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PHERMEX APPLICATIONS TO STUDIES OF DETONATION
WAVES AND SHOCK WAVES

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ABSTRACT

A 20-MeV, high intensity, high current, flash radiographic machine, PHERMEX, has been built to complement other hydrodynamics facilities of the Los Alamos Scientific Laboratory. In many experimental situations, observations of hydrodynamic phenomena may be obtained by means of techniques unique to flash radiography. This device is used primarily to implement studies in areas related to detonation and shock waves, jet formation and the interaction of jets with matter, spalling and cratering. In certain simple geometries, shock wave and rarefaction wave velocities, particle velocities, and time variation of both edge positions and mass density distributions can be obtained. This facility and the choice of its design parameters are discussed. Radiographs illustrating typical experiments are included. Results of several experiments, germane to this symposium, are presented; these include measurements of the Hugoniot pressure at zero particle velocity, and the particle velocity and sound speed behind a detonation wave in solid explosives.

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INTRODUCTION

For many years flash radiography has provided and continues to provide an elegant technique for observing high-speed hydrodynamic phenomena (1-18) associated with shock and detonation waves.

Although many other methods are used to acquire information relative to these same phenomena, flash radiography is one of very few schemes that offers direct observations. Until recently only modest flash radiographic facilities existed. Commercially available equipment, as well as the state of the art, still impose rather severe constraints upon both techniques and apparatus. When utilizing conventional flash radiographic equipment, the choice of object size may be dictated not by what is optimum hydrodynamically, but rather overwhelmingly by the penetration capability of available radiation flux consistent with blast protection. Often this choice is not consistent with acquiring the most precise information.

Precision radiography requires accurate resolution of edges and discontinuities as well as accurate resolution of mass density distributions. Precision is degraded by many things but especially by scattered radiation. In this sense scattered radiation, which increases with object thickness, can serve to establish a practical upper limit of object thickness which can be radiographed usefully. Results of both theoretical and experimental studies at Los Alamos (19)

clearly demonstrated that precision determination of mass distributions in very thick sections, even greater than ten mean-free-paths thick, is not only physically feasible with adequate flux but also practical with a variety of object configurations provided careful control is exercised over alignment, penumbra effects, geometric symmetry, scattered radiation, detector latitude (20), calibration techniques, and the host of other problems which are ever present. This study also demonstrated the feasibility for constructing an electron accelerator capable of performing tasks of interest to the Los Alamos Scientific Laboratory. Indeed, such a device was considered practical as early as 1952 utilizing techniques and commercially available apparatus which existed then. However, this project formally began with the initiation of detailed design and construction in 1957 at which time both techniques and equipment had matured vastly, resulting in a far superior flash radiographic facility than could have been constructed in 1952.

PERMEX is capable of performing precision flash radiography in objects about four mean-free-paths thick when using conventional film techniques and about ten mean free paths when using electronic detectors.

Although there has been significant advancement in the production of intense sources of x rays, almost insignificant progress has been achieved in the techniques of precise data acquisition in

this field. The great increase of useful radiation flux has only made the application of photographic processes, i. e., film blackening techniques, somewhat less unpalatable.

PERMEX CHARACTERISTICS

In flash radiographic studies of explosives and explosive-driven systems there are two significantly important aspects. One of these is the precise location of edges as well as hydrodynamic discontinuities; the other is the statistically significant measurement of areal distributions of mass density. Areal density is defined here as the integral of the mass density taken over the rectilinear path followed by the primary radiation traversing the object. It is this function which radiography is so well suited to determine. These two aspects are not mutually exclusive; both demand high radiation intensity, considerable total flux and a small but finite size radiation source. Therefore the choice of optimum x-ray machine characteristics needed for a given class of problems requires consideration of radiation production efficiency, absorption statistics, detector efficiency and latitude, total flux, as well as radiation intensity, and the spatial distribution of the useful portion of the radiation field. A detailed study of these parameters was made with respect to experiments of general interest to this laboratory (21). It was demonstrated that for many experiments an acceptable radiation flux was equivalent to

that generated by 5 to 10 μC of 20-MeV electrons providing they were delivered to a 3-mm diameter tungsten target for 0.2 to 0.1 μsec or less.

When this project formally started, the most attractive device for this service was the standing wave linear accelerator (22, 23, 24). This same situation is still true today. The PHERMEX accelerator system consists of three cylindrical copper-lined cavities operating at 50 Mc/sec in the TM_{010} mode. Physically each cavity is about 4.6 meters in diameter and about 2.6 meters long. Each contributes about 7 MeV to the injected electrons. Although the present ejected current is about 70 A, averaged over 0.1- or 0.2- μsec pulses, only a fraction of these electrons are useful in that one-fourth to one-third have momenta components which, upon striking a tungsten target, can produce radiation within a useful spectral range and spatial distribution.

Finally the electron beam is focused upon a 3-mm diameter aperture in a thick beryllium collimator. After emerging from this collimator, the beam passes through a 0.5-mm thick beryllium window and falls on a 1-mm thick tungsten target. Target currents greater than 20 A at about 20 MeV now provide fluxes of about 10 roentgen per 0.2- μsec pulse or 5 roentgen per 0.1- μsec pulse measured on-axis at 1 meter from the target. Because of the nature of this accelerator, a 0.2- μsec pulse of gamma rays consists of

10 sub-bursts, each about 6-nsec long. The average dose rate during a pulse is 50 r/ μ sec. Considering a bremsstrahlung production efficiency in the tungsten target of say 42 percent, gamma radiation is produced at an average rate of about 170 MW for 0.2 μ sec whereas the on-axis intensity at 1 meter is several megawatts per square centimeter.

PHERMEX is illustrated by the line drawing in Fig. 1. Here the course of the electron beam can be traced from the thermionic cathode in the electron gun to the radiation generating target. The physical layout of the PHERMEX complex was dictated primarily by its reinforced concrete housing which provides necessary protection from blast and shrapnel. Indeed, this is one reason why the ejected electrons are piped about 10 meters to the target located outside of the blast-proof bunker.

The present capability of PHERMEX has been expressed in terms of its beam energy, radiation flux output, pulse length, and spot size. It should be mentioned in passing that a program aimed at virtually doubling the radiation intensity and increasing the beam energy to about 25 MeV is nearing completion. This should greatly enhance the radiographic capability of the machine.

ARRANGEMENTS AND PROCEDURES FOR EXPLOSIVE EXPERIMENTS

Figure 2 represents schematically a radiographic geometry used for many of the explosive experiments reviewed below. Target protection is also shown in this illustration. Data are recorded on photographic film which must be protected from blast damage. The photograph in Fig. 3 is an illustration of the type of blast-proof cassette that is used most often. The hollow aluminum cone is capable of protecting a 35.5-cm diameter film from the ravages of about 20 kg of high explosive located with the film plane as close as 70 cm from the charge center. Experience has demonstrated that film can be protected even less expensively by using thick plates of duraluminum; indeed other workers have found this method satisfactory for their specific applications. However, scattered radiation which reaches the film from such an array effects a significant loss of radiographic resolution. As a result of this attendant degradation of information the conical aluminum cassettes, developed at Los Alamos, are preferred.

Because of the extreme latitude of the transmitted radiation intensity that is encountered in some experiments, several film-screen combinations may be used in one cassette. For example, with the typical geometry shown in Fig. 2, useful film blackening has been realized for x-ray flux transmission ranging from 10^{-3} to

almost unity. Typical film-screen combinations could include three films: one Kodak KK film intensified with two 1-mm thick lead screens, one Kodak KK film intensified by one 1-mm thick lead screen, and one Kodak AA film intensified with two 1-mm thick lead screens. In those experiments having adequate flux, wherein transmission is bound within a small range of latitude, one type KK film with lead screens is often adequate. Where greater sensitivity is required, type F films, intensified by tungstate screens, are used.

Although high-speed electronic detectors, about 10^3 times more sensitive than the fastest film-screen combination, have been developed for special radiographic experiments, these involve only standard electronic techniques, hence they will not be discussed. In general, mass distribution measurements are obtained from film by means of existing well known photometric techniques supported by appropriate film calibration. In spite of the fact that recent radiation detection schemes, such as thermoluminescent devices, have extended detector latitude by several orders of magnitude, the best known method of measuring radiation flux for flash radiographic applications is still conventional industrial photometry.

TYPICAL EXPERIMENTS

Among the experiments that are reported below there are several that pertain to measurements of the Chapman-Jouguet particle

velocity and sound speed and one that is concerned with an examination of the polytropic equation of state for reaction products of condensed explosives. Other experiments are discussed to indicate the scope of parameters that can be investigated by flash radiographic techniques.

By embedding a series of foils at precisely known initial positions in an explosive to be studied and allowing the detonation wave to sweep by these foils, a flash radiograph, appropriately timed, permits a study of foil displacement as a function of time. This displacement can in turn be related to the particle velocity behind the front by the theory being examined. The quality of fit of these data thus provides the means of testing the applicability of the theoretical model. One model is in rather good agreement with experiment. Such a model assumes plane wave motion, that mass and momentum are conserved, and that the Chapman-Jouguet condition is satisfied. A polytropic equation of state, $P = K\rho^{\gamma}$, is assumed to describe the adiabatic relation at any point behind the front (25). The K and γ are taken to be constant throughout the region of interest. Analysis of this model leads to a linear relationship between the instantaneous position of each foil as normalized to the position of the detonation front and the particle velocity at the foil position as normalized to the Chapman-Jouguet particle velocity.

Figure 4 illustrates such an experiment. A 10-cm cube of Composition B was initiated by a plane wave generator. Eight foils

of 2.5×10^{-3} cm thick tantalum were embedded in the HE. Another was placed on the surface and the assembly was then capped with two 0.635-cm thick slabs of Lucite, with the tenth foil sandwiched between them to serve as a position fiducial. When the detonation wave had proceeded to a point roughly midway between the eighth and ninth foils, the radiograph was taken. The resultant data are shown in Fig. 5. Circles represent experimental points—one for each of the eight foils acted upon by the detonation. The solid line is derived from the polytropic equation of state (25). The dashed line is of interest inasmuch as it originates from use of the Becker-Kistiakowsky-Wilson equation of state in a one-dimensional hydrodynamic calculation (26).

These data can also be used to determine that value of the C-J particle velocity which satisfies the assumed model. A weighted average of the velocity data gives a value for the C-J particle velocity of 0.208 cm/ μ sec. No error is assignable until an error analysis of the overall experiment has been performed.

The foregoing discussion of the hydrodynamic model of a detonation wave leads naturally into the second experiment in which the sound speed behind a plane detonation wave was determined. When a detonation wave strikes a free-surface of explosive, a rarefaction wave is born and immediately proceeds into the explosive reaction products. With a sufficiently high degree of reproducibility

of explosive systems, the progress of such a rarefaction wave can be followed by means of radiographs of successive shots. A radiograph of such a rarefaction wave is seen in Fig. 6. This was formed when a plane detonation wave in Composition B impinged normally upon a planar free-surface. Here the free-surface expanded into a vacuum to eliminate the complications of shock waves in air.

The slope of the space-time history of this wave, taken at the instant the detonation wave struck the free-surface, provides a measure of the rarefaction wave velocity, u_r . With an independent measure of the Chapman-Jouguet particle velocity, u_1 , the sound speed is simply $c_1 = u_1 + u_r$, when accounting for the relative direction of the rarefaction wave and the particle flow.

This work is still in progress and, as yet, there is insufficient evidence to establish the ultimate precision with which the Chapman-Jouguet sound speed can be determined by this technique. So far, preliminary data, without an error estimate, show a sound speed value of about 0.578 cm/ μ sec in Composition B.

A third experiment was performed to determine the zero-particle-velocity Hugoniot pressure (27). This involved observing the speed of the reflected shock waves U_2 which arise from the normal collision of two identical plane detonation waves of speed D . The ratio of the pressure behind the shock wave, P_2 , to the C-J pressure, P_1 , is given by the equations of conservation of mass and momentum

$$\frac{P_2}{P_1} = \pi_{2,1} = \frac{D + U_2}{D - u_1} \quad (1)$$

If D and u_1 are already known then a measure of U_2 provides the missing piece of information. Equation (1) can be further modified if one invokes the Chapman-Jouguet hypothesis and assumes a constant gamma polytropic equation of state for the detonation reaction products.

Thus

$$\pi_{2,1} = \frac{\gamma_1 + 1}{\gamma_1} \left(1 + \frac{U_2}{D} \right) \quad (2)$$

Using the value of $\gamma_1 = 2.767 \pm 0.035$ given by Deal (28) for Composition B and the measured values of U_2 and D of 0.575 cm/ μ sec and 0.795 cm/ μ sec respectively, the pressure ratio is 2.345. The error in the ratio U_2/D is about 1%. The data from which U_2 was determined are shown in Fig. 7 in a space-time plot, and a typical radiograph of reflected shock waves in Composition B may be seen in Fig. 8.

A bit more information might be inferred from these same values of U_2 and D . If one uses the equations of conservation of mass, momentum, and energy, assumes a constant gamma polytropic equation of state for the gases, and invokes the Chapman-Jouguet hypothesis, then the velocity ratio, U_2/D , can be described by a function of gamma only. Indeed, if γ_1 and γ_2 represent respectively the gas ahead of and the gas behind the reflected shock, the pressure ratio

across the reflected shock can be expressed as

$$\overline{P}_{2,1} = \frac{A}{2} \left[1 + \sqrt{1 - 2A^{-2} \left(\frac{\gamma_2 - 1}{\gamma_1} \right) \left(\frac{\gamma_1 + 1}{\gamma_1 - 1} \right)} \right] \quad (3)$$

where

$$A = \frac{2\gamma_1 + \gamma_2 + 1}{2\gamma_1} + \frac{\gamma_2 - 1}{\gamma_1 - 1}$$

Thus

$$\frac{U_2}{D} = \frac{\gamma_1 \overline{P}_{2,1}}{\gamma_1 + 1} - 1 \quad (4)$$

Equation (3) obviously implies a double gamma Hugoniot equation. However, if a single polytropic equation were to be used with $\gamma_1 = \gamma_2 = \gamma$, then the experimentally measured ratio of U_2/D implies $\gamma_2 = 2.514 \pm 0.045$ for the gases behind reflected shock. On the other hand, if $\gamma_1 = 2.769$ as reported in reference (28), then $\gamma_2 = 2.692$ from Eq. (4). Furthermore, the pressure ratio as given by Eq. (2) remains unchanged since the gamma in that equation is always γ_1 .

This experiment may appear to question the validity of the constant gamma polytropic equation of state for the reaction products of solid explosives. However, inconsistency of data, small aplanarities of the detonation waves and even deviation from the Chapman-Jouguet hypothesis (29) could provide comparable results.

Much more extensive work is needed to uniquely clarify some of these issues.

Figures 9 and 10 illustrate the development of a Munroe jet which is formed in a flat-bottomed rectangular cross section groove in Composition B. The first of these radiographs indicates an early state in the growth process. The second shows the equilibrium form of the jet. Over a rather wide range of parameters the transient shape of this jet scales with the ratio of detonation wave excursion from the groove bottom to the width of the groove.

The radiograph of Fig. 11 is that of an explosive-driven thin aluminum plate colliding obliquely with a thicker plate of the same material. This radiograph shows the collision process, the shock wave generated in the thicker aluminum, a reflected shock wave in the high explosive gas products, and rarefaction waves in both the aluminum and the HE gases. The store of information in these kinds of experiments is obvious.

Several 25-mm thick aluminum plates were driven by 10-cm cubes of Composition B. The trajectories of the back surface, the transmitted shock, the reflected shock, and the front surface were determined radiographically from a sequence of shots. The unadjusted raw data, plotted in Fig. 12, illustrate these trajectories in space and time. The solid lines were computed by means of codes developed at the Los Alamos Scientific Laboratory (26). The radiograph of

Fig. 13 represents this type of experiment. A series of experiments like these, using suitable target materials can provide directly Hugoniot and isentrope data on the reaction products in a way that is independent of measurements of free-surface velocities of plates.

Figure 14 is typical of spalling experiments. In this case a 25-mm thick plate of nickel was driven by Composition B. Dynamic tensile strengths of a number of metals have been determined for a variety of pressure gradients and stress rates. Since this work is still incomplete no results will be reported here.

The last example of PHERMEX experiments presented here is illustrated in the radiograph of Fig. 15, where two aluminum jets have collided at right angles and appear to be vaporizing. This is representative of studies now under way to investigate the formation of jets, especially metallic jets arising from known surface perturbations. Unlike the more common Munroe jets which are formed by explosive-driven metal lined cavities, these kinds of jets seem to possess many of the characteristics of the gaseous Munroe jets discussed earlier in that their origin lies in the collision of the expanding free-surfaces provided the free-surface collision occurs before spalling.

DISCUSSION

PHERMEX can be employed in multiple experiment flash radiography to obtain time histories of various hydrodynamic phenomena. It is possible to locate edges as in normal skiagraphy, to measure the velocity of shock waves, rarefaction waves, contact surfaces, and to measure particle velocity behind shocks, detonations, and rarefactions. Mass density distributions can be obtained. A time sequence of such distributions provides a means of determining velocity gradients, hence viscosity as well as the time variation of mass density gradients. Accurate measurements of these hydrodynamic variables provide Hugoniot and isentrope information for extreme states of matter.

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FIG. 1 SCHEMATIC DIAGRAM OF PHERMEX

FIG. 2 EXPERIMENTAL GEOMETRY

Fig. 3. Blast proof cassettes. Typical damage is shown.

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A-1

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Fig. 4. Dynamic radiograph of foils embedded
in high explosive.

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FIG. 5 FOIL EXPERIMENT DATA

Fig. 6. Radiograph of rarefaction wave.

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FIG. 7 X-T PLOT OF
REFLECTED SHOCK WAVE

Fig. 8. Reflected shock waves arising from
two colliding detonation waves.

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Fig. 9. Formation of a Munroe jet.

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Fig. 10. Equilibrium shape of a Munroe jet.

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Fig. 11. Oblique collision of a flying plate with a
stationary plate.

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FIG. 12 TRAJECTORIES OF VARIOUS DISCONTINUITIES IN EXPLOSIVE DRIVEN PLATE EXPERIMENTS

Fig. 13. Radiograph of explosive driven aluminum plate showing shock wave in metal and shock wave in detonation products.

Fig 13

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Fig. 14. Spalling in nickel plate.

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FIG 14

Fig. 15. Colliding aluminum jets.

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