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FCT SIMULATION OF HOB AIRBLAST PHENOMENA,(U)
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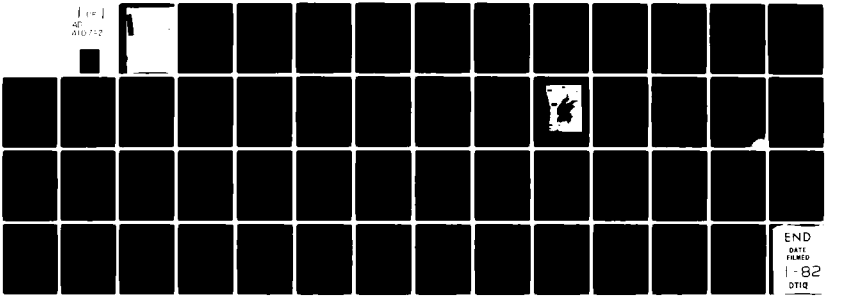

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Height-of-burst (HOB) detonations can create airblast environments which are more severe than surface burst environments at high overpressures (>100 psi). A double Mach stem structure develops during shock reflection from the ground at a range approximately equal to the HOB. This creates double peak static pressure waveforms with enhanced early-time impulses. Blast diffraction on above ground structures also

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18. Supplementary Notes (Continued)

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20. Abstract (Continued)

contains multiple peaks with enhanced loads and impulses. There is an ongoing interest in simulating these HOB environments for military applications. High explosives (HE) charges can be used to simulate the nuclear surface burst case below about 100 psi for reasonable yields (100T or more), but it appears that it is impractical to elevate large HE charges above grade to simulate the HOB case. In this paper we propose a new method for naturally simulating such HOB environments on a large scale. A hemispherical HE charge could be detonated near a natural slope which had been graded to form a large ramp. When the spherical blast wave reflects from this ramp a shock structure and environment is created which is similar to the HOB case. Validity of this concept is demonstrated by numerical simulations with a nonsteady 2-D FCT hydrocode. These calculations indicate that a 30° ramp located 200 ft from a 500T hemispherical HE charge will create 400 to 600 psi double peak static pressure waveforms at distances of 40 to 60 ft up the ramp; time between peaks is 1 ms. These waveforms correspond to a nuclear detonation at 100 to 120 ft/KT$^{1/3}$ and a ground range of 190 to 210 ft/KT$^{1/3}$.

CONTENTS

FCT SIMULATION OF HOB AIRBLAST PHENOMENA

I. INTRODUCTION

It is now recognized that height-of-burst (HOB) detonations can create more severe airblast environments than surface burst (SB) detonations, especially at high overpressures. In the HOB case, the spherical blast wave reflects from the ground, initially as a regular reflection. Then at a ground range approximately equal to the height-of-burst, the shock reflection makes a transition to a double Mach shock structure. This double shock structure creates secondary peaks in the static pressure at and near the ground and thus enhances the early-time HOB airblast impulses compared to the SB case. As shown experimentally by H. J. Carpenter at MABS-IV (Ref. 1), these secondary peaks of the HOB case can be much greater than the first peaks.

When a double Mach shock structure reflects from an above-ground structure, it can produce enhanced diffraction loads. HOB diffraction loads are compared with SB loads in Fig. 1 which was constructed by scaling data from the 1000-lb Pentolite sphere experiments on the recent MIGHTY MACH test series (Ref. 2). As is evident from this figure, the early-time HOB loading impulses are about twice the SB values. Similar effects are shown in Fig. 1 for the static pressure histories and impulses which apply to loads on flush mounted structures.

For military applications, there is a need to simulate these HOB blast environments on a large scale in order to test the response and survivability of large-scale or full-scale military systems. Explosive yields from kilotons to megatons are required. Suspension of such large high explosive (HE) charges is impractical and could lead to poor quality blast fields due to interference effects from the charge support structure.

In this paper we propose a novel approach for simulating HOB blast environments on a large scale. The concept is shown in Fig. 2. A hemispherical surface burst HE charge would be used to create a free-field blast wave. The charge would be situated near an up-slope which had been graded to form a large ramp. When the spherical blast reflects from the ramp, a double Mach shock structure can be created (within certain constraints on wedge angle, θ_W, and incident shock Mach number). This concept relies on the similarity between the HOB-produced environments on horizontal surfaces and the environments produced by shock reflections on wedges or ramps. In Fig. 3 we compare some recent

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calculations with the FAST2D code:* a nuclear detonation at HOB = 104 ft/$KT_N^{1/3}$ versus a Mach seven square wave shock reflection from a wedge. The pressure contours show that for similar shock strengths and angles, the shock structures in the wedge and HOB cases are qualitatively similar; density contours are also qualitatively similar with a slip line emanating from the primary triple point. There are, however, quantitative differences: the Mach stem structure in the nuclear HOB case is more complex, with a bulge at the foot of the Mach stem; also, in the nuclear case, the reflected shock races rapidly through the high temperature (10^4 to 10^5 °K) fireball, while in the wedge case, the reflected wave propagates slowly into the lower ($\sim 10^3$ °K) temperature constant field behind the incident square wave shock. We believe, however, that these differences are of secondary importance.

A remaining question is: how well does the blast wave from a hemispherical HE charge simulate the nuclear free-field environment? In Figure 4 we compare the static and dynamic pressure waveforms for the HE and nuclear cases from Brode's one-dimensional (1-D) free air burst calculations (Refs. 3,4) at shock overpressures of approximately 100, 200 and 400 psig. In the HE case a contact surface (CS) separates the air from the detonation products. This contact surface causes a sharp jump in dynamic pressure due to the high densities of the products. Also evident in the HE case is a secondary shock, S_2, which faces inward but is being swept outward by the rapid expansion of the charge. The HE-driven blast wave gives a rather poor simulation of the complete nuclear waveform at high overpressures, due principally to the HE contact surface and secondary shock. However, the HE blast wave outside the contact surface is a reasonably good simulation of the nuclear case. We propose to use precisely this part of the HE blast wave and reflect it from the ramp to simulate the early-time nuclear HOB cases.

The remainder of the paper is organized as follows: Section II gives a conceptual design of the ramp HOB simulator; Section III describes the 2-D finite difference scheme which we used to investigate numerically the flow fields on and near the ramp; Section IV presents the results of these calculations, while conclusions and recommendations are offered in Sections V and VI.

*This code uses the Flux Corrected Transport (FCT) algorithm, described in Section III, to maintain sharp discontinuities.

II. CONCEPTUAL DESIGN OF THE HOB SIMULATOR

The design objective for this simulator is to produce the high overpressure (say 100 to 1000 psi) double-peak flow fields which simulate nuclear HOB detonations in the Mach reflection regime with high fidelity. The simulator should be reasonably inexpensive and readily constructed. The design concept should be extendable to large yields.

The primary design parameters for the simulator are the location of the front edge of the ramp, GR_R, and the ramp angle, θ_W. The conceptual design process begins with an HE free-air pressure-range curve for 1 lb of Pentolite. A ramp was assumed to be located at a GR_R corresponding to free field shock overpressures of 500 psi or 150 psi. Assuming various ramp angles, we used reflection factors (Ref. 1) to determine the peak static pressure versus ramp ground range, RGR. Parametric results are presented in Fig. 5. Inserts give the results scaled to a 500T surface burst which are equivalent to about a one-kiloton nuclear surface burst case. Examination of the results in Fig. 5 indicates the following trends:

- A requirement for a high pressure (400 psi to 600 psi) simulator forces one to either move the ramp closer to the charge, or increase the ramp angle, or both.
- One would prefer to move the ramp away from the charge so that the HE free field is close to the nuclear case; however, this leads to large (and presumably impractical) ramp angles.
- Decreasing the ramp angle tends to make the Mach stem rise more rapidly thus increasing the separation between the first and second peaks; we speculate that this could lead to a yield amplification on the front-end of the waveform.
- Transition to Mach reflection occurs at the leading edge of the ramp for $\theta_W = 30^\circ$ and 40°; the transition point (TP) for the $\theta_W = 60^\circ$ occurs at about one-half the distance up the ramp.

The 30° ramp at the 500 psi station appears to be an interesting case--it is feasible to construct and the 600-psi shock overpressure will occur at about 50 ft up the ramp, thus allowing plenty of time for the Mach stem height to grow. Peak pressures will range from 1500 psi at the beginning of the ramp to about 300 psi at the far end.

III. COMPUTATIONAL TECHNIQUE

A numerical simulation of the shock diffraction for the ramp HOB simulator (a 30° ramp starting at 200 feet from a 500T hemispherical HE charge) was performed with a nonsteady two-dimensional (2-D) hydrocode, FAST2D. The objectives of the calculation were to validate the ramp HOB simulator design and to evaluate, in detail, the flow field in the vicinity of the ramp. The FAST2D code solves the balance laws of gasdynamics on a sliding grid in the general form:

$$\frac{\partial}{\partial t}\int_{\delta V(t)} \phi dV = -\oint_{\delta A(t)} \phi\,(\underline{u}-\underline{u}_g)\cdot d\underline{A} + \oint_{\delta A(t)} \tau dA \qquad (1)$$

where ϕ represents the mass, momentum, energy or species mass density (for multi-material calculations) in cell $\delta V(t)$, u and u_g represent the fluid and grid velocities, respectively, and τ represents the pressure/work terms. The finite-difference approximation to Eq. (1) uses a vectorized Flux-Corrected Transport (FCT) algorithm, ETBFCT (Ref. 5), which gives an accurate and well-resolved description of shock wave propagation without the necessity of an *a priori* knowledge of the number, location or character of the gasdynamic discontinuities in the problem. The linear portion of this algorithm is fourth-order-accurate spatially for constant-velocity advection problems, and has a nonlinear flux-corrected antidiffusion stage which automatically provides the local dissipation needed to accurately model discontinuities. The formulation of the algorithm allows the grid to slide with respect to the fluid without introducing additional numerical diffusion. This general adaptive regridding technique permits fine zones to be concentrated in the region of greatest physical interest, thus reducing computational costs with no serious loss in resolution.

Since the ETBFCT algorithm is one-dimensional, time-splitting must be employed to solve two-dimensional problems. Time-splitting makes the boundary condition on the ramp particularly easy to implement. The ramp is represented as a series of "stairsteps" (of varying height and depth) along the interface between the extremal interior zones and a corresponding set of guard cells. A guard cell is defined as the right-most cell in the r-direction during the r-sweep, and the bottom-most cell in the z-direction during the z-sweep. The stairstep boundary conditions are reflective, which requires pressure, density and energy to be continuous and the corresponding velocity normal to the stairstep to vanish.

The numerical simulation began with a 1-D FCT calculation of the blast wave driven by a one pound spherical charge of PBX-9404 in air. The initial conditions, which are shown in Fig. 6, were taken to be the self-similar flow field corresponding to a spherical Chapman-Jouguet detonation wave (Ref. 6), at the time the detonation wave reaches the charge radius, r_o = 3.89 cm/lb$^{1/3}$. A Jones-Wilkins-Lee (JWL) equation of state (EOS) was used for the detonation products and a real air equation of state was used outside the HE/air interface. These EOS specify the pressure as a function of density and internal energy. The HE/air interface was followed by solving a conservation law for the mass fraction ρf (where f=1 in the pure HE and f=0 in the pure air). The equations of state were blended in the mixed cells (0<f<1) according to Dalton's law. A fixed grid of 500 cells was used with a mesh spacing Δr = 0.1025 cm/lb$^{1/3}$, so that the initial flow field in the charge occupied about 38 computational cells. The flow field results at the end of the 1-D calculation (cycle 1281, t = 152 μs/lb$^{1/3}$) are shown in Fig. 6. The shock overpressure is 445 psig. The density distribution shows a jump at the HE/air interface; inside the interface is a secondary inward-facing shock which is being swept outward by the supersonic flow.

These results were scaled up to the 500 ton HE surface burst case by multiplying all times and ranges by the scale factor, SF = $(2\text{x}10^6)^{1/3}$ = 125.992. The shock radius at this time of 19.15 ms/500T$^{1/3}$ was found to be 198 ft/500T$^{1/3}$ with an overpressure of 445 psig (note that this point checks with the HE free air curve in Fig. 5). These results were then inserted as initial conditions in the cylindrical r-z FAST2D code, with one approximation. Since the γ's ahead and behind the HE/air interface were quite close (γ_{HE} = 1.25 versus γ_{air} = 1.30), the HE products were modeled with the real air equation of state, and the 2-D interface was not followed specifically with a mass species conservation law. The 2-D mesh consisted of 150 x 150 cells with a moving fine mesh region (55 x 55 cells, Δr = 5 cm and Δz = 2.8868 cm with $\Delta z/\Delta r$ = tan 30°) which followed the Mach stem. The calculation was run 5601 cycles. Diagnostics for the 2-D calculation consisted of 46 environment time histories (at 40 stations on the ramp and 6 stations perpendicular to the ramp at a RGR = 60.5 ft) and contour plots of the flow field every 200 cycles. Times are denoted by the label $\Delta t=t-t_o$, which references everything to the incident shock arrival time at the foot of the ramp t_o=19.2 ms.

IV. CALCULATIONAL RESULTS

An overall picture of the spherical shock reflection from the ramp is displayed in Fig. 7 which gives the calculated pressure and density contours at various times (Δt=3, 5.61, 9.27 and 13.4 ms/500$T^{1/3}$); Fig. 8 gives a magnified view of the flow field at Δt=9.61 ms/500$T^{1/3}$. The shape of the shock structure for the simulator (i.e., the geometry of the incident wave, the Mach stem, and the kinked reflected wave) more closely resemble the shock structure for square wave reflections from a ramp (Ref. 7) than the nuclear HOB case (see Fig. 3). The density contours indicate that a contact surface (a slip line) emanates from the triple point (the confluence of the incident, Mach and reflected waves) and approaches the ramp at an angle of about 60°. Pressure contours indicate that a high pressure region is located in the vicinity of where the projection of the contact surface would strike the ramp.

Figure 9 gives an experimental shadowgraph of the shock wave structure formed by an 8 lb TNT driven blast wave (HOB = 1.04 ft/$lb^{1/3}$) diffracting on a 31° ramp. The incident shock pressure was about 120 psi at the foot of the ramp and about 75 psi at the time of the photograph (compliments of W. Dudziak, Ref. 8). The shock structure is qualitatively similar to that in Figs. 7 and 8. Fig. 9 shows that the reflected wave pushes the TNT products away from the ramp, thus maintaining a clean air flow (unpolluted by HE products) in the Mach stem region--a truly beneficial result! Note that this happens even in the low HOB case where the TNT products squish along the ground and push the TNT/air interface closer to the shock.

The calculated shock properties for the ramp HOB simulator are shown in Fig. 10 as a function of ramp ground range, RGR. The primary Mach stem pressure, p_1, ranged from about 600 psi to 400 psi. The second peak pressure, p_2, decayed from 1300 psi at the foot of the ramp to 400 psi at the 60 foot station. The peak pressures were determined from two methods: for RGR < 30 ft peaks were evaluated from pressure distributions at a fixed time, and these data are somewhat noisy due to the stairstep boundary condition modeling of the ramp; for RGR > 30 ft, peaks were evaluated by smoothing the pressure time histories two cells above the ramp, giving a smooth pressure-range curve.* Note that the second peaks are in reasonably good agreement with

*Unfortunately the pressure histories for RGR < 30 ft were not available for data analysis.

the prediction technique used to design the simulator. Also note that for RGR $\geq$ 40 ft the first and second peaks are equal.

The calculated shock arrival times for the first and second static pressure peaks are included in Fig. 10 The arrival time difference between peaks grows rapidly for the first 30 feet up the ramp, and then remains constant at about $1 ms/500T^{1/3}$. In addition, Fig. 10 depicts the Mach stem growth versus ramp ground range. The top of the Mach stem traces a path at an average angle of about 9 degrees above the ramp surface, which is consistent with shock tube data for square wave shock reflections from wedges (Ref. 7). Note that the Mach stem growth for the equivalent nuclear case is more rapid than in the case of the simulator.

Calculated static pressure histories are presented in Fig. 11 for various stations on the ramp (34 ft $\leq$ RGR $\leq$ 60 ft). The second peak dominates for RGR $\leq$ 34 ft, and then gradually melts into backside of the waveform. For RGR > 60 ft, the second peak has essentially disappeared. Comparisons of static pressure histories at h = 0, 1 and 5.5 ft normal to the ramp for station 17 indicate that there is no vertical pressure gradient on the front end of the waveform.

Fig. 12 gives the calculated dynamic pressure histories on the ramp at stations corresponding to the static pressure histories of Fig. 11. At small ground ranges, the second peak dominates the first peak. The second peak decays in magnitude and duration as the Mach stem progresses up the ramp, and has essentially disappeared for RGR > 60 ft. Comparisons of dynamic pressure histories at h = 0, 1 and 5.5 ft normal to the ramp for station 17 indicate very little vertical gradient for times less than 0.8 ms after shock arrival. However, the h = 1 ft station shows a strong second peak at about 1 ms which is absent from the h = 0 and 5 ft records. We believe that this is caused by a high density slug of gas at this altitude. A slip line (with high density material above and lower density material below) emanates from the triple point. As the slip line approaches the ramp it curls forward forming a region of high density fluid near the ramp surface (h $\sim$ $1 ft/500T^{1/3}$) while the Mach stem at this station is about 10 ft high. This effect is similar to the contact surface rollup observed in numerical simulations of nuclear HOB detonations and square wave shock reflections from wedges (Ref. 9). This increase in dynamic pressure near the ramp can be very important to airblast loads on above ground

structures--it increases both the peak loads and the impulses to approximately 2 ms/500$T^{1/3}$.

Let us now relate the simulator environment to an equivalent nuclear height-of-burst case. Fig. 13 gives the ideal, nuclear peak overpressure HOB curves as constructed by H. J. Carpenter (Ref. 10). Region A corresponds to the regular reflection regime, and region B corresponds to the Mach reflection regime where the static pressure waveforms on the ground contain two peaks. In regions B_1 and B_2, first and second peaks dominate, respectively. Along the dashed curve the first and second peaks are equal. Figure 9 indicates that for 30 ft $\leq$ RGR $\leq$ 60 ft, first and second peaks are equal and range from 600 psi down to 400 psi. Figure 13 then indicates that for this range in pressure, the nuclear HOB parameters are the following:

$$100 \text{ ft/KT}^{1/3} \leq \text{HOB} \leq 120 \text{ ft/KT}^{1/3}$$
$$190 \text{ ft/KT}^{1/3} \leq \text{GR} \leq 210 \text{ ft/KT}^{1/3}$$

Thus the simulator as analyzed in this report gives an airblast environment which is equivalent to a nuclear detonation at height-of-burst of about 110 ft/$KT^{1/3}$ and a ground range of about 200 ft/$KT^{1/3}$.

Finally, let us consider the effective yield of the simulator. A 500T high explosives surface burst produces a blast wave flow field which is equivalent to about a 1-KT nuclear surface burst (or a 2-KT nuclear free air burst). Nuclear static pressure waveforms in the 400 psi to 600 psi Mach reflection regime have double peaks with a time separation between peaks of about 2 ms/$KT_N^{1/3}$ (Ref. 10). The FAST2D calculation of the simulator flow field indicates a time separation between peaks of about 1 ms/$500_{HE}^{1/3}$/SB, i.e., the time separation for the simulator is too small by a factor of about two. We believe that the time separation between peaks can be increased by making the Mach stem climb more rapidly. This can be accomplished by simultaneously decreasing the ramp angle and moving the ramp toward the charge.

V. SUMMARY AND CONCLUSIONS

Height-of-burst detonations create airblast environments and diffraction loads which are more severe than the surface burst case in the high overpressure Mach reflection regime. There is an ongoing need to simulate these HOB environments on a large scale to validate the survivability of military systems to blast effects. We propose using an existing high explosives test bed, say a 500T hemispherical charge,

to create the free field blast environment. A large ramp would be located near the charge. Shock diffraction on the ramp generates, in a rather natural way, a flow field which simulates the HOB blast environment with high fidelity.

A parametric analysis of such HOB simulators indicates that a 30^{o} ramp situated about 200 feet from a 500T hemispherical charge would give useful environments. The flow field details near such a ramp were investigated with a 2-D hydrocode calculation. The calculation indicates that double peaked static and dynamic pressure waveforms were created near the ramp surface. In the 400 to 600 psi range, the calculated first and second static pressure peaks were equal. By use of the nuclear HOB curves, it was determined that the blast flow field corresponds to a nuclear detonation at a height-of-burst of 100 to 120 $ft/KT_N^{1/3}$ and a ground range of 190 to 210 $ft/KT_N^{1/3}$. Time separations between static pressure peaks were found to be about 1 $ms/500T_{HE/SB}^{1/3}$; this value was too small by about a factor of two for the nuclear case.

VI. RECOMMENDATIONS

Additional analysis should be performed to refine the HOB simulator design. The 2-D hydrocode simulations are quite useful because they allow one to examine the entire flow field in a non-interfering way. An improvement is needed on the boundary condition modeling of the ramp--the stairstep model gave very noisy results on the ramp surface. Small charge (say 4-lb hemispherical PBX-9404 charges) tests can provide an experimental definition of the blast environment. Ramp angle, location and surface curvature could be varied parametrically in such tests. Pressure gauges on the ramps can measure static pressure histories with high fidelity, while shadowgraph photography can capture the shock structure on the ramp. These results could be used to design a simulator which, we suggest, should be fielded on the next 500T HE test.

ACKNOWLDEGMENTS

We would like to acknowledge the contributions of H. J. Carpenter in this work. In July of 1980, he and one of the authors (A. Kuhl) first postulated the idea that a large ramp, in conjunction with an HE charge, could be used to simulate HOB environments on a large scale. His careful critique of the manuscript and his stimulating discussions on this subject are greatly appreciated.

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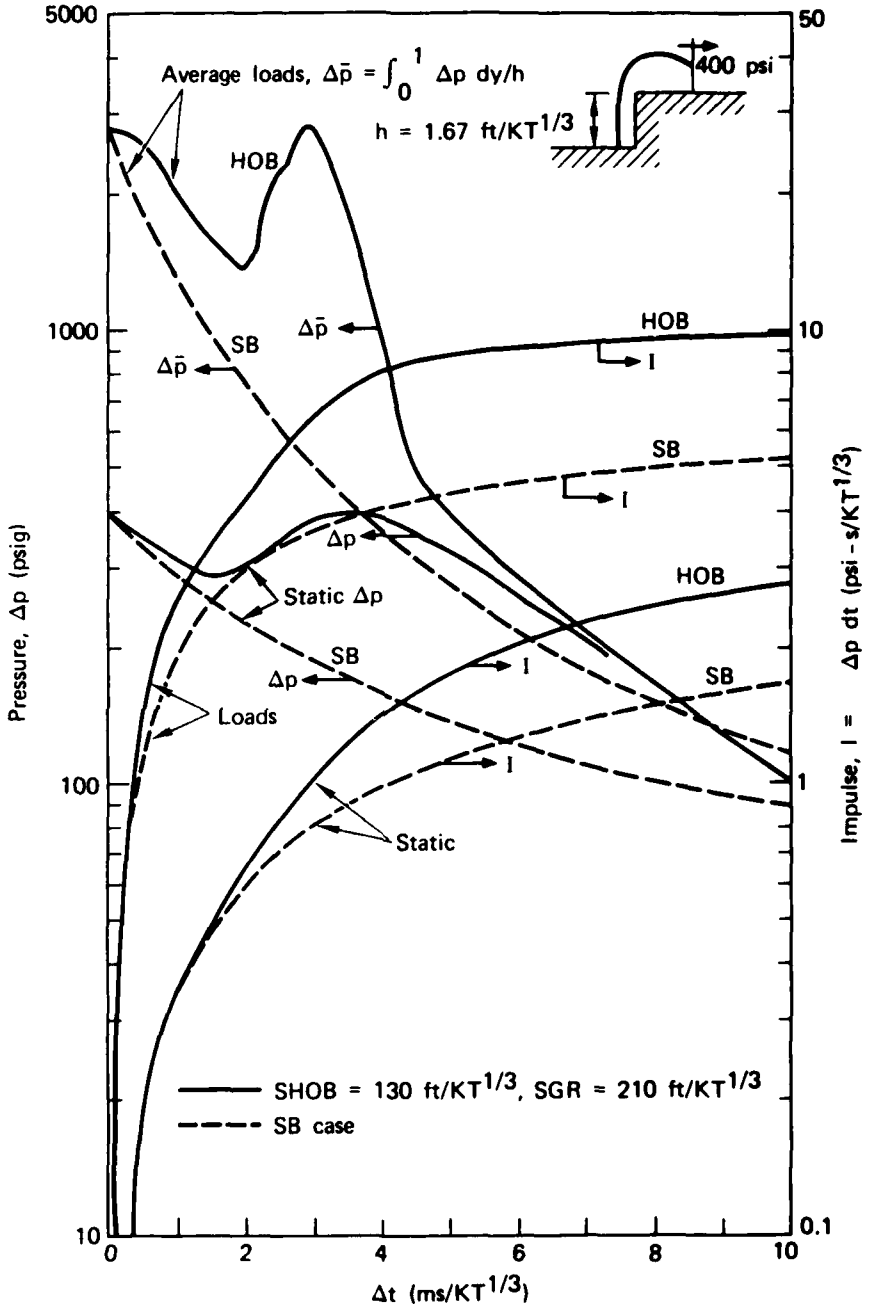

Fig. 1 — Comparison of nuclear surface burst and height-of-burst loads and impulses at the 400-psi station

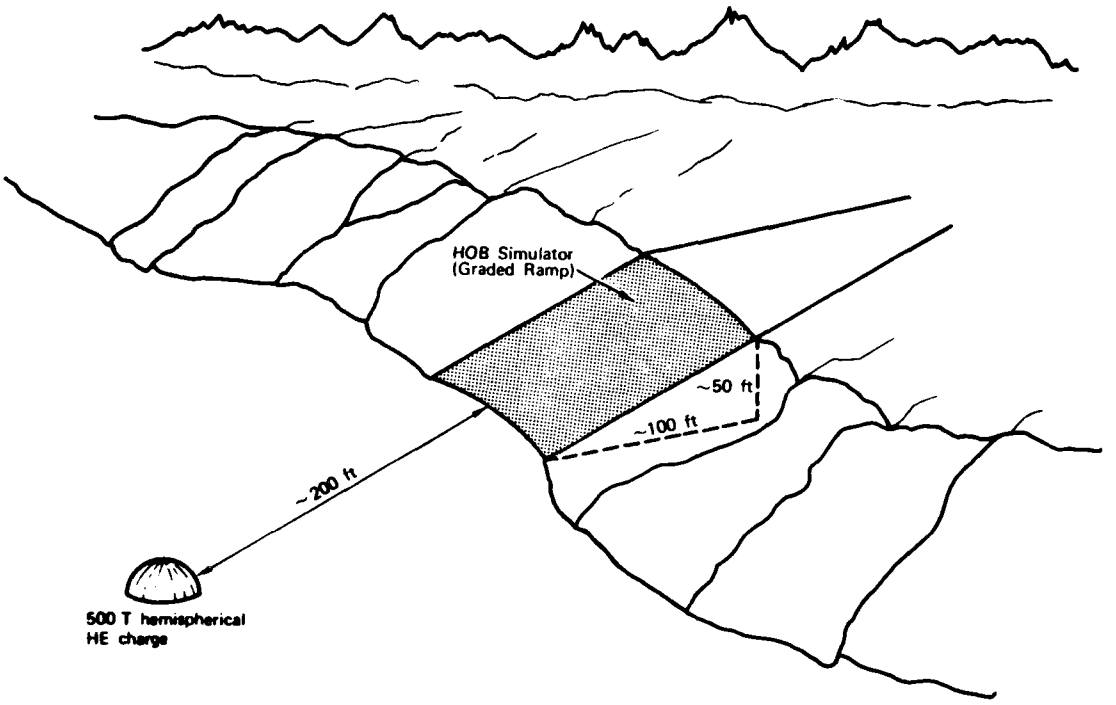

Fig. 2 — HOB simulator concept (graded ramp) on a large-scale HE test

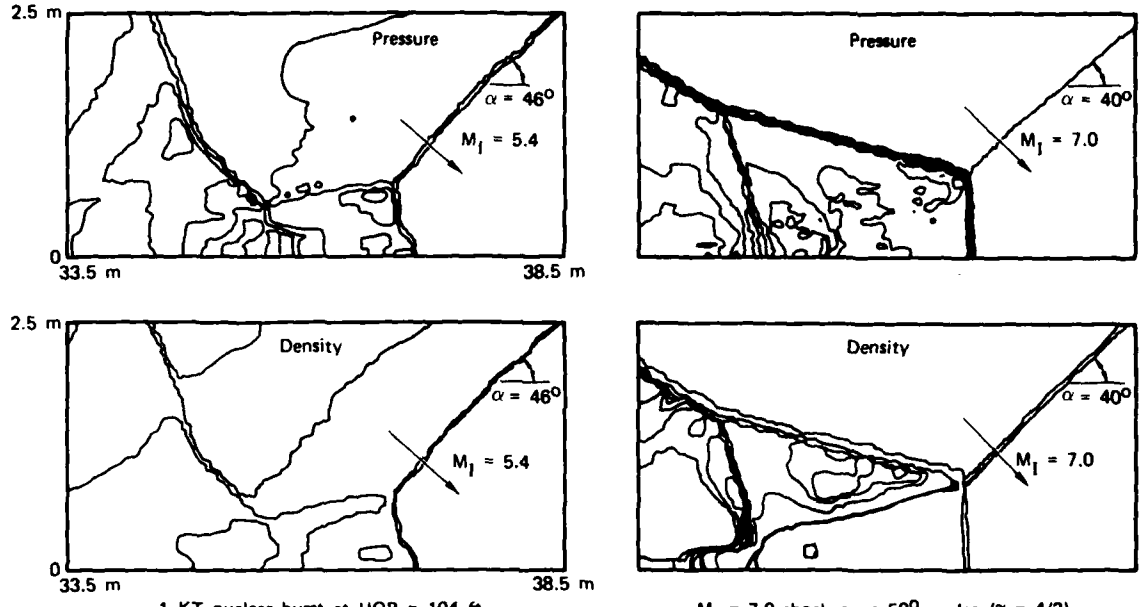

Fig. 3 — Comparison of calculated pressure and density contours for a nuclear HOB case and a square wave shock on a wedge

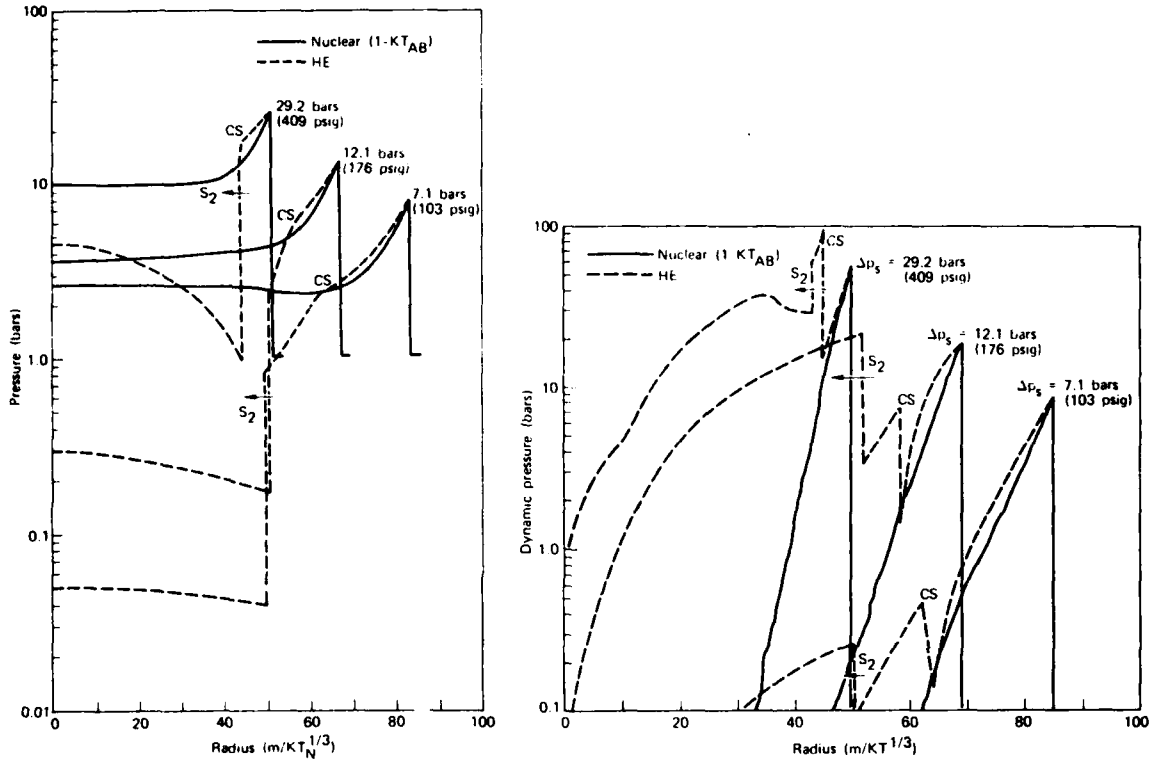

Fig. 4 — Comparison of HE and nuclear free-air burst static and dynamic pressure waveforms at shock overpressures ~ 100, 200, and 400 psi

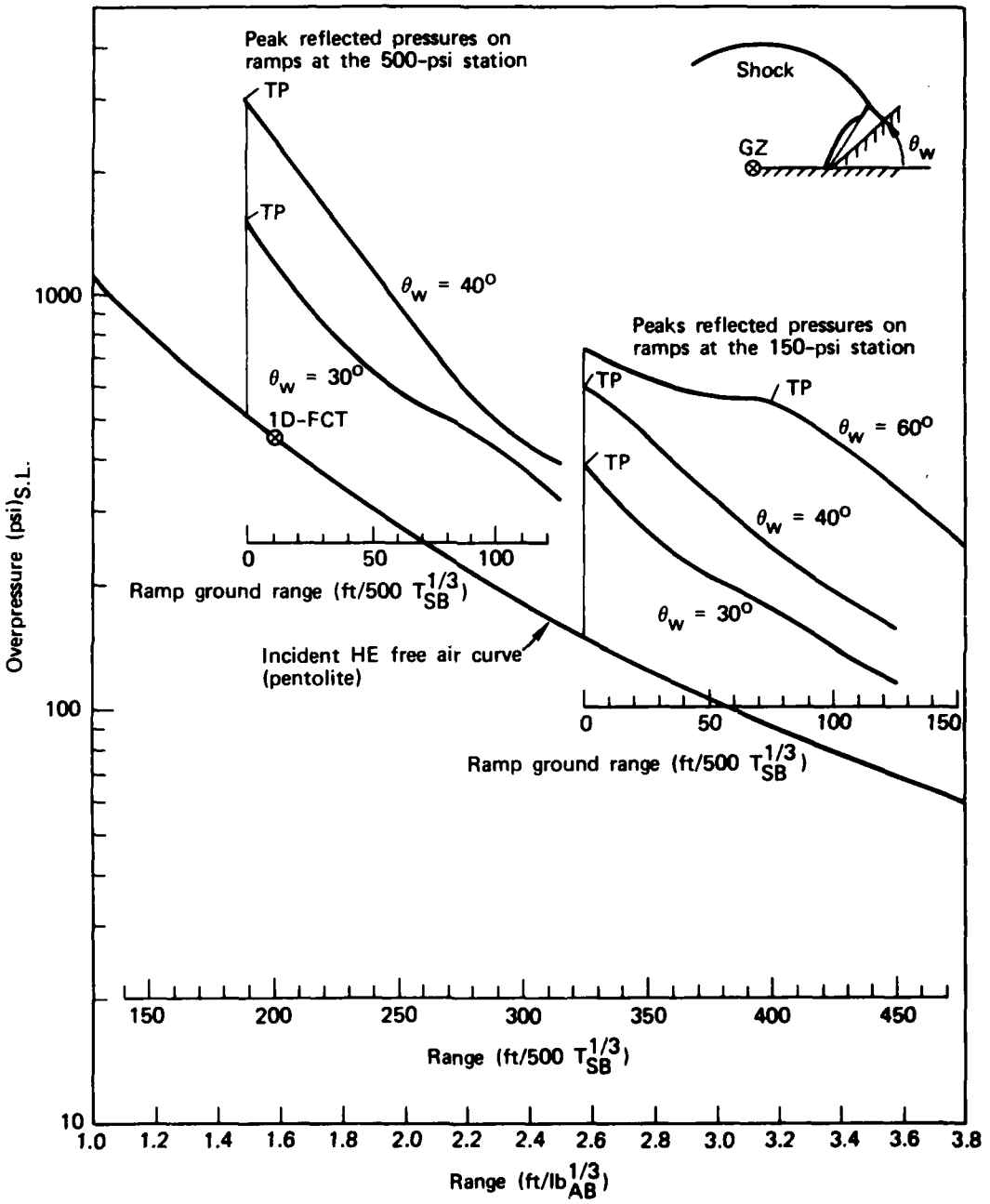

Fig. 5 — Parametric results of peak reflected pressures on the ramp HOB simulator

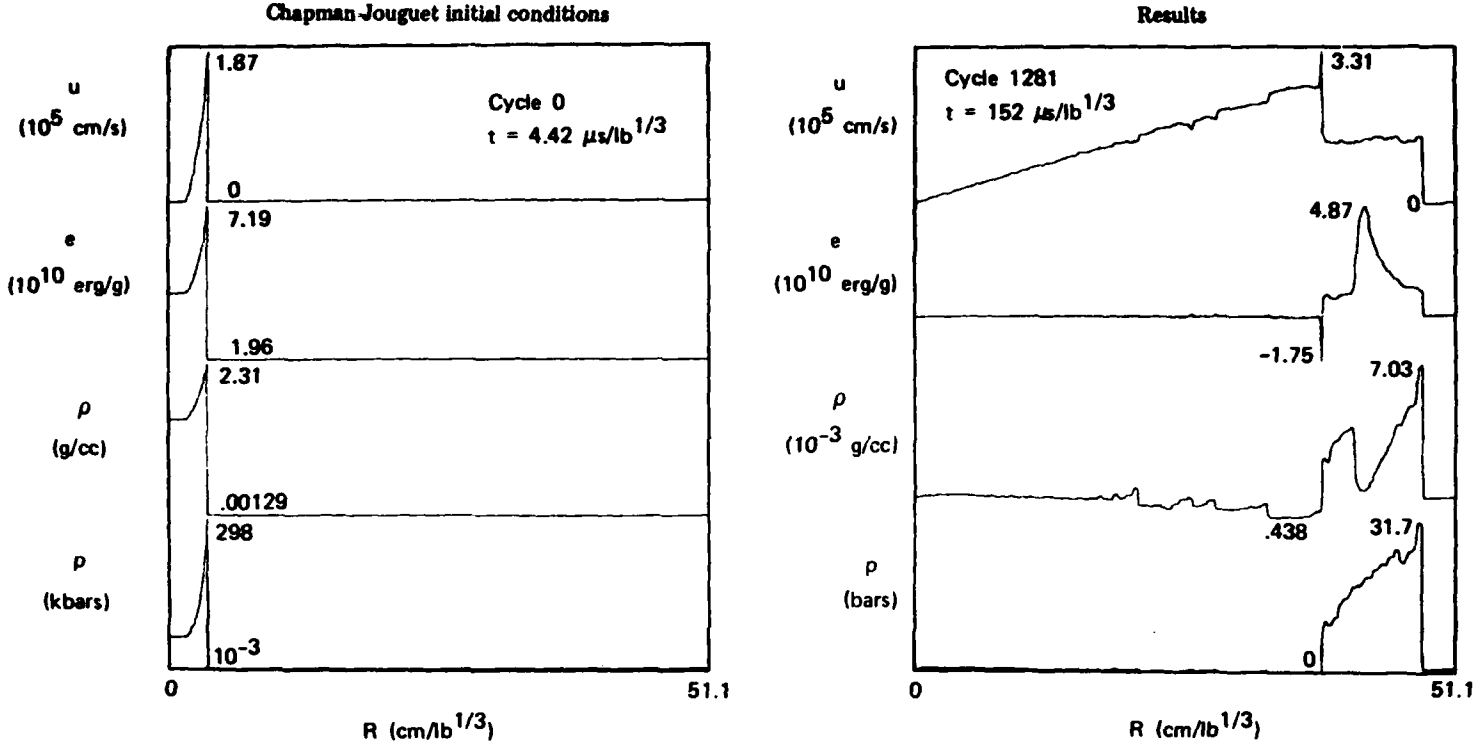

Fig. 6 — Calculated 1-D flow field distribution of a spherical 1-lb PBX-9404 charge
(Δr = 0.1025 cm, 500 cells, real air and JWL EOS)

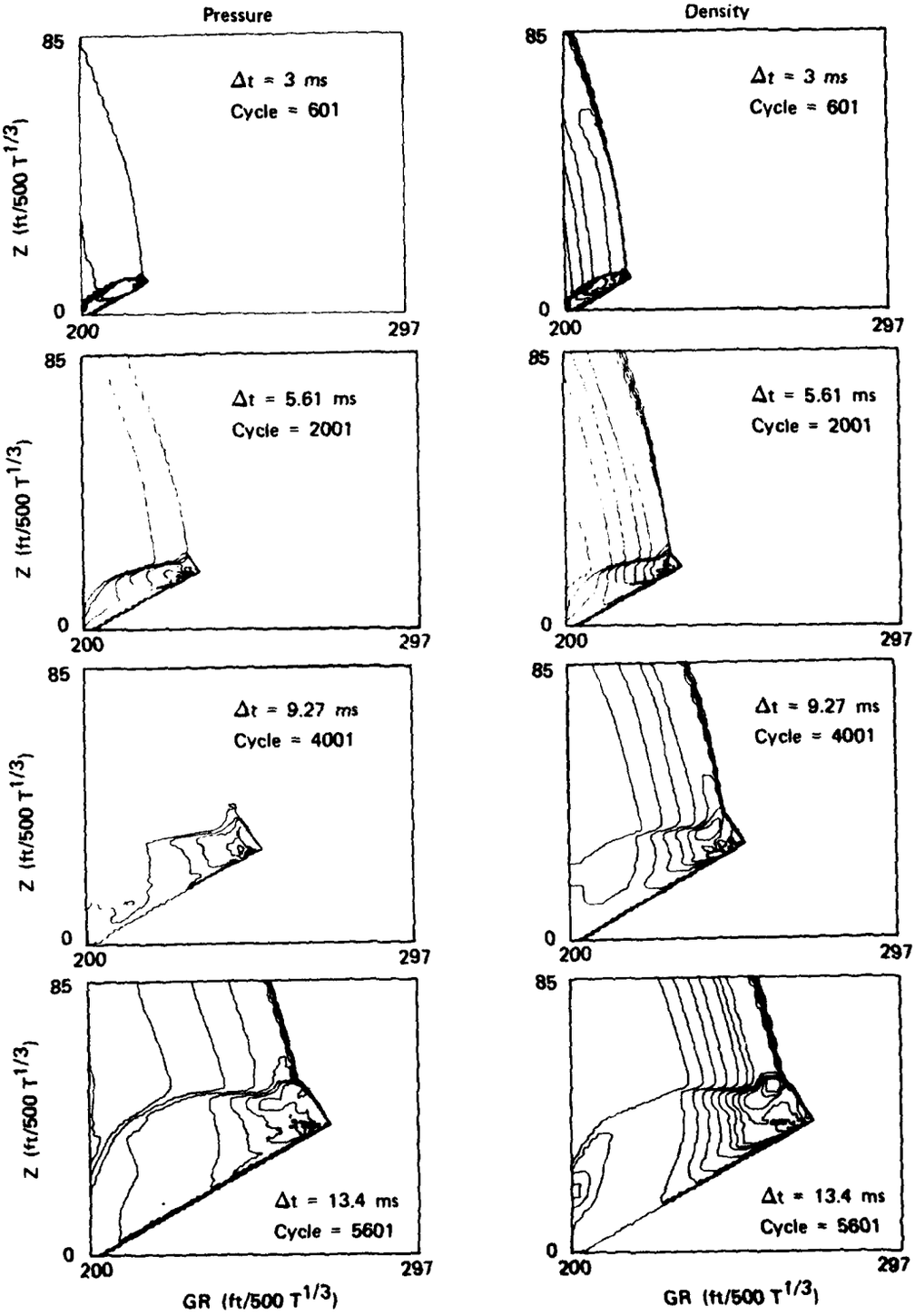

Fig. 7 — Calculated pressure and density contours at times Δt = 3.0, 5.61, 9.27, and 13.4 ms/500 $T^{1/3}$ (t_o = 19.2 ms/500 $T^{1/3}$)

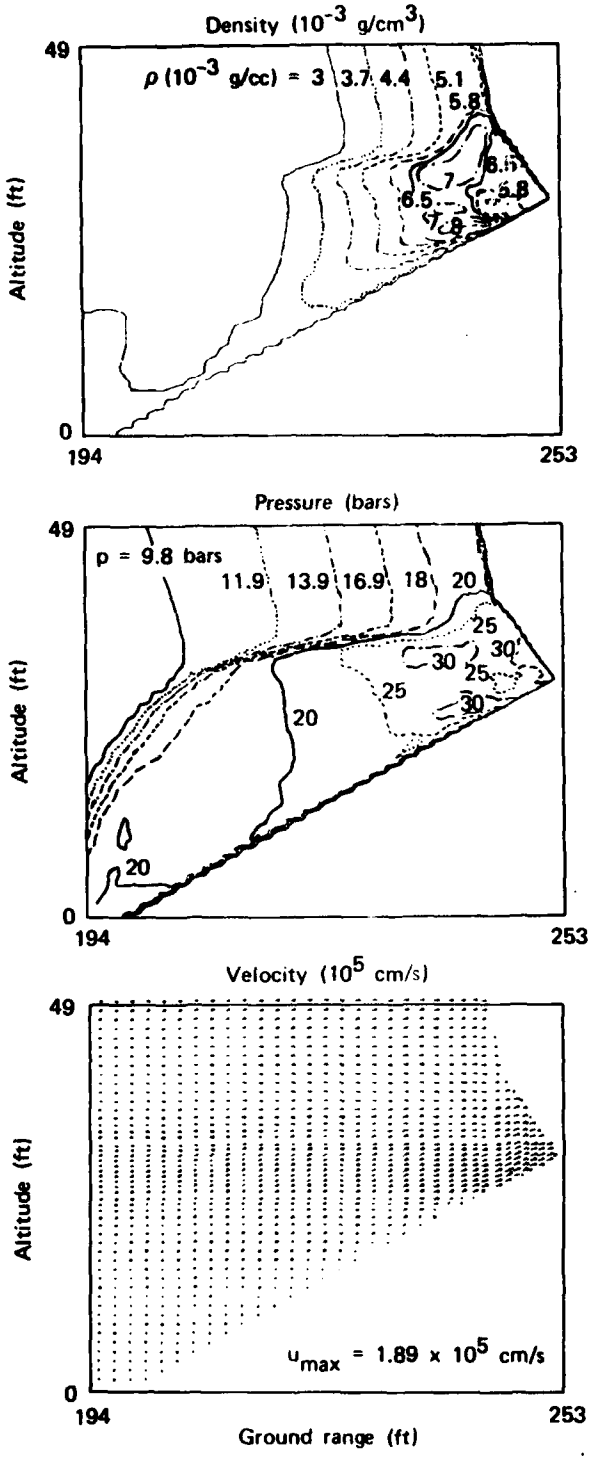

Fig. 8 — Calculated flow details at $\Delta t = 9.61$ ms/500 $T^{1/3}$

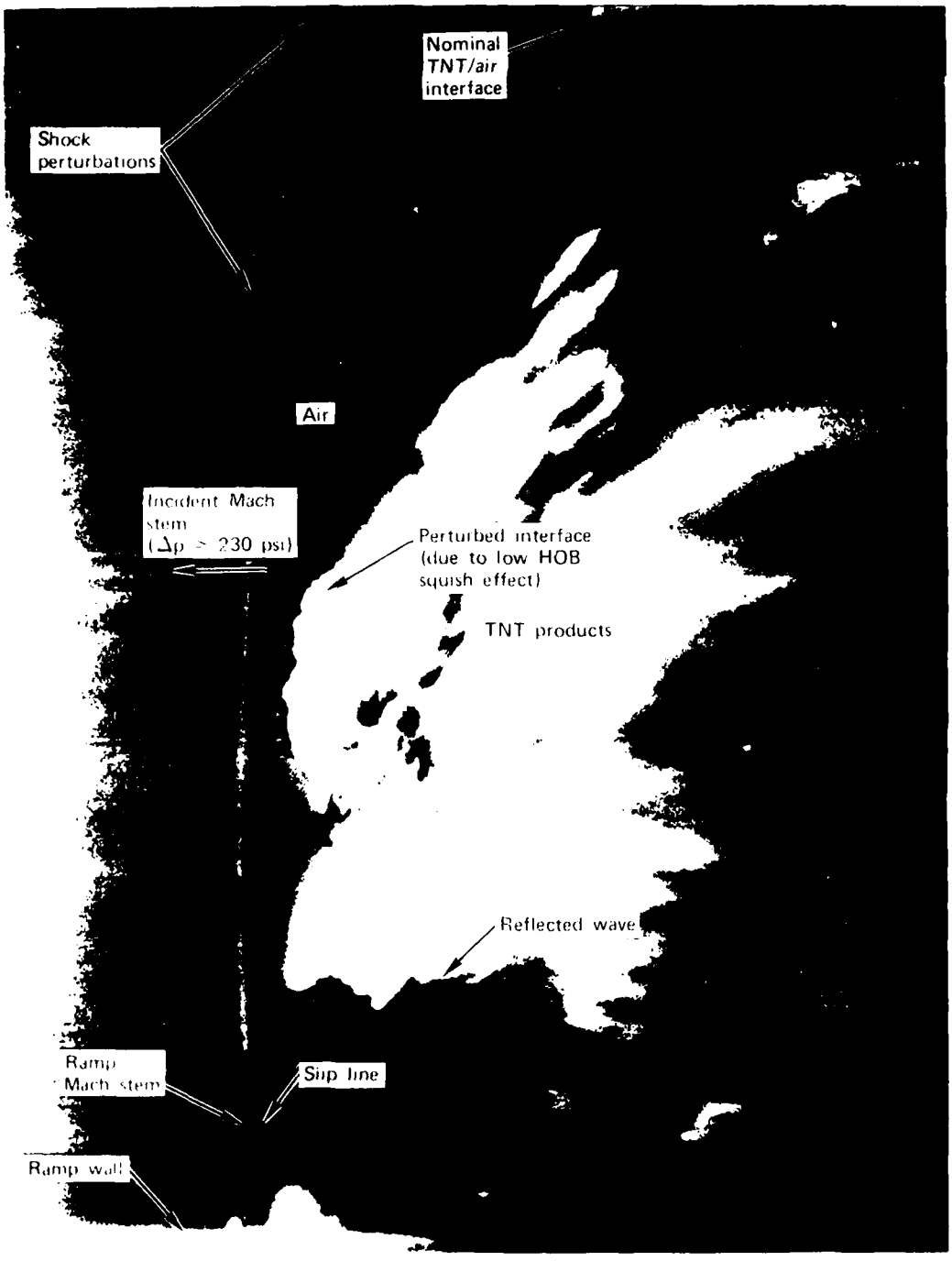

Fig. 9 — Shadowgraph of the shock wave structure formed by an 8-lb TNT-driven blast wave (HOB = 1.04 ft/lb$^{1/3}$) diffracting on a 31° ramp; incident pressure at the beginning of the ramp was about 120 psi. (Courtesy of W. F. Dudziak, *Information Science, Inc.*)

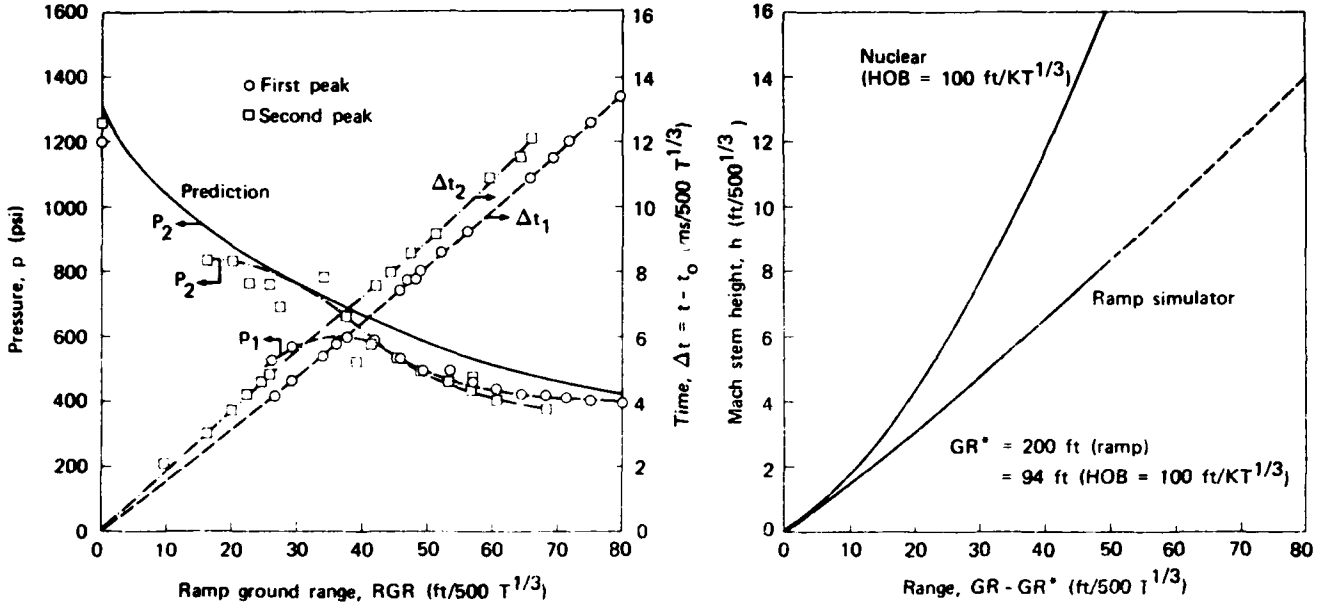

Fig. 10 — Calculated peak pressure, shock arrival time and Mach stem height vs ground range for the ramp HOB simulator (GR_{ramp} = 200 ft/500 $T^{1/3}$, t_o = 19.2 ms/500 $T^{1/3}$).

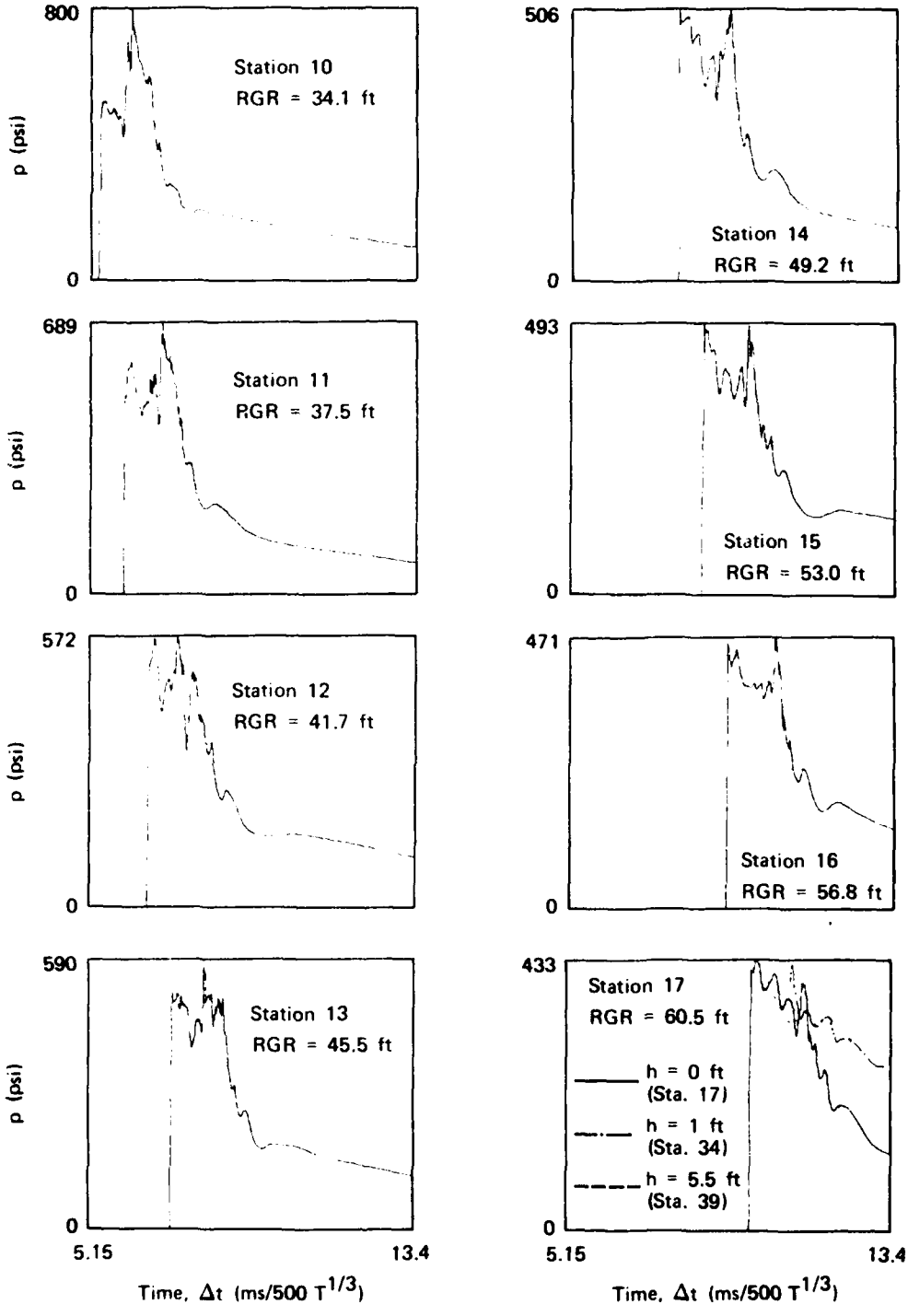

Fig. 11 — Calculated static pressure time histories at various stations on the ramp (t_o = 19.2 ms/500 $T^{1/3}$)

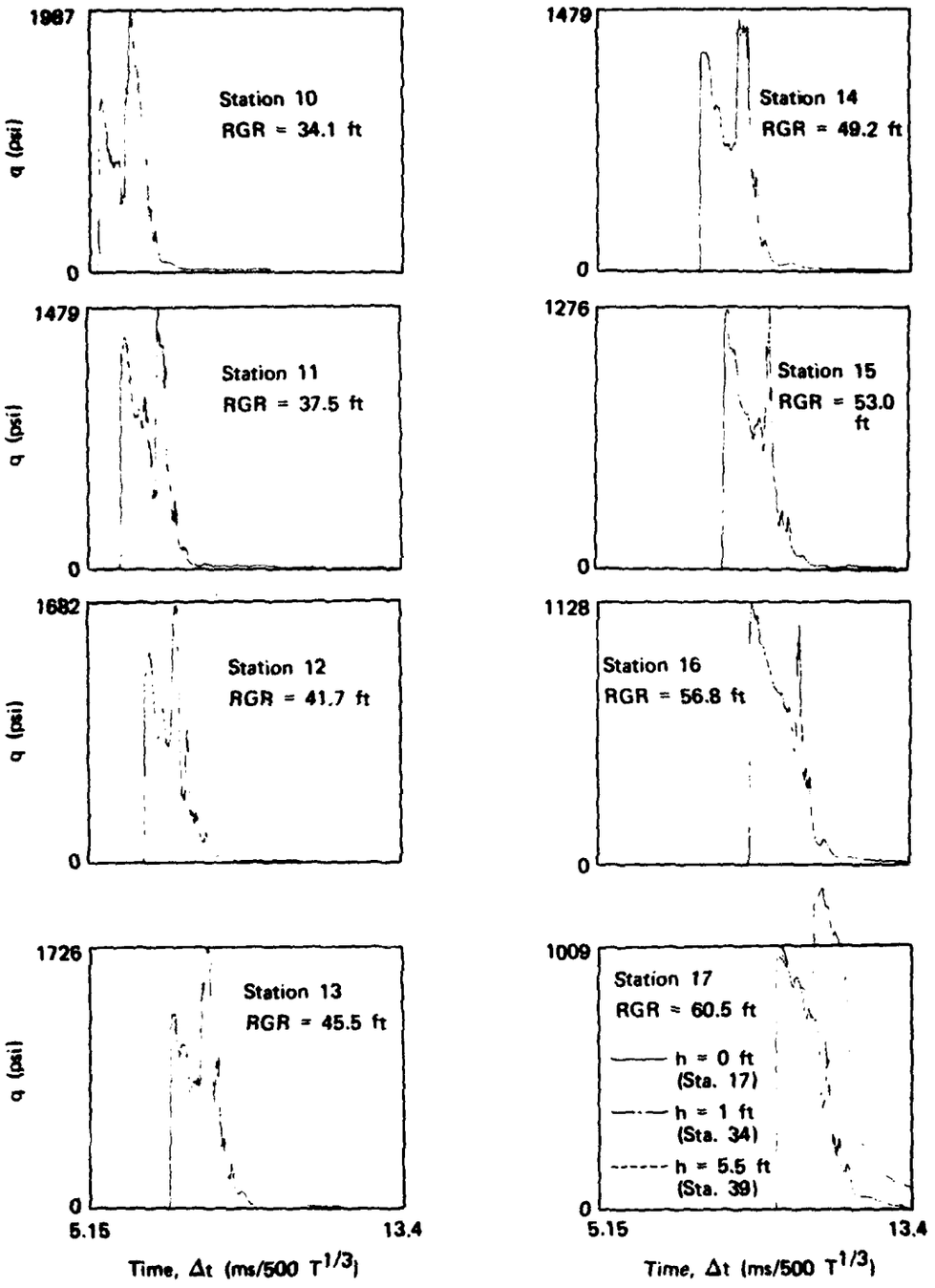

Fig. 12 — Calculated dynamic pressure time histories at various stations on the ramp (t_o = 19.2 ms/500 $T^{1/3}$)

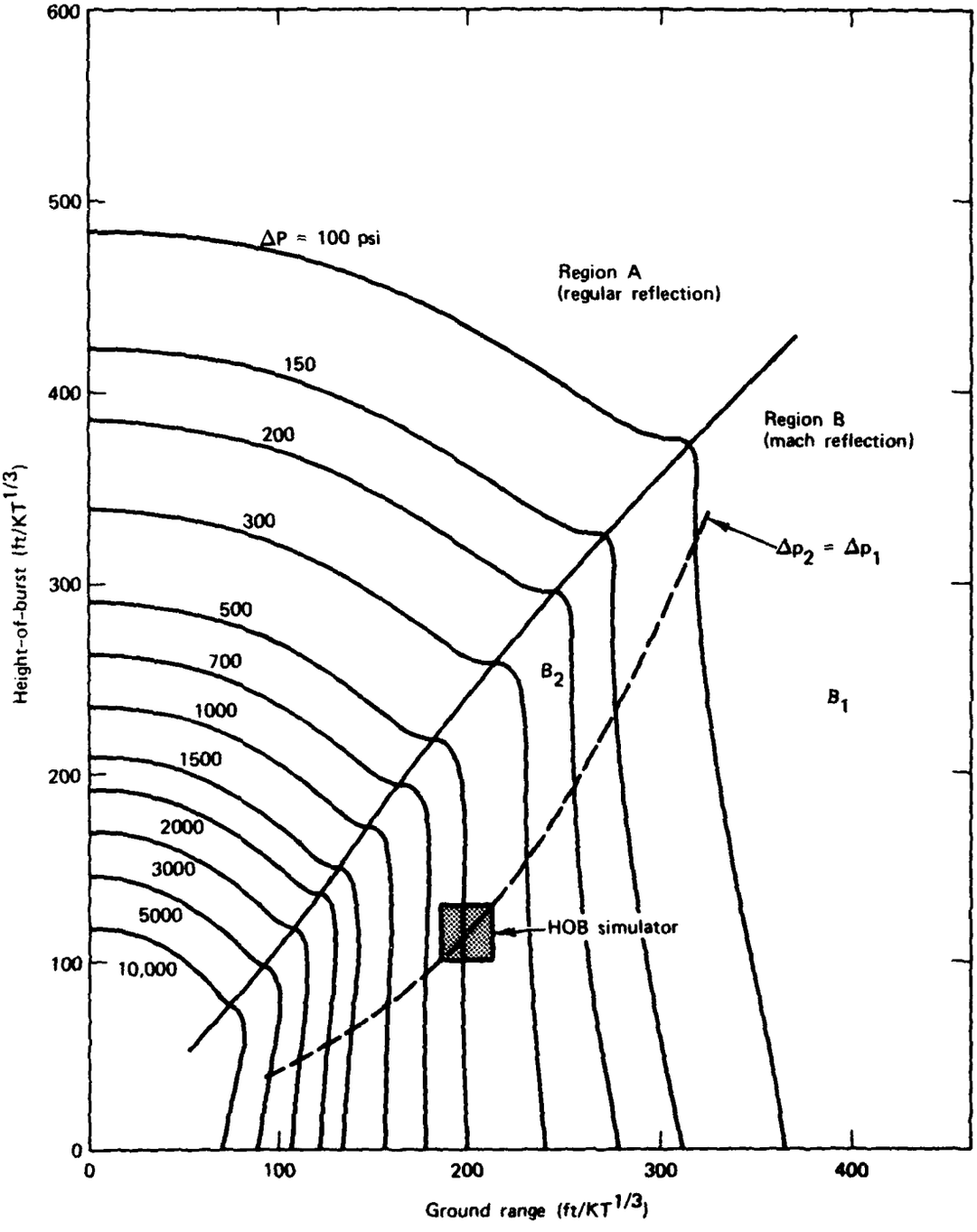

Fig. 13 — Ideal nuclear peak overpressure height-of-burst curves (Ref. 10)

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