Transition to Double Mach Stem for Nuclear Explosion at 104 Ft Height of Burst

M. Fay
Science Applications, Inc.
McLean, VA 22102

J. M. Picone, J. P. Boris, and D. L. Book
Laboratory for Computational Physics

November 17, 1981

This work was supported by the Defense Nuclear Agency under Subtask Y99QAXSG0003, work unit 003001, and work unit title "Flux-Corrected Transport."

NAVAL RESEARCH LABORATORY
Washington, D.C.

Approved for public release; distribution unlimited.
**REPORT DOCUMENTATION PAGE**

**SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)**

<table>
<thead>
<tr>
<th>1. REPORT NUMBER</th>
<th>2. GOVT. ACCESSION NO.</th>
<th>3. RECEIVED'S CATALOG NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRL Memorandum Report 4630</td>
<td>AD-A 120 778</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4. TITLE (and Subtitle)</th>
<th>5. TYPE OF REPORT &amp; PERIOD COVERED</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRANSITION TO DOUBLE MACH STEM FOR NUCLEAR EXPLOSION AT 104 FT HEIGHT OF BURST</td>
<td>Interim report on a continuing NRL problem.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6. AUTHOR(S)</th>
<th>7. CONTRACT OR GRANT NUMBER(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M. Fry*, J. M. Picone, J. P. Boris, and D. L. Book</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>8. PERFORMING ORGANIZATION NAME AND ADDRESS</th>
<th>9. PROGRAM ELEMENT PROJECT, TASK AREA &amp; WORK UNIT NUMBERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naval Research Laboratory, Washington, DC 20375</td>
<td>44-0578-0-1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>10. CONTROLLING OFFICE NAME AND ADDRESS</th>
<th>11. REPORT DATE</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>12. NUMBER OF PAGES</th>
<th>13. SECURITY CLASS. (of this report)</th>
</tr>
</thead>
<tbody>
<tr>
<td>71</td>
<td>UNCLASSIFIED</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>14. DISTRIBUTION STATEMENT (of this Report)</th>
<th>15a. DECLASSIFICATION/DOWNGRADING SCHEDULE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approved for public release; distribution unlimited.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>16. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>17. SUPPLEMENTARY NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Present address: Science Applications, Inc., McLean, VA 22102</td>
</tr>
<tr>
<td>This work was supported by the Defense Nuclear Agency under Subtask Y99QAXSG, work unit 00001, and work unit title, &quot;Flux-Corrected Transport.&quot;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>18. KEY WORDS (Continue on reverse side if necessary and identify by block number)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Mach stem</td>
</tr>
<tr>
<td>Height-of-burst (HOB)</td>
</tr>
<tr>
<td>Flux-corrected transport (FCT)</td>
</tr>
<tr>
<td>High-over-pressure</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>19. ABSTRACT (Continue on reverse side if necessary and identify by block number)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A nuclear height-of-burst (HOB) calculation has been performed using a two-dimensional flux-corrected transport (FCT) code. The calculation predicts the transition from regular to Mach reflection at ground ranges approximately equal to the HOB. The characteristics of the resulting waveforms are basically the same as those found in shock tube experiments when planar shocks reflect from wedges, and appear highly regular. In the double-Mach reflection region the first Mach stem is observed to toe out markedly compared with the planar case. In the high-over-pressure (regular reflection) region initialization errors and inadequate resolution caused pressure peaks to appear too low by about 20%. In the Mach reflection region the peak pressures are in good agreement with experimental data.</td>
</tr>
</tbody>
</table>

DD FORM 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE S/N 0102-014-6601 SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)
CONTENTS

I. INTRODUCTION ................................................. 1

II. DESIGN OF PROBLEM ........................................... 4

III. COMPUTATIONAL DETAILS ...................................... 6

IV. RESULTS AND PHENOMENOLOGY ................................ 9

V. SUMMARY .......................................................... 19

ACKNOWLEDGMENT .................................................. 22

REFERENCES ......................................................... 23

APPENDIX A. DETAILED TIME HISTORY OF CALCULATION .... 24
TRANSITION TO DOUBLE MACH STEM FOR NUCLEAR EXPLOSION AT
104 FT HEIGHT OF BURST

I. INTRODUCTION

In a nuclear height-of-burst (HOB) detonation the spherical blast
wave reflects from the ground, initially producing a regular reflection
region. When the shock reaches a ground range approximately equal to the
HOB an abrupt transition to Mach reflection occurs. This transition is
responsible for an airblast environment more severe than the surface burst
nuclear case. Qualitatively, it can be thought of as a partial flow stagnation
in the Mach region that leads to the production of two static pressure peaks.

A 1 Kiloton (1 KT) atmospheric nuclear explosion at a HOB of 104 feet has
been simulated using the two dimensional FAST2D code (Ref .1). Figure 1
illustrates the shock structure. The calculation predicts the transition of the
shock from regular reflection to double Mach reflection. Because the
spherical waves are expanding and thus decreasing in Mach number as well as angle of
incidence with the ground, they create a dynamic Mach stem formation. In comparison
to planar shocks on wedges one finds them to be qualitatively alike. The appearance of
double peaks in the pressure and density profiles (versus time and distance) is
interpreted as the point of transition. Other interesting phenomena such as the
rollup of the contact surface generating a vortex ring and the associated
phenomenon of toeing out of the first Mach stem can be observed.

The ability of the calculation to accurately predict the gasdynamic effects
both temporally and spatially is due in part to the shock capturing and adaptive
rezone features of the FAST2D code. A minimal number of very fine zones was placed
around the shock front and these zones then moved with the first Mach stem to
prevent shock smearing and distortion. This calculation is the first attempt to
model the nuclear HOB case through the use of a Flux-Corrected Transport (FCT)
algorithm (Ref. 2).

Manuscript submitted August 24, 1981.
Fig. 1 - Mach stem structure from HOB
The results of this calculation agree well with the pressure-distance curve generated by the high explosive (HE) data of Carpenter (Ref. 3) and the analysis of Kuhl (Ref. 4). The peak overpressure of the first shock at the time of transition is about 4300 psi. Our simulation was run to 11.6 ms (total time with $t_0 = 3.76$ ms), which corresponds to pressure peaks of about 2000 psi. In the regular reflection region the peak values tend to be about 20% low due to the clipping of the FCT algorithm and inaccuracies in the initialization of the flow. Reducing the minimum zone size from 5 cm to 1 cm in a one-dimensional test calculation eliminated this discrepancy, however. In the two-peak regions the agreement between the experimental data and the values presented here is very good. The resolution of the calculation is adequate for studying qualitatively the characteristics of the flow field. For future work we recommend that the transition region be explored with improved resolution.
II. DESIGN OF PROBLEM

The problem of a 1-KT nuclear detonation at 104 ft (31.7m) HOB was chosen since it can be scaled conveniently to various HE tests. The use of the 1KT standard is also expedient; one could, however, have used realistic initial conditions, such as the Los Alamos Scientific Laboratory RADFLO or Air Force Weapons Laboratory (AFWL) SPUTTER calculations. A simple constant ambient atmosphere was used with a density of $1.22 \times 10^{-3}$ g/cm$^3$ and pressure $1.01 \times 10^6$ dyne/cm$^2$. To relate the energy and mass densities to the pressure, a real-air equation of state (EOS) was used. This "table-lookup" EOS is derived from Gilmore's data (Ref. 5.) and has been vectorized for the TI Advanced Scientific Computer at NRL (Ref. 6). Figure 2 illustrates the effective gamma versus specific energy per unit mass for different values of the density. The internal energy density used in the call to the EOS is found by subtracting kinetic energy from the total energy; this can be negative due to phase errors in the fluid variables. When this occurs, the value of the pressure is reset to zero.

The transition from regular reflection to double Mach reflection is known to occur at a ground range approximately equal to the HOB. Therefore, the size of the mesh should be roughly twice the HOB in both directions. The upper boundary should be far enough away from the blast front to be noninterfering. We set the boundaries at $5.5 \times 10^3$ cm for the radial direction and $1.035 \times 10^4$ cm for the axial direction. The fine grid in the radial direction contained 140 out of 200 total zones, each 5 cm in length. The largest zones initially filled the right section of the grid and were 80 cm in length. A smoothing involving 40 zones was performed between the region to guarantee that the zone sizes varied slowly. In the vertical direction the fine grid contained 75 out of 150 total zones, each 5 cm in length. Beyond that region the zones increased geometrically by a factor of 1.112.
Fig. 2 - Gamma -1 vs. specific energy for Air EOS
Placement of the fine grid at the origin (ground zero – the point at which first reflection occurs) was determined to be optimum for capturing peak pressures in the airblast wave front. Thus, as the expanding wave moved along the ground surface, the fine grid was always locked to it, and each point along the incident blast front encountered the same spatial gridding as it approached the ground. By treating each point of the incident front in the same manner, we insured that the calculation was internally consistent and that the computed transition point was accurate to within the limits of the resolution. Finally, we point out that, as a section of the incident blast wave propagated within the fine grid, the wave steepened. The size of the fine grid was sufficient to insure that the incident wave had reached the maximum steepness prior to intersecting the ground.

The initialization provides a strong shock with Mach number $M_I = 12$. This speed and the need for restart capability led to the choice of 200 timesteps as an interval for the spatial display ("snapshots"). The dump interval that resulted was $\Delta t = 0.3$ milliseconds. These dumps were stored on magnetic tape and postprocessed.

Additional diagnostics were implemented in the calculation. Stations were created to gain information from fixed spatial positions within the calculational grid. These 25 physical variable sensors were placed along the ground and stored values of the energy and mass densities and velocity for every timestep. From this information one can construct static and dynamic pressure curves.

III. COMPUTATIONAL DETAILS

The evolution of the nuclear HOB flow field was modeled numerically with the FCT code FAST2D (Ref. 7). FCT yields accurate and well-resolved descriptions of shock wave propagation without the necessity of a priori knowledge of the essential gasdynamic discontinuities in the problem. Additionally, the code has a general adaptive regridding capability which permits fine zones to be concentrated in the region of greatest physical interest while the
remainder of the system is covered with coarse zones. Figure 3 depicts the grid setup initially and at transition to the double Mach stem structure. The rezone algorithm is programmed to track the Mach stem with the fine grid.

The transport algorithm used a low-phase-error phoenical FCT algorithm in a model called JPBFCT, an advanced version of the ETBFCT algorithm described in Ref 1. The linear part of this algorithm is fourth-order accurate spatially in advection problems with a given constant velocity and has a (nonlinear) flux-corrected antidiffusion needed to model shocks correctly. Finally, the transport subroutine is written in sliding-rezone form, which means that the mesh at the beginning and the end of the timestep need not be the same. Since the algorithm is one-dimensional, timestep splitting is employed to solve the 2-D problem.

The fluid transport routine JPBFCT is fully vectorized and requires about 2 us per meshpoint-cycle. This time would have been still less if a vectorized fully two-dimensional routine had been used, since the 1-D loops are too short to permit full advantage to be taken of the vector capabilities of the NRL ASC. The table lookup in the EOS was also fully vectorized, so that pressure calculations required about 20% of the time needed for the hydrodynamics. These two items took up nearly all of the running time in the blast calculation itself. The cost of initialization was negligible, but the diagnostics cost up to 30% as much as the hydrodynamics, depending on how many of the various possible quantities were actually plotted. This latter number would be greatly reduced if the plot routines were fully vectorized.

A version of the AFWL 1 KT standard (Ref 8) was used to initialize the energy, density and velocity (flow field) at 3.76 milliseconds. The corresponding shock radius was 103.9 ft (31.69 m) peak overpressure of 1645 psi (1.134 x 10^6 K Pa). Because some areas of the grid were very coarse, interpolation onto the grid was performed. After the 1 KT flow was laid down inside a radius of 104 feet (31.7 m) the fine-zoned grid was activated to follow the peak pressure as it moved along
Fig. 3 - Adaptive gridding. The grid at initialization and at transition point (lines are drawn for every other zone, lines in fine-zone region are indistinguishable).
the ground surface, modelled as a perfectly reflecting boundary. This region comprised 140 zones, and a switch was set to keep 40 of these zones ahead of the reflection point. Permeable boundary conditions were used on the top and right edges of the mesh; i.e., density, pressure and velocity were set equal to ambient preshock conditions. Reflecting conditions were applied to the left and bottom.

The timestep was recalculate$\text{d}$ at every cycle according to the Courant condition

$$dt = 0.5 \min \frac{(\Delta x_i, \Delta y_j)}{(c+|V|)_{ij}}$$

where $c$ is the speed of sound and $|V|$ is the modulus of the flow speed. This could have been relaxed somewhat by allowing violation of the local Courant limit at points ("hot spots") far from the region of chief physical interest. The total elapsed time in the 2-D calculation, 7.6 ms, required 5600 cycles.

Three types of diagnostics were employed, all in the form of plots made by post processing a dump tape. The first type of diagnostic consisted of CRT contour plots of density and static pressure, and arrows indicating the magnitude and direction of the velocity field, obtained at the dump intervals (every 200 cycles). The second type was pressure-range curves at $z=0$, obtained by finding the pressure peak(s) along the ground at each dump interval and hand-plotting them on the same graph. The third type consisted of pressure histories at a series of 24 stations, obtained by saving the energy and mass densities and the velocities at every cycle.

IV. RESULTS AND PHENOMENOLOGY

This calculation has been done to understand the violent effects of 1 KT of energy being released in the atmosphere at a HOB of 104 ft (31.7m). A strong spherical shock is created in the surrounding air, and reflects from the ground.
The outward-traveling airblast is then composed of two parts: one reflected upward approximately normal to the ground, and the original spherical blast. The peak pressure is coincident with the intersection of the two waves. This intersection continues to move outward until the angle of the spherical shock with respect to the ground reaches a critical value and the transition to a double Mach stem occurs. As shown by Ben-Dor and Glass (Ref. 9), this angle depends upon the incident strength of the shock (Fig. 4). Shocks with Mach numbers greater than 10 are not shown. Initially, the Mach number for the HOB simulation is well above 10. The Mach number at transition is approximately 11 and the angle is less than 50°. From Fig. 4 the corresponding region is double Mach reflection.

Figure 1 has been labeled with the notation of Ben-Dor and Glass (Ref. 9). It should be noted that what is generally regarded as the second Mach stem is in fact the second reflected wave, which is part of the second Mach structure. To be consistent, one must label the second Mach stem as \( M^1 \) at the indicated location. The definition used is the state of the fluid one obtains by passing through one shock wave \( (M^1) \) or two shock waves \( (R \) and \( R^1) \). The first reflected wave \( R \) becomes the incident wave for the second Mach structure. Density contours are shown in Fig. 5 for an planar shock on wedge with a Mach number of 7 and an angle of 50°. The complimentary figure illustrates the proper labeling of the multiple waves. Comparison of Fig. 5 and the HOB simulation (Fig. 6) shows that corresponding waves can be identified. Differences between the planar shock on wedge and the HOB can be explained in terms of the unsteady nature of the HOB case (a spherically expanding wave that continuously decreases in Mach number and angle.) Although the term irregular Mach reflection has been used to describe the complex shock structure that evolves from HOB events, we believe it to be very regular and explainable as a double Mach reflection that evolves as a function of time.
Fig. 4 - Types of shock reflection: RR, CMR, SMR, and DMR denote regular reflection and single, complex and double mach reflection, respectively. The D and A refer to attached and detached shocks.
Fig. 5 - Planar shock (Mach 7) on 50° wedge with wave identification
The HOB numerical simulation begins just before the shock first reflects from the ground. As a summary of how the flow field then develops, we present snap-shots at the important stages. (A more complete display is presented in Appendix A). Figure 6a indicates the pressure and density contours and velocity vectors at \( t = 3.18 \) ms. In Fig. 6b the reflected shock is shown moving upward, the outward flow begins to stagnate at the ground (transition). Fig. 6c, at \( t = 5.99 \) ms, shows an enlargement of the shock front, and the development of the Mach stem, slip surface and second Mach stem. The angle of the shock with respect to the ground is increasing with time, so that the effective wedge angle is decreasing. From the work of Ben-Dor and Glass one expects a transition to double Mach stem to occur at approximately 45°. The angle in Fig. 6b is about 45° and the shock front has entered the transition phase. Figure 6d shows the fully developed shock structure at 7.79 ms. Toeing out of the first Mach stem can be also seen in the contours of Fig. 6d and occurs as the fluid rolls forward where the slip line would otherwise intersect the ground. The velocity field in Fig. 6d also shows this detail.

Note the reflected shock properties (that part of the structure that contains the second Mach stem \( M_1 \)). The reflected shock propagates rapidly through the high temperature fireball, due to the high local sound speed. The shape of this reflected wave is a primary difference between the HOB case and the planar wave on wedge case. The other major difference, of course, is the spherically expanding blast wave which decreases in strength approximately as \( r^{-2} \).
Fig. 6 - Pressure, density, and velocity fields for HOB calculation (a) in regular reflection state; (b) at transition to Mach reflection; (c) shortly afterward, when second peak has become larger than first; and (d) fully developed (note toe at base of first Mach stem). Units in cgs.

\[ \begin{align*}
\text{PRESSURE} & : P_{\text{max}} = 3.75 \times 10^8, \\
\text{DENSITY} & : \rho_{\text{max}} = 3.35 \times 10^{-2}, \\
\text{VELOCITY} & : V_{\text{max}} = 3.3 \times 10^5,
\end{align*} \]
An effective way to quantitatively evaluate the calculation and observe in detail the transition to a Mach stem regime can be seen by examining the station data. The station sensors were placed in the bottom row of the calculation 100 to 200 cm apart. In Table 1 the maximum pressure recorded for each station along with the location can be found.

Besides giving a reliable value for the peak pressure to be used for constructing the pressure-distance curve, these data allow one to see effects fixed in space but varying in time. Figure 7 is a superposition of the pressure profiles from stations 15 to 24 (the transition region). Noteworthy is the profile from station 17, which is the first station to record a second peak on the back side. At station 19, 200 cm further away from ground zero, the second peak is almost equal to the first. The visible transition (as seen in Fig. 6b, occurs at a ground range between 3100 cm and 3300 cm (stations 19-21) revealing a dominant second peak and a "first peak" (i.e., first seen by the sensor) that is about half the magnitude of the second. The second peak does not exhibit a sharp almost discontinuous rise and then a rapid but slower decrease along the back side. Instead, it has the appearance of a density compression. This behavior has dramatic consequences for military planners because the pressure-distance curve is modified and the dynamic pressure is enhanced.

The analogous profiles for dynamic pressure are presented in Fig. 8. Again data from stations 15 to 24 is utilized. The development of the second peak and its correlation with the Mach stem formation can be observed. There is, in addition, a noticeable increase in the first peak values (station 15 to the maximum at station 18). After the structure becomes visibly resolved (station 20 and beyond) the second peak resembles a rounded profile suggesting the formation of a stagnation region behind the first peak (Mach stem).
<table>
<thead>
<tr>
<th>Station No.</th>
<th>Location (cm)</th>
<th>Time (sec)</th>
<th>Pres (dynes/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.0000E 02</td>
<td>2.25E-04</td>
<td>8.11E 08</td>
</tr>
<tr>
<td>2</td>
<td>4.0000E 02</td>
<td>2.80E-04</td>
<td>7.92E 08</td>
</tr>
<tr>
<td>3</td>
<td>8.0000E 02</td>
<td>5.28E-04</td>
<td>7.17E 08</td>
</tr>
<tr>
<td>4</td>
<td>1.0000E 03</td>
<td>7.23E-04</td>
<td>6.73E 08</td>
</tr>
<tr>
<td>5</td>
<td>1.2000E 03</td>
<td>9.54E-04</td>
<td>6.24E 08</td>
</tr>
<tr>
<td>6</td>
<td>1.4000E 03</td>
<td>1.23E-03</td>
<td>5.65E 08</td>
</tr>
<tr>
<td>7</td>
<td>1.6000E 03</td>
<td>1.54E-03</td>
<td>5.21E 08</td>
</tr>
<tr>
<td>8</td>
<td>1.8000E 03</td>
<td>1.91E-03</td>
<td>4.70E 08</td>
</tr>
<tr>
<td>9</td>
<td>2.0000E 03</td>
<td>2.34E-03</td>
<td>4.54E 08</td>
</tr>
<tr>
<td>10</td>
<td>2.2000E 03</td>
<td>2.81E-03</td>
<td>4.14E 08</td>
</tr>
<tr>
<td>11</td>
<td>2.3000E 03</td>
<td>3.07E-03</td>
<td>4.03E 08</td>
</tr>
<tr>
<td>12</td>
<td>2.4000E 03</td>
<td>3.35E-03</td>
<td>3.92E 08</td>
</tr>
<tr>
<td>13</td>
<td>2.5000E 03</td>
<td>3.62E-03</td>
<td>3.82E 08</td>
</tr>
<tr>
<td>14</td>
<td>2.6000E 03</td>
<td>3.88E-03</td>
<td>3.73E 08</td>
</tr>
<tr>
<td>15</td>
<td>2.7000E 03</td>
<td>4.19E-03</td>
<td>3.37E 08</td>
</tr>
<tr>
<td>16</td>
<td>2.8000E 03</td>
<td>4.48E-03</td>
<td>3.33E 08</td>
</tr>
<tr>
<td>17</td>
<td>2.9000E 03</td>
<td>4.79E-03</td>
<td>3.05E 08</td>
</tr>
<tr>
<td>18</td>
<td>3.0000E 03</td>
<td>5.11E-03</td>
<td>3.01E 08</td>
</tr>
<tr>
<td>19</td>
<td>3.1000E 03</td>
<td>5.41E-03</td>
<td>2.33E 08</td>
</tr>
<tr>
<td>20</td>
<td>3.2000E 03</td>
<td>6.06E-03</td>
<td>1.96E 08</td>
</tr>
<tr>
<td>21</td>
<td>3.3000E 03</td>
<td>6.49E-03</td>
<td>1.79E 08</td>
</tr>
<tr>
<td>22</td>
<td>3.4000E 03</td>
<td>6.82E-03</td>
<td>1.87E 08</td>
</tr>
<tr>
<td>23</td>
<td>3.5000E 03</td>
<td>7.28E-03</td>
<td>1.85E 08</td>
</tr>
<tr>
<td>24</td>
<td>3.6000E 03</td>
<td>7.73E-03</td>
<td>1.69E 08</td>
</tr>
</tbody>
</table>
Fig. 7 - Station pressure data (nos. 15-24)
Fig. 8 - Station dynamic pressure data (nos. 15-24)
Finally we consider the pressure-distance relation for the HOB case. In Fig. 9 we compare the results of the numerical simulation with the data of Carpenter and with empirical analysis. Carpenter's data are based upon careful HOB experiments with 8 lb PBX9404 spheres. The empirical analysis was based on a 1 KT nuclear free air curve and HOB construction factors. The calculated values in the regular reflection regime are 20% low, which may be attributed to a combination of FCT clipping, the resolution of the grid, and inaccuracies in the initialization of the flow field. During and after Mach reflection, the peaks remain low until the Mach stem structure has grown large enough to be resolved on the mesh. By the time it occupies a region of 15 cells high and 35 cells wide, the peak pressures are in good agreement with the HE data and the empirical analysis.

Other attempts to model the transition region have been made. Needham and Booen (Ref. 10) present results of a 110 lb pentolite sphere at 15 feet HOB. The general phenomena of the flow field can be seen from their simulation. When a pressure distance curve is constructed from this calculation, one finds that in the regular reflection region their results are 15% to 30% high relative to theory. After transition to double Mach reflection the first peaks are 20% low while the second peaks are 40% low (Ref. 4).

V. SUMMARY

The airblast from a 1KT nuclear event at 104 ft HOB has been numerically simulated with the FAST2D computer code. The results give insight to the formation and subsequent evolution of the Mach stem, the triple point, and the contact discontinuity. The transition from regular reflection to double Mach reflection is predicted. We suggest that the first signal for
Fig. 9 - Pressure-range curves for first and second (after transition denoted by TP - to double Mach reflection) peaks.
transition is the appearance of a second peak behind the shock front due to stagnation in the flow. Comparison with the pressure-distance curves of Carpenter and Kuhl indicates agreement within 20%. Both first and second peaks are predicted with similar accuracy.

ACKNOWLEDGEMENT

We are grateful to Dr. Allen Kuhl of R&D Associates for his valuable advice and technical guidance.

This work was supported by the Defense Nuclear Agency under Subtask Y99QAXSG, work unit 00001, work unit title, "Flux-Corrected Transport."
References


APPENDIX A. DETAILED TIME HISTORY OF CALCULATION

The following figures comprise a temporal history of the numerical simulation. Each page contains pressure contours, velocity vectors, density contours, and the corresponding grid for a particular time. The series begins at $t_0 = 0$ ($t_I = 3.76 \, ms$) and continues to $t_F = 8.28 \, ms$. 
1 kt AT 104 ft HOB
TIME = 0.0 msec
CYCLE = 0

PRESSURE

VELOCITY

DENSITY

GRID
1 kt AT 104 ft HOB
TIME = 0.34 msec
CYCLE = 400

PRESSURE

VELOCITY

DENSITY

GRID
1 kt AT 104 ft HOB

TIME = 0.91 msec
CYCLE = 800
1 kt AT 104 ft HOB
TIME = 1.05 msec
CYCLE = 1200

PRESSURE

VELOCITY

DENSITY

GRID
1 kt AT 104 ft HOB

TIME = 1.42 msec
CYCLE = 1600

PRESSURE

VELOCITY

DENSITY

GRID

28
1 kt at 104 ft HOB

TIME = 1.80 msec
CYCLE = 2000

---

**PRESSURE**

**VELOCITY**

**DENSITY**

**GRID**
1 kt AT 104 ft HOB
TIME = 2.81 msec
CYCLE = 3000

PRESSURE

DENSITY

VELOCITY

GRID
1 kt AT 104 ft HOB
TIME = 3.24 msec
CYCLE = 3400

PRESURE

VELOCITY

DENSITY

GRID
1 kT AT 104 ft HOB
TIME: 4.10 msec
CYCLE: 4200
1 kt AT 104 ft HOB
TIME = 4.54 msec
CYCLE = 4600

PRESSURE

VELOCITY

DENSITY

GRID

34
1 kt AT 104 ft HOB
TIME = 4.99 msec
CYCLE = 5000
1 kt AT 104 ft HOB
TIME = 5.47 msec
CYCLE = 5400
1 kt AT 104 ft HOB
TIME = 5.99 msec
CYCLE: 5800
1 kt AT 104 ft HOB
TIME = 6.26 msec
CYCLE = 6000

PRESURE

VELOCITY

DENSITY

GRID

RADIUS cm

ALTITUDE cm

RADIUS cm

RADIUS cm
1 kt AT 104 ft HOB
TIME = 7.05 msec
CYCLE = 6600

PRESSURE

VELOCITY

DENSITY

GRID
1 kt AT 104 ft HOB
TIME = 7.39 msec
CYCLE = 6800

PRESSURE

VELOCITY

DENSITY

GRID
1 kt AT 104 ft HOB
TIME = 8.28 msec
CYCLE = 7200

PRESSURE

VELCITY

DENSITY

GRID
DEPARTMENT OF ARMY

DIRECTOR
BMD ADVANCED TECHNOLOGY CENTER
DEPARTMENT OF THE ARMY
P.O. BOX 1500
HUNTSVILLE, AL 35897
OICY ATTN ATC-T
OICY ATTN 1CRDASH-Y
OICY ATTN ATC-T

COMMANDER
BMD SYSTEMS COMMAND
DEPARTMENT OF THE ARMY
P.O. BOX 1500
HUNTSVILLE, AL 35897
OICY ATTN BMNSC-HE
OICY ATTN BMNSC-HE P DEKALB
OICY ATTN BMNSC-H & HURST
OICY ATTN BMNSC - AL. WEGRO

CHIEF OF ENGINEERS
DEPARTMENT OF THE ARMY
FORRESTAL BUILDING
WASHINGTON, DC 20314
OICY ATTN DAEN-CF
OICY ATTN DAEN-RCl
OICY ATTN DAEN-YRE-T R REYNOLDS

DEP. CH. OF STAFF FOR CPS & PLANS
DEPARTMENT OF THE ARMY
WASHINGTON, DC 20310
OICY ATTN DAWS-HC

COMMANDER
HARRY DIAMOND LABORATORIES
DEPARTMENT OF THE ARMY
2300 POWDER MILL ROAD
ADELPHI, MD 20783
(OUTER ENVELOPPE: ATTN: DELHO-RBH FOR)
OICY ATTN DELHO-RBH (TECH LIB)
OICY ATTN CHIEF DIV 20000
DEPARTMENT OF NAVY

COMMANDER
NAVAL WEAPONS CENTER
CHINA LAKE, CA 93555
OICY ATTN CODE 3201 P CORDEL
OICY ATTN CODE 266 C AUSTIN
OICY ATTN CODE 223 (TECH LIB)

COMMANDING OFFICER
NAVAL WEAPONS EVALUATION FACILITY
KIRTLAND AIR FORCE BASE
ALBUQUERQUE, NM 87117
OICY ATTN R HUGHES
OICY ATTN CODE 1C (TECH LIB)

OFFICE OF NAVAL RESEARCH
ARLINGTON, VA 22217
OICY ATTN CODE 474 N PERONE

OFFICE OF THE CHIEF OF NAVAL OPERATIONS
WASHINGTON, DC 20350
OICY ATTN OP 541
OICY ATTN OP 035C

DIRECTOR
STRATEGIC SYSTEMS PROJECT OFFICE
DEPARTMENT OF THE NAVY
WASHINGTON, DC 20376
OICY ATTN NSP-272
OICY ATTN NSP-42 (TECH LIB)

49
DEPARTMENT OF THE AIR FORCE

ASSISTANT CHIEF OF STAFF
INTELLIGENCE
DEPARTMENT OF THE AIR FORCE
WASHINGTON, DC 20330
OICY ATTN IN RM 4A527

ASSISTANT CHIEF OF STAFF
STUDIES & ANALYSES
DEPARTMENT OF THE AIR FORCE
WASHINGTON, DC 20330
OICY ATTN AF/SAMI (TECH LIB)

ASSISTANT SECRETARY OF THE AF
RESEARCH, DEVELOPMENT & LOGISTICS
DEPARTMENT OF THE AIR FORCE
WASHINGTON, DC 20330
OICY ATTN SAFALD/CED FOR STRAT & SPACE SYS

BALLISTIC MISSILE OFFICE/IN
AIR FORCE SYSTEMS COMMAND
MORTON AFB, CA 92409
(MINUTEMAN)
OICY ATTN MNNXH G KALANSKY
OICY ATTN MNNXH W CELVECCHIN
OICY ATTN MNN W CRABTREE
OICY ATTN MNNXH D GAGE
OICY ATTN MNNXH

DEPUTY CHIEF OF STAFF
RESEARCH, DEVELOPMENT, & ACC
DEPARTMENT OF THE AIR FORCE
WASHINGTON, DC 20330
OICY ATTN AFPROW K ALEXANDROW
OICY ATTN AFPROW
OICY ATTN AFPROW
DEPARTMENT OF THE AIR FORCE

DEPUTY CHIEF OF STAFF
LOGISTICS & ENGINEERING
DEPARTMENT OF THE AIR FORCE
WASHINGTON, DC 20330
OICY ATTN LEFF

COMMANDER
FOREIGN TECHNOLOGY DIVISION, AFSC
WRIGHT-PATTERSON AFB, OH 45433
OICY ATTN NFIIS LIBRARY

COMMANDER
PROFE AIR DEVELOPMENT CENTER, AFSC
GRIFFISS AFB, NY 13441
OICY ATTN TSC

STRATEGIC AIR COMMAND
DEPARTMENT OF THE AIR FORCE
OFFUTT AFB, NB 68112
OICY ATTN NR1-STAFF LIBRARY
OICY ATTN XPPS
OICY ATTN INT J MCCLNNEY

VELA SEISMOLOGICAL CENTER
312 MONTGOMERY STREET
ALEXANDRIA, VA 22314
OICY ATTN G HILPICH
DEPARTMENT OF ENERGY/DOE CONTRACTORS

DEPARTMENT OF ENERGY
ALBUQUERQUE OPERATIONS OFFICE
P.O. BOX 5400
ALBUQUERQUE, NM 87115
OICY ATTN CTMN

DEPARTMENT OF ENERGY
WASHINGTON, DC 20545
OICY ATTN CHIEF

DEPARTMENT OF ENERGY
NEVADA OPERATIONS OFFICE
P.O. BOX 14100
LAS VEGAS, NV 89114
OICY ATTN MAIL & RECORDS FOR TECHNICAL LIBRARY

LAWRENCE LIVERMORE NATIONAL LAB
P.O. BOX 808
LIVERMORE, CA 94550
OICY ATTN L-760 P. DENG
OICY ATTN L-205 J. HEARST (CLASS L-205)
OICY ATTN L-90 P. NOHRIS (CLASS L-504)
OICY ATTN L-7 J. KAHN
OICY ATTN D. GLENN
OICY ATTN L-437 R. SCHOCK
OICY ATTN TECHNICAL INFO DEPT. LIBRARY
OICY ATTN L-200 T. ALTSAVICH

LOS ALAMOS NATIONAL SCIENTIFIC LAB
MAIL STATION 5000
P.O. BOX 1663
LOS ALAMOS, NM 87545
OICY ATTN P. WHITTAKER
OICY ATTN P. KELLY
OICY ATTN T. STANDER
OICY ATTN M.T. JAMBRI
OICY ATTN MS 844 (CLASS REPORTS LIB)
OICY ATTN & JURES

53
LOVELACE BIOMEDICAL & 
ENVIRONMENTAL SCIENCE INSTITUTE, INC. 
P O BOX 5990 
ALBUQUERQUE, NM 87115 
OICY ATTN R JONES (UNCL. ONLY) 

OAK RIDGE NATIONAL LABORATORY 
NUCLEAR DIVISION 
X-10 LAB RECORDS DIVISION 
P O BOX X 
OAK RIDGE, TN 37830 
OICY ATTN CIVIL DEF PFS PROJ 
OICY ATTN CENTRAL PSCI LIBRARY 

SANDIA LABORATORIES 
LIVERMORE LABORATORY 
P O BOX 969 
LIVERMORE, CA 94550 

SANDIA NATIONAL LAB 
P O BOX 5800 
ALBUQUERQUE, NM 87185 
(ALL CLASS ATTN SEC CONTROL OEC FOR) 
OICY ATTN A CHABA 
OICY ATTN L HILL 
OICY ATTN O RG 1250 W BROWN 
OICY ATTN A CHABIA 
OICY ATTN W ROHERTY 
OICY ATTN 314 
OICY ATTN L VERTMAN 
OICY AND T BANISTER 

DEPARTMENT OF ENERGY/DOE CONTRACTORS

54
DEPARTMENT OF DEFENSE CONTRACTORS

ACUREX CORP.
485 CLYDE AVENUE
MOUNTAIN VIEW, CA 94043
01CY ATTN C WOLF

AEROSPACE CORP.
P.O. BOX 92957
LOS ANGELES, CA 90009
01CY ATTN H VIERES
01CY ATTN TECHNICAL INFORMATION SERVICES

AGBAIAN ASSOCIATES
250 N NASH STREET
EL SEGUNDO, CA 90245
01CY ATTN W AGBAIBAIN

ANALYTIC SERVICES, INC.
400 ARMY-NAVY DRIVE
ARLINGTON, VA 22202
01CY ATTN G HESSLEBACHER

APPLIED RESEARCH ASSOCIATES, INC
2601 WYCHING BLVD NE SUITE 1-1
ALBUQUERQUE, NM 87112
01CY ATTN J ERATTON
01CY ATTN N HIGGINS

APPLIED THEORY, INC.
1010 WESTWOOD PLZ
LOS ANGELES, CA 90024
(7 CY5 IF INCLASS OR 1 CY IF CLASS)
01CY ATTN J TRUDE

55
FRIC H. WANG
CIVIL ENGINEERING DSCH FAC
UNIVERSITY OF NEW MEXICO
UNIVERSITY STATION
P O BOX 25
ALBUQUERQUE, NM 87131
OICY ATTN J LAMB
OICY ATTN P LLOYD
OICY ATTN N RAIN
OICY ATTN J KOVARAA

GARD, INC.
7449 N NATCHES AVENUE
NILES, IL 60648
OICY ATTN G VEHAPOT (UNCL ONLY)

GENERAL ELECTRIC CO.
SPACE DIVISION
VALLEY FORGE SPACE CENTER
P O BOX 9555
PHILADELPHIA, PA 19101
OICY ATTN M BORTNEP

GENERAL RESEARCH CORP.
SANTA BARBARA DIVISION
P O BOX 6770
SANTA BARBARA, CA 93111
OICY ATTN TIC

H-TECH LABS, INC.
P O BOX 1686
SANTA MONICA, CA 90406
OICY ATTN B HAPTEARALY
DEPARTMENT OF DEFENSE CONTRACTORS

HORIZONS TECHNOLOGY, INC.
7830 CLAIREMONT MESA BLVD
SAN DIEGO, CA 92111
OICY ATTN R KRUGER

IIT RESEARCH INSTITUTE
19 W 35TH STREET
CHICAGO, IL 60616
OICY ATTN R LELCH
OICY ATTN W JOHNSON
OICY ATTN DOCUMENTS LIBRARY

INFORMATION SCIENCE, INC.
123 W PADRE STREET
SANTA BARBARA, CA 93105
OICY ATTN W DUDIAK

INSTITUTE FOR DEFENSE ANALYSES
400 ARMY-NAVY DRIVE
ARLINGTON, VA 22202
OICY ATTN CLASSIFIED LIBRARY

J D HALTIWANGER CONSULT ENG SVCs
84 106A CIVIL ENGINEERING BLDG
208 N ROMINE STREET
URBANA, IL 61801
OICY ATTN W HALL

J. H. WIGGINS CO., INC.
1650 S PACIFIC COAST HIGHWAY
REDONDO BEACH, CA 90277
OICY ATTN J COLLINS
DEPARTMENT OF DEFENSE CONTRACTORS

KAMAN AVIDyne
83 SECOND AVENUE
NORTHWEST INDUSTRIAL PARK
WORLINGTON, MA 01203
OICY ATTN P. ULENEIK
OICY ATTN LIBRARY
OICY ATTN M. HOPPE
OICY ATTN E. CRISCIEN

KAMAN SCIENCES CORP.
P. O. BOX 7463
COLORADO SPRINGS, Co 80933
OICY ATTN D. SACHS
OICY ATTN F. SHELTON
OICY ATTN LIBRARY

KAMAN TEMPO
816 STATE STREET (P. O. DRAWER 00)
SANTA BARBARA, CA 92105
OICY ATTN DASIAK

LOCKHEED MISSILES & SPACE CO., INC.
P.O. BOX 504
SUNNYVALE, CA 94086
OICY ATTN J. WEISNER
OICY ATTN TIC-LIBRARY

MARTIN MARIETTA CORP.
P.O. BOX 5937
ORLANDO, FL 32855
OICY ATTN G. FCTIEC

MARTIN MARIETTA CORP.
P.O. BOX 179
DENVER, CO 80201
OICY ATTN G. FREYER
DEPARTMENT OF DEFENSE CONTRACTORS

MCDONNELL DOUGLAS CORP.
5301 BOLSA AVENUE
HUNTINGTON BEACH, CA 92647
OICY ATTN H HERMAN
OICY ATTN R HALPINE
OICY ATTN D DFAY

MCDONNELL DOUGLAS CORP.
3855 LAKEWOOD BOULEVARD
LONG BEACH, CA 90846
OICY ATTN M POTTER

MERRITT CASES, INC.
P.O. BOX 1206
REDLANDS, CA 92373
OICY ATTN J MERRITT
OICY ATTN LIPPSREY

METEOROLOGY RESEARCH, INC.
466 W WOODRURY ROAD
ALTADENA, CA 91001
OICY ATTN W GREEN

MISSION RESEARCH CORP.
P.O. BOX 719
SANTA BARBARA, CA 93102
(ALL CLASS: ATTN: SEC OEC FOR)
OICY ATTN C LONGHIRE
OICY ATTN G MCCARTER

PACIFIC-SIERRA RESEARCH CORP.
1456 CLOVERFIELD BLVD
SANTA MONICA, CA 90404
OICY ATTN H BONNE
DEPARTMENT OF DEFENSE CONTRACTORS

PACIFIC-SIERRA RESEARCH CORP.
WASHINGTON OPERATIONS
1401 WILSON BLVD
SUITE 1100
ARLINGTON, VA 22209
OICY ATTN O. GORBYLEY

PACIFICA TECHNOLOGY
P.O. BOX 149
DEL MAR, CA 92014
OICY ATTN R. J. CRUK
OICY ATTN G. KENT
OICY ATTN TECH LIBRARY

PATTEL ENTERPRISES, INC.
P.O. BOX 3531
HUNTSVILLE, AL 35810
OICY ATTN M. PATTEL

PHYSICS INTERNATIONAL CORP.
2700 MERCEDE STREETS
SAN LEANDRO, CA 94577
OICY ATTN L. PENHORN
OICY ATTN TECH NICAL LIBRARY
OICY ATTN E. COPE
OICY ATTN J. THayer
OICY ATTN E. CATER

R & D ASSOCIATES
P.O. BOX 9695
MARINA DEL REY, CA 90291
OICY ATTN R. PORT
OICY ATTN A. KIYORI
OICY ATTN J. LEWITS
OICY ATTN W. WRIGHT
OICY ATTN J. CARPENTER
OICY ATTN TECHNICAL INFORMATION CENTER

62
SOUTHWEST RESEARCH INSTITUTE
P O DRAWER 28510
SAN ANTONIO, TX 78294
OICY ATTN A WENZEL
OICY ATTN W BAKER

SRI INTERNATIONAL
333 RAVENSWOOD AVENUE
MENLO PARK, CA 94025
OICY ATTN G ARRAHANCA
OICY ATTN LIBRARY
OICY ATTN J COLVEN

SYSTEMS, SCIENCE & SOFTWARE INC
P O BOX 8243
ALBUQUERQUE NM 87108
OICY ATTN C NEIDHAM

SYSTEMS, SCIENCE & SOFTWARE, INC.
P O BOX 1620
LA JOLLA, CA 92038
OICY ATTN J PANTHEL
OICY ATTN T PINEY
OICY ATTN D GRIME
OICY ATTN LIBRARY
OICY ATTN C HASTING
OICY ATTN K PYATT
OICY ATTN C DUSKES
OICY ATTN T CHERRY

SYSTEMS, SCIENCE & SOFTWARE, INC.
11000 SUNRISE VALLEY DRIVE
RESTON, VA 22091
OICY ATTN J MURPHY
TELEDYNE BROWN ENGINEERING
CUMMINGS RESEARCH PARK
HUNTSVILLE, AL 35805
OICY ATTN J RAVENSCRAFT
OICY ATTN J MCNAIR

TERPA TEK, INC.
420 WAKARA WAY
SALT LAKE CITY, UT 84107
OICY ATTN A AGHJ-SAVES
OICY ATTN LIBRARY
OICY ATTN J JONES
OICY ATTN S GREEN

TITRA TFCH, INC.
630 N CITYHEA BLVD
PASADENA, CA 91107
OICY ATTN L HUANG

TRW DEFENSE & SPACE SYS GROUP
ONE SPACE PARK
REDONDO BEACH, CA 90278
OICY ATTN N LIPNER
OICY ATTN TECHNICAL INFORMATION CENTER
OICY ATTN T MAZZOLA

TRW DEFENSE & SPACE SYS GROUP
P.O. BOX 1310
SAN BERNARDINO, CA 92407
OICY ATTN E HILCHEP
OICY ATTN P DAI
OICY ATTN E HONG
DEPARTMENT OF DEFENSE CONTRACTORS

UNIVERSAL ANALYTICS, INC.
7740 W MANCHESTER BLVD
PLAYA DEL REY, CA 90291
OICY ATTN E FIELD

WEIDINGER ASSOC., CONSULTING ENGINEERS
110 E 59TH STREET
NEW YORK, NY 10022
OICY ATTN I SANDLER
OICY ATTN M PARSON

WEIDINGER ASSOC., CONSULTING ENGINEERS
3000 SAND HILL ROAD
MENLO PARK, CA 94025
OICY ATTN J ISENPEER

Chief Scientist
Naval Research Laboratory
Laboratory for Computational Physics
Code 4040
Washington, D.C. 20375
OICY ATTN J. Boris
DEPARTMENT OF DEFENSE

ASSISTANT TO THE SECRETARY OF DEFENSE
(ATOMIC ENERGY)
WASHINGTON, DC 20301
OICY ATTN EXECUTIVE ASSISTANT

DIRECTOR
DEFENSE COMMUNICATIONS AGENCY
WASHINGTON, DC 20308
(OFFICIAL; ATTN CODE 140 FOR)
OICY ATTN CODE 570 O LIPP

DIRECTOR
DEFENSE INTELLIGENCE AGENCY
WASHINGTON, DC 20301
OICY ATTN DDS-2 A (TECH LID)
OICY ATTN OD 4H
OICY ATTN OT 1C
OICY ATTN OT-2
OICY ATTN OD 4C F CEPRELL

DIRECTOR
DEFENSE NUCLEAR AGENCY
WASHINGTON, DC 20305
OICY ATTN SPSS
OICY ATTN SPSS C ULLRICH
OICY ATTN SPSS T DEEVY
O4CY ATTN TITL

DEFENSE TECHNICAL INFORMATION CENTER
CAMERON STATION
ALEXANDRIA, VA 22314
(OFFICIAL; ATTN CODE 7, OTHERWIZE 2, NO MAINTEL)
OICY ATTN OD

CHAIRMAN
DEPARTMENT OF DEFENSE EXPLO SAFETY BOARD
HOFFMAN BLDG 1, RM 556-C
2461 EISENHOWER AVENUE
ALEXANDRIA, VA 22331
OICY ATTN CHAIRMAN

67