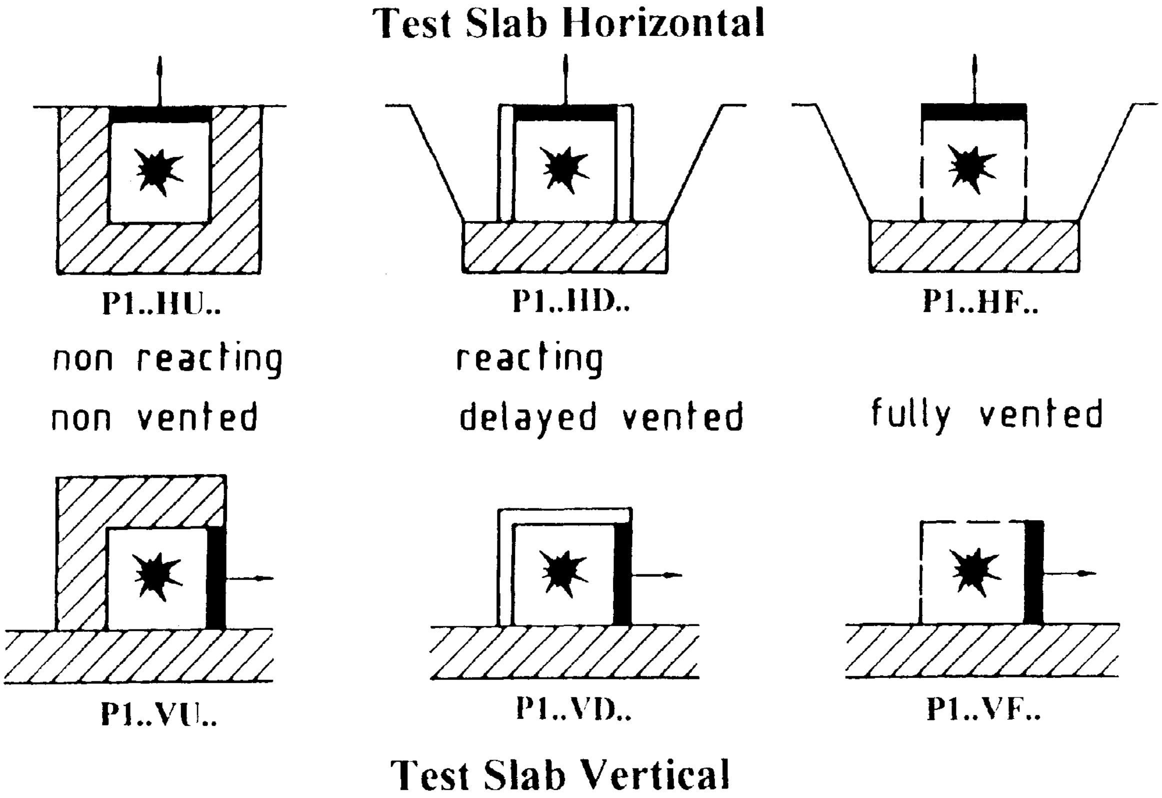


Figure 3 **DPM Phase I Test Arrangements**