

DTIC FILE COPY

4

TECHNICAL REPORT BRL-TR-2935

**BRL**

1938 - Serving the Army for Fifty Years - 1988

AD-A199 532

AXISYMMETRIC CALCULATIONS FOR THE LARGE  
BLAST/THERMAL SIMULATOR (LB/TS)  
SHOCK TUBE CONFIGURATION

DIXIE M. HISLEY  
GREGORY A. MOLVIK

SEPTEMBER 1988

DTIC  
ELECTE  
OCT 14 1988  
S E D

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

U.S. ARMY LABORATORY COMMAND

**BALLISTIC RESEARCH LABORATORY**  
**ABERDEEN PROVING GROUND, MARYLAND**

88 10 11 274

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
1a. REPORT SECURITY CLASSIFICATION Unclassified			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION / AVAILABILITY OF REPORT		
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) BRL-TR-2935			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION Ballistic Research Laboratory		6b. OFFICE SYMBOL (If applicable) SLCBR-TB-B	7a. NAME OF MONITORING ORGANIZATION Harry Diamond Laboratories		
6c. ADDRESS (City, State, and ZIP Code) Aberdeen Proving Ground, MD 21005-5066			7b. ADDRESS (City, State, and ZIP Code) Adelphi, MD 20783-1197		
8a. NAME OF FUNDING / SPONSORING ORGANIZATION Harry Diamond Laboratories		8b. OFFICE SYMBOL (If applicable) SLCHD-TI	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c. ADDRESS (City, State, and ZIP Code) Adelphi, MD 20783-1197			10. SOURCE OF FUNDING NUMBERS		
PROGRAM ELEMENT NO.		PROJECT NO. 1L162120 AH25	TASK NO. 44061- 801-63	WORK UNIT ACCESSION NO.	
11. TITLE (Include Security Classification) Axisymmetric Calculations for the Large Blast/Thermal Simulator (LB/TS) Shock Tube Configuration					
12. PERSONAL AUTHOR(S) Hisley, Dixie M., and Molvik, Gregory A					
13a. TYPE OF REPORT Technical		13b. TIME COVERED FROM Jan 86 TO Sep 86		14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	Euler Finite Volume Nozzle Flow		
20	04		Blast 2D Code Large-Scale Blast Simulator Upwind		
01	01		Heated Driver Total Variation Diminishing		
19. ABSTRACT (Continue on reverse if necessary and identify by block number)					
<p>Computational fluid dynamics (CFD) is a tool which predicts the gas dynamics of blast problems of interest to the Army by solving a set of mathematical equations with a high-speed digital computer. The governing equations for the blast problems presented here are the two-dimensional unsteady Euler equations. The computations were performed on a Cray XMP/48 supercomputer by discretizing the Euler equations with an upwind, Total Variation Diminishing (TVD), finite volume, implicit scheme. Details of the scheme are presented in the paper. The algorithm is used here to provide gas dynamic information for a candidate large-scale blast simulator (LBS) concept.</p> <p style="text-align: center;"><i>er. s. t.;</i></p> <p>The Army has a growing need for nuclear blast survivability testing of tactical equipment. In order to meet this need, <del>the Army is conducting</del> <sup>is conducting</sup> research into the design and operation of a Large-scale Blast Thermal Simulator (LBS), essentially a large multi-driver shock tube. Experiments with heated and unheated driver gas have been performed in a single driver, 1/57.</p>					
20. DISTRIBUTION / AVAILABILITY OF ABSTRACT <input type="checkbox"/> UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL Dixie M. Hisley			22b. TELEPHONE (Include Area Code) (301) 278-6027	22c. OFFICE SYMBOL SLCBR-TB-B	

19. ABSTRACT (Continued):

scale model of the LB/TS design concept but without the thermal simulation (LBS). One dimensional calculations have been performed for the 1/57 scale LBS with useful results. However, the one-dimensional calculations have had limited success for accurately predicting the flow through the diverging portion of the LBS design because the flow in this region is multi-dimensional. The flow is multi-dimensional due to the rapid and large area change that exists in the diverging nozzle. The paper presents results which demonstrate the nature of fluid physics in the 1/57 scale LBS.

# DISPOSITION FORM

For use of this form, see AR 340-15; the proponent agency is TAGO.

REFERENCE OR OFFICE SYMBOL SLCBR-TB	SUBJECT Submission of Manuscript for Publication		
TO Chief, STINFO (Tech Reports)	FROM TBD	DATE 9 June 1988	CMT 1
1. The enclosed manuscript is submitted for publication, as follows:			
a. This report does _____ does not <input checked="" type="checkbox"/> supersede an IMR. IMR No. _____ dated _____.			
b. Title: <u>Axisymmetric Calculations for the Large Blast/Thermal Simulator (LB/TS)</u> <u>Shock Tube Configuration</u>			
c. BRL Author(s): <u>Hisley, Dixie M.</u> Non-BRL Author(s): <u>Molvik, Gregory A.</u>			
d. Report Classification: <u>Unclassified</u> Classified by: _____			
e. The following distribution will be applied to this report:			
A <input checked="" type="checkbox"/>	D _____	Reason: _____	
B _____	E _____	_____	
C _____	_____		
f. Project No: <u>1L162120AH25</u>			
g. Remarks: _____			
h. Type of Report: TR <input checked="" type="checkbox"/> MR _____ CR _____ SP _____ IMR _____			
i. Report was composed on (type of machine used): <u>Zenith/Jove editor</u> , using a (type of element/type style) <u>Laser printer font 404</u> .			
2. We attest to the accuracy of technical content and security classification of the enclosed manuscript, and are satisfied with its technical organization. We, the undersigned, submit this report for publication.			
Author(s)/COR <u>Dixie M Hisley, Dixie M Hisley for Gregory A Molvik</u>			
Reviewer(s) <u>Richard E Lotters Michael J. Rusea</u>			
Encl _____ <i>for</i> <u>CLARENCE W. KITCHENS, JR.</u> Chief			
Branch Chief <u>Andrew Mark</u> ANDREW MARK, Chief, Blast Dynamics Branch, TBD			

SLCBR Form 3R, 1 Jun 86

TABLE OF CONTENTS

	Page
LIST OF FIGURES .....	v
Paragraph 1 INTRODUCTION .....	1
2 GOVERNING EQUATIONS .....	2
3 THE COMPUTATIONAL ALGORITHM .....	5
3.1 <u>Introduction</u> .....	5
3.2 <u>First-Order Scheme</u> .....	6
3.3 <u>Second-Order Scheme</u> .....	8
3.4 <u>Implicit Scheme</u> .....	10
3.5 <u>Iterative Scheme</u> .....	11
3.6 <u>Axisymmetric Source Term</u> .....	12
3.7 <u>Boundary Conditions</u> .....	13
4 GEOMETRY, GRID, AND INITIAL CONDITIONS FOR LBS COMPUTATIONS .....	14
5 RESULTS AND DISCUSSION .....	15
6 CONCLUSIONS .....	19
REFERENCES .....	21
DISTRIBUTION LIST .....	41



Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By _____	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

## LIST OF FIGURES

		Page
FIGURE	1. Schematic of the Proposed U.S. Large Blast/Thermal Simulator Facility.....	22
	2. Single-driver 1/57 Scale Model of LBS Design Concept.....	23
	3. Finite Volume Cell in Computational Space.....	24
	4. Riemann Problem.....	24
	5. Pressure versus Time Plots, 34 kPa (5 psi) Peak Overpressure, Shot #2.....	25
	6. Contour Plots at .5 ms and 1.0 ms, 34 kPa (5 psi) Peak Overpressure, Shot #2.....	26
	7. Contour Plots at 1.4 ms and 1.9 ms, 34 kPa (5 psi) Peak Overpressure, Shot #2.....	27
	8. Contour Plots at 5.4 ms and 23.0 ms, 34 kPa (5 psi) Peak Overpressure, Shot #2.....	28
	9. Development of Primary Shock, Contact, and Backward-facing Shock in Diverging Nozzle, Amann(8).....	29
	10. Pressure versus Time Plots, 175 kPa (25 psi) Peak Overpressure, Unheated Driver, Shot #12...	30
	11. Pressure versus Time Plots, 175 kPa (25 psi) Peak Overpressure, Heated Driver, Shot #85-11..	31
	12. Pressure versus Time Plots, 241 kPa (35 psi) Peak Overpressure, Unheated Driver, Shot #85-21.....	32
	13. Pressure versus Time Plots, 241 kPa (35 psi) Peak Overpressure, Heated Driver, Shot #85-23.....	33

LIST OF FIGURES

	Page
FIGURE 14. Contour Plots at .5 ms and 1.0 ms, 241 kPa (35 psi) Peak Overpressure, Shot #85-21, Unheated Driver.....	34
15. Contour Plots at 1.5 ms and 2.0 ms, 241 kPa (35 psi) Peak Overpressure, Shot #85-21, Unheated Driver.....	35
16. Contour Plots at 5.6 ms and 23.4 ms, 241 kPa (35 psi) Peak Overpressure, Shot #85-21, Unheated Driver.....	36
17. Contour Plots at .4 ms and .7 ms, 241 kPa (35 psi) Peak Overpressure, Shot #85-23, Heated Driver.....	37
18. Contour Plots at 1.1 ms and 1.5 ms, 241 kPa (35 psi) Peak Overpressure, Shot #85-23, Heated Driver.....	38
19. Contour Plots at 4.1 ms and 17.3 ms, 241 kPa (35 psi) Peak Overpressure, Shot #85-23, Heated Driver.....	39

## 1. INTRODUCTION

Computational fluid dynamics (CFD) is a tool which predicts the gas dynamics of blast problems of interest to the Army by solving a set of mathematical equations with a high-speed digital computer. The governing equations for the blast problem presented here are the two-dimensional unsteady Euler equations. The computations were performed on a Cray XMP/48 supercomputer by discretizing the Euler equations with an upwind, Total Variation Diminishing (TVD), finite-volume, implicit scheme. In a paper by Molvik,(1)\* the scheme was presented in detail and proved to be well suited for blast wave calculations. The scheme is discussed in the computational algorithm section. The algorithm is used here to provide gas dynamic information for a candidate Large-Scale Blast and Thermal Simulator (LB/TS) concept.

The Army has a growing need for nuclear blast and thermal survivability testing of tactical equipment. In order to meet this need, the Army is conducting research into the design and operation of a Large-Scale Blast and Thermal Simulator (LB/TS), essentially a large multi-driver shock tube with thermal capabilities. The LB/TS design(2) currently consists of a number of driver tubes releasing compressed gas through a series of converging-diverging nozzles into a large expansion tunnel, Figure 1. The compressed gas forms a shock which travels down the expansion tunnel and produces the blast simulation. The thermal simulation is accomplished by igniting a Thermal Radiation Source (TRS) based on aluminum/oxygen combustion just before the arrival of the blast wave at the test section. The expansion tunnel is physically large enough to accommodate the testing of full-sized tactical vehicles such as tanks and helicopters at low blockage of the test section.

The LB/TS can be modeled in a 2-D axisymmetric sense by combining the drivers and nozzles to form one equivalent driver as shown in Figure 3. This simplified model of the LB/TS was actually built for experimental testing at Aberdeen Proving

---

\* The numbers inside ( ) denote the reference number.



Ground. The thermal radiation source was not experimentally or computationally modeled. This shock tube is 1/57th of the scale of the proposed LB/TS. The experimental data obtained in this tube was used for LB/TS design studies and BLAST2D code validation. All of the experimental and computational data presented in this paper was from this shock tube configuration. Blast waveforms were produced with peak overpressures ranging from approximately 5 psi to 35 psi. Heating of the driver gas was performed for some of the high pressure cases to reduce the driver pressure required to obtain a given shock overpressure, and to alleviate the temperature (density) discontinuity at the contact surface between the expanded driver gas and shocked expansion section gas.

Currently, one-dimensional calculations have been performed for the 1/57 scale LBS with useful results.(3,4) However, the one-dimensional calculations have had limited success for accurately predicting the flow through the diverging portion of the LBS design because the flow in this region is multi-dimensional. The flow is multi-dimensional due to the rapid and large area change that exists in the diverging nozzle. The remainder of this paper presents the upwind, TVD, finite-volume, implicit scheme in the BRL BLAST2D code and results which capture and reveal the nature of the flow physics in the 1/57 scale LBS.

## 2. GOVERNING EQUATIONS

The governing equation is the Euler equation written in integral form:

$$\frac{d}{dt} \int_V Q dV + \int_S n \cdot F dS = 0 \quad (1)$$

The integral form of the Euler equation can be rewritten for a two-dimensional generalized cell volume (Figure 3) as :

$$0 = \frac{d}{dt} \int_V Q dV + \int_{j-\frac{1}{2}}^{j+\frac{1}{2}} (E_{i+\frac{1}{2}} - E_{i-\frac{1}{2}}) d\eta + \int_{i-\frac{1}{2}}^{i+\frac{1}{2}} (F_{j+\frac{1}{2}} - F_{j-\frac{1}{2}}) d\xi \quad (2)$$

where;

$$Q = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ e \end{pmatrix} \quad E = \begin{pmatrix} \rho U \\ \rho U u + Y_n p \\ \rho U v - x_n p \\ (e+p)U \end{pmatrix} \quad F = \begin{pmatrix} \rho V \\ \rho V u - y_\xi p \\ \rho V v + x_\xi p \\ (e+p)V \end{pmatrix} \quad (3)$$

This set of four integral equations represents the conservation of mass, momentum in x and y directions, and energy, per unit volume where  $\rho$  is the density,  $p$  is the pressure,  $u$  and  $v$  are the velocities in the x (longitudinal) and y (height) directions respectively, and  $e$  is the total internal energy per unit volume:

$$e = \frac{p}{(\gamma-1)} + 1/2 \rho (u^2 + v^2) \quad (4)$$

The volume fluxes are defined as:

$$U = y_n u - x_n v \quad (5)$$

$$V = y_\xi u + x_\xi v \quad (6)$$

For the two dimensional cell shown in Figure 3, the integration of flux over the surface in Equation 1 has been replaced in Equation 2 by an integral over each face of the cell. The  $n$ -direction is taken as the body normal and the  $\xi$ -direction is tangential to the surface of the body. The cell volume and walls are assumed to be fixed in time. The metrics  $x_\xi, y_\xi, x_n, y_n$  are the vector elements of the cell walls and  $V$  is the volume of the grid cell.

The physical, independent variables  $(x,y,t)$  were transformed into a uniformly spaced computational grid  $(\xi, \eta, \tau)$  by a general transformation of the form:

$$\begin{aligned}
\tau &= t \\
\xi &= \zeta(t, x, y) \\
\eta &= \eta(t, x, y)
\end{aligned}
\tag{7}$$

The transformations were chosen so that the grid spacing in the computational space is uniform and of unit length,  $\Delta\xi = 1$ ,  $\Delta\eta = 1$ . Thus, the uniform equi-spaced mesh in psi and eta allows the use of unweighted differencing schemes. As a result, the computational code can be applied to a variety of physical geometries and grids.

If an average flux is defined on the cell faces, and  $\Delta\xi$  and  $\Delta\eta$  are taken as unity, the integral form of the Euler equation, Equation 2 can be rewritten in finite volume form as:

$$V_{i,j} \frac{\bar{Q}_{i,j}^{n+1} - \bar{Q}_{i,j}^n}{\Delta\tau} + \frac{\hat{E}_{i+\frac{1}{2},j}^m - \hat{E}_{i-\frac{1}{2},j}^m}{\Delta\xi} + \frac{\hat{F}_{i,j+\frac{1}{2}}^m - \hat{F}_{i,j-\frac{1}{2}}^m}{\Delta\eta} = 0 \tag{8}$$

where the indices  $i$  and  $j$  correspond to the  $\xi$  and  $\eta$  directions respectively in the computational mesh as shown in Figure 3. The vectors  $E$  and  $F$  are the convective numerical fluxes in computational space  $(\xi, \eta, \tau)$  consistent with the physical fluxes  $E$  and  $F$  in  $(x, y, t)$ . The vector  $Q$  consists of the cell averaged dependent variables. The integration scheme is fully implicit if  $m=n+1$  and is explicit if  $m=n$ . The variables have been nondimensionalized as follows;

$$\begin{aligned}
\tilde{x} &= \frac{x}{L} & \tilde{u} &= \frac{u}{c_1} & \tilde{p} &= \frac{p}{\rho_4 c_1^2} \\
\tilde{y} &= \frac{y}{L} & \tilde{v} &= \frac{v}{c_1} & \tilde{e} &= \frac{e}{\rho_4 c_1^2} \\
\tilde{\rho} &= \frac{\rho}{\rho_4} & \tilde{t} &= \frac{tc_1}{L}
\end{aligned} \tag{9}$$

where  $L=1$ ,  $c$ =sound speed, and subscripts 1 and 4 represent conditions in the driven and driver sections respectively.

### 3. THE COMPUTATIONAL ALGORITHM

**3.1 Introduction.** Discretization of the governing equations into an upwind, TVD, finite-volume, implicit scheme produces an algorithm that is well suited for blast wave calculations. (1) Upwind flux difference splitting with TVD achieves second-order accuracy without introducing spurious oscillations near discontinuities. Strong gradients and complex flow fields are resolved accurately. Older techniques used central differencing schemes with arbitrary smoothing parameters which could not be relied on to capture strong gradients (i.e., pressure ratio across the shock  $> 10.0$ ) accurately. (5) The advantages of the central differencing techniques were programming simplicity and adequate resolution for weak gradient problems. However, for the complex flow fields and strong gradients typical of blast problems upwind differencing with TVD provides better resolution. The disadvantages of upwind differencing with TVD are long computing times caused by an increase in the number of arithmetic operations per integration step and loss of programming simplicity. The BLAST2D code results shown in this paper were generated on a Cray XMP/48 and typically took six to seven hours of cpu time.

Conservative schemes capture shocks and other discontinuities automatically. The finite volume philosophy ensures conservation at interior and boundary points. The scheme is made implicit by linearizing only the first-order

contribution and by employing a Newton iteration of the type described by Rai(5) to eliminate any approximations made. The implicit version of the scheme requires more computations per integration step than the explicit version, but permits larger time steps which overall reduces computational expense.

The next section presents the first-order accurate upwind scheme(1) which is the basic building block of the computational algorithm. Subsequently, the first-order scheme is expanded to second order accuracy with the addition of second-order terms and TVD concepts. Development of the implicit version of the algorithm and the Newton iterative procedure used is presented. Finally, boundary conditions are discussed briefly.

**3.2 First-Order Scheme.** The first-order scheme is based upon Roe's approximate Riemann solver (6,7) coupled with upwind flux difference splitting. First, approximate Riemann solvers are discussed. Then, the information supplied by the Riemann solver is used with upwind flux difference splitting concepts to provide the first-order convective fluxes E and F in the finite volume form of the Euler equation, Equation 8.

Riemann problems are incorporated into the numerical solution by considering the dependent variables at cell centers for each cell in turn, as pairs of states defining a sequence of Riemann problems, Figure 4. The Riemann problem for the  $x$  direction in Figure 4 is : given two states  $(\rho_1, u_1, p_1)$  and  $(\rho_4, u_4, p_4)$  determine the combination of shocks, contact discontinuities, and expansions which result in these end states, that is, determine  $(\rho_2, u_2, p_2)$  and  $(\rho_3, u_3, p_3)$ . To obtain a solution, exact Riemann solvers require an iterative procedure which is computationally expensive when performed for a large number of cells and time steps. The expense of producing an exact solution to the Riemann problem is justified only if the information made available could be put to some sophisticated use. The approximate Riemann solvers are considerably less expensive because the Riemann problem is solved with a direct non-iterative method which is about as time consuming as one cycle of the iterative procedures. Comparisons of the solutions from the exact vs. approximate Riemann solvers reveal slight differences. Other approximate Riemann solvers could have been used, but Roe's method is the approach recommended by Chakravarthy when computational

efficiency is important.(6)

References 6 and 7 outline in detail Roe's method for determining the intermediate states of the Riemann problem. In general, the solution consists of four constant property states separated by three waves, Figure 4. Once the dependent variables are obtained at the intermediate states, the flux at the cell interface is calculated by determining the flux change across the waves. The flux change associated with the waves traveling in the positive  $\xi$  direction is given the symbol  $\Delta E^+$  and that in the negative direction is represented by  $\Delta E^-$ . The waves carry information from the "upwind" direction to the cell center, thus the notion of upwind differencing. The flux remaining at the interface for all time associated with this Riemann problem must then be represented by either of the following equations:

$$\hat{E}_{i+\frac{1}{2}} = E_i + \Delta E_{i+\frac{1}{2}}^- \quad (10)$$

$$\hat{E}_{i+\frac{1}{2}} = E_{i+1} - \Delta E_{i+\frac{1}{2}}^+ \quad (11)$$

or, by averaging the two equations above,

$$\hat{E}_{i+\frac{1}{2}} = 1/2 \left( E_i + E_{i+1} + \Delta E_{i+\frac{1}{2}}^- - \Delta E_{i+\frac{1}{2}}^+ \right) \quad (12)$$

Let  $\Lambda$ ,  $R$ , and  $R^-$  denote the eigenvalue matrix, and the right and left eigenvector matrices respectively, evaluated at the cell interface.(7) The flux difference across the positive and negative velocity waves can be calculated. They are:

$$\Delta E_{i+\frac{1}{2}}^+ = \left( R_{i+\frac{1}{2}} (\Lambda + |\Lambda|)_{i+\frac{1}{2}} R_{i+\frac{1}{2}}^{-1} \right) (\bar{Q}_{i+1} - \bar{Q}_i) = A^+ (\bar{Q}_{i+1} - \bar{Q}_i) \quad (13)$$

$$\Delta E_{i+\frac{1}{2}}^- = \left( R_{i+\frac{1}{2}} (\Lambda + |\Lambda|)_{i+\frac{1}{2}} R_{i+\frac{1}{2}}^{-1} \right) (\bar{Q}_{i+1} - \bar{Q}_i) = A^- (\bar{Q}_{i+1} - \bar{Q}_i) \quad (14)$$

However, the dependent variables are not defined at the cell

interfaces where these matrices must be evaluated. Roe(7) has developed a special averaging process to calculate the dependent variables on the cell interface and satisfy the following relation.

$$\begin{aligned} \hat{E}_{i+1/2} - \hat{E}_i &= [A]_{i+1/2}^{\text{Roe}} (\bar{Q}_{i+1} - \bar{Q}_i) \\ &= [A^+ + A^-]_{i+1/2}^{\text{Roe}} (\bar{Q}_{i+1} - \bar{Q}_i) \end{aligned} \quad (15)$$

The superscript Roe denotes a Roe averaged quantity. By satisfying the relations above, the shock capturing capabilities of the algorithm are retained and correct wave speeds are assured. Roe's averaging of the dependent variables proceeds as follows:

$$\begin{aligned} u_{i+1/2} &= \frac{u_i \sqrt{\rho_i} + u_{i+1} \sqrt{\rho_{i+1}}}{\sqrt{\rho_i} + \sqrt{\rho_{i+1}}} & v_{i+1/2} &= \frac{v_i \sqrt{\rho_i} + v_{i+1} \sqrt{\rho_{i+1}}}{\sqrt{\rho_i} + \sqrt{\rho_{i+1}}} \\ h_{i+1/2} &= \frac{h_i \sqrt{\rho_i} + h_{i+1} \sqrt{\rho_{i+1}}}{\sqrt{\rho_i} + \sqrt{\rho_{i+1}}} \\ c_{i+1/2} &= \left\{ \left( h_{i+1/2} - 1/2 \left( u_{i+1/2}^2 + v_{i+1/2}^2 \right) \right) (\gamma - 1) \right\}^{1/2} \end{aligned} \quad (16)$$

where the total enthalpy per unit mass is

$$h = (e + p)/\rho \quad (17)$$

The first-order flux on the  $j+1/2$  interface can be obtained in a similar manner by replacing  $x_\xi$  with  $-x_\eta$  and  $y_\xi$  with  $-y_\eta$ .

**3.3 Second-Order Scheme.** A second-order convective flux can be produced by adding a correction term to the first-order flux. However, in order to avoid spurious oscillations, the correction term must fulfill the criteria for the algorithm to be TVD. TVD schemes achieve second-order accuracy without introducing spurious oscillations near discontinuities by employing a feedback mechanism - "smart numerical dissipation" - wherein fluxes are compared at neighboring control volumes. In regions of little change no numerical dissipation is added to the second order correction

terms, while in regions of large change, numerical dissipation is added to ensure stability.

During this process no new extrema are created by the numerical dissipation. TVD data preserve monotonicity; a) no new extrema must be created and b) the absolute value of any extrema must not increase. TVD schemes yield oscillation-free solutions by modifying flux differences to meet the above criteria. Reference 7 outlines a class of explicit flux limiting schemes that fulfill this criteria. The second-order flux for the fully upwind scheme can be written as(1):

$$\hat{E}_{i+1/2}^{2nd} = \hat{E}_{i+1/2}^{1st} + 1/2 \left[ \Delta \tilde{E}_{i-1/2}^+ - \Delta \tilde{E}_{i+3/2}^- \right] \quad (18)$$

If the following definitions are made,

$$\Delta \sigma_{i+1/2}^+ = \left( (\lambda + |\lambda|)_{i+1/2} R_{i+1/2}^{-1} \right) (\bar{Q}_{i+1} - \bar{Q}_i) \quad (19)$$

$$\Delta \sigma_{i+1/2}^- = \left( (\lambda + |\lambda|)_{i+1/2} R_{i+1/2}^{-1} \right) (\bar{Q}_{i+1} - \bar{Q}_i) \quad (20)$$

then the limited values of the flux can be written as

$$\Delta \tilde{E}_{i+1/2}^- = R_{i+1/2} \tilde{\Delta \sigma}_{i+1/2}^-, \quad \Delta \tilde{E}_{i+1/2}^+ = R_{i+1/2} \tilde{\Delta \sigma}_{i+1/2}^+ \quad (21)$$

Note that the characteristic fluxes are limited, not the fluxes given in Equation 3. The symbols  $\sim$  and  $\approx$  shown over the  $\Delta \sigma$  denote flux-limited values of  $\Delta \sigma$  and are computed as follows:

$$\tilde{\Delta \sigma}_{i+1/2}^- = \text{minmod} \left[ \Delta \sigma_{i+1/2}^-, \beta \Delta \sigma_{i-1/2}^- \right] \quad (22)$$

$$\tilde{\Delta \sigma}_{i+1/2}^+ = \text{minmod} \left[ \Delta \sigma_{i+1/2}^+, \beta \Delta \sigma_{i+3/2}^+ \right] \quad (23)$$

Where the "minmod" is defined as

$$\text{minmod} [x,y] = \text{sign}(x) * \max [0, \min \{ |x|, y \text{sign}(x) \}] \quad (24)$$

and beta is a compression parameter that is restricted to fall in the range



$$1 < \beta \leq 2 \quad (25)$$

Equation 8 can be rewritten with the first-order convective fluxes, E and F, replaced with the second-order fluxes:

$$v_{i,j} \frac{\bar{Q}_{i,j}^{n+1} - \bar{Q}_{i,j}^n}{\Delta\tau} + \left[ \frac{\hat{E}_{i+\frac{1}{2},j}^{2nd} - \hat{E}_{i-\frac{1}{2},j}^{2nd}}{\Delta\xi} + \frac{\hat{F}_{i,j+\frac{1}{2}}^{2nd} - \hat{F}_{i,j-\frac{1}{2}}^{2nd}}{\Delta\eta} \right]^n = 0 \quad (26)$$

The above discussion describes the explicit second-order accurate in space scheme. Second-order accuracy in time is achieved by simply replacing the first-order, backward derivative of the time-dependent variables with a second-order backward difference.

**3.4 Implicit Scheme.** For a fully implicit scheme, the fluxes must be evaluated at the n+1 time level. In order to calculate a flux at the n+1 time level the flux must be linearized with respect to time, t. The first-order numerical flux on the i+1/2 cell interface evaluated at the n+1 time level is represented as:

$$\hat{E}_{i+\frac{1}{2}}^{n+1} = \left[ \frac{1}{2} E_{i+1}^{n+1} + E_i^{n+1} + (A^- - A^+)_{i+\frac{1}{2}}^{n+1} (\bar{Q}_{i+1}^{n+1} - \bar{Q}_i^{n+1}) \right] \quad (27)$$

An approximate linearization of this interface flux may be achieved by freezing the coefficient matrix  $(A^- - A^+)$  at time level n and linearizing the remaining terms. Numerical experiments have shown that such an approximation is acceptable. The linearized numerical flux is then written as:

$$\begin{aligned} \hat{E}_{i+\frac{1}{2}}^{n+1} &= \frac{1}{2} \left[ A_{i+1}^n + (A^- - A^+)_{i+\frac{1}{2}}^n \right] \Delta\bar{Q}_{i+1} + \frac{1}{2} \left[ A_i^n - (A^- - A^+)_{i+\frac{1}{2}}^n \right] \Delta\bar{Q}_i + \hat{E}_{i+\frac{1}{2}}^n \quad (28) \\ &= (A^R)_{i+\frac{1}{2}}^n \Delta\bar{Q}_{i+1} + (A^L)_{i+\frac{1}{2}}^n \Delta\bar{Q}_i + \hat{E}_{i+\frac{1}{2}}^n \end{aligned}$$

where,

$$\Delta\bar{Q}_i = \bar{Q}_i^{n+1} - \bar{Q}_i^n$$

Using a similar type of linearization for the body normal flux, F, as for the streamwise flux, E, the first-order, implicit

numerical algorithm is written as:

$$\begin{aligned}
 & \left\{ \Delta \bar{Q}_{i,j} + \frac{\Delta t}{V_{i,j}} \left[ (A^R)_{i+\frac{1}{2}}^n \Delta \bar{Q}_{i+1,j} + \{ (A^L)_{i+\frac{1}{2}}^n - (A^R)_{i-\frac{1}{2}}^n \} \Delta \bar{Q}_{i,j} - (A^L)_{i-\frac{1}{2}}^n \Delta \bar{Q}_{i-1,j} \right] \right. \\
 & \quad \left. + \frac{\Delta t}{V_{i,j}} \left[ (B^R)_{j+\frac{1}{2}}^n \Delta \bar{Q}_{i,j+1} + \{ (B^L)_{j+\frac{1}{2}}^n - (B^R)_{j-\frac{1}{2}}^n \} \Delta \bar{Q}_{i,j} - (B^L)_{j-\frac{1}{2}}^n \Delta \bar{Q}_{i,j-1} \right] \right\} \quad (29) \\
 & = - \frac{\Delta t}{V_{i,j}} \left[ (\hat{E}_{i+\frac{1}{2},j}^n - \hat{E}_{i-\frac{1}{2},j}^n) + (\hat{F}_{i,j+\frac{1}{2}}^n - \hat{F}_{i,j-\frac{1}{2}}^n) \right]
 \end{aligned}$$

To avoid the expense of inverting a large sparse matrix, an approximate factorization is done to break the banded matrix into two tridiagonal matrices. This is written in two steps with the asterisked \* variables denoting an intermediate step as:

$$\begin{aligned}
 \Delta \bar{Q}_{i,j}^* + \frac{\Delta t}{V_{i,j}} \left[ (A^R)_{i+\frac{1}{2}}^n \Delta \bar{Q}_{i+1,j}^* + \{ (A^L)_{i+\frac{1}{2}}^n \right. \\
 \left. - (A^R)_{i-\frac{1}{2}}^n \} \Delta \bar{Q}_{i,j}^* - (A^L)_{i-\frac{1}{2}}^n \Delta \bar{Q}_{i-1,j}^* \right] = \text{RHS}(32) \quad (30)
 \end{aligned}$$

$$\begin{aligned}
 \Delta \bar{Q}_{i,j} + \frac{\Delta t}{V_{i,j}} \left[ (B^R)_{j+\frac{1}{2}}^n \Delta \bar{Q}_{i,j+1} + \{ (B^L)_{j+\frac{1}{2}}^n - (B^R)_{j-\frac{1}{2}}^n \} \Delta \bar{Q}_{i,j} \right. \\
 \left. + (B^L)_{j-\frac{1}{2}}^n \Delta \bar{Q}_{i,j-1} \right] = \Delta \bar{Q}_{i,j}^* \quad (31)
 \end{aligned}$$

**3.5 Iterative Scheme.** In order to eliminate the linearization and approximate factorization errors that might occur, a Newton iteration technique is employed. The iteration takes the form:

$$\begin{aligned}
 & \left\{ \Delta \bar{Q}_{i,j}^* + \frac{\Delta t}{V_{i,j}} \left[ (A^R)_{i+\frac{1}{2}}^p \Delta \bar{Q}_{i+1,j}^* + \{ (A^L)_{i+\frac{1}{2}}^p - (A^R)_{i-\frac{1}{2}}^p \} \Delta \bar{Q}_{i,j}^* - (A^L)_{i-\frac{1}{2}}^p \Delta \bar{Q}_{i-1,j}^* \right] \right\} \\
 & = - (\bar{Q}_{i,j}^p - \bar{Q}_{i,j}^n) - \frac{\Delta t}{V_{i,j}} \left[ (\hat{E}_{i+\frac{1}{2},j}^{2nd} - \hat{E}_{i-\frac{1}{2},j}^{2nd}) + (\hat{F}_{i,j+\frac{1}{2}}^{2nd} - \hat{F}_{i,j-\frac{1}{2}}^{2nd}) \right]^p \quad (32)
 \end{aligned}$$

$$\left\{ \Delta \bar{Q}_{i,j} + \frac{\Delta t}{V_{i,j}} \left[ (B^R)^p_{j+\frac{1}{2}} \Delta \bar{Q}_{i,j+1} + \{ (B^L)^p_{j+\frac{1}{2}} - (B^R)^p_{j-\frac{1}{2}} \} \Delta \bar{Q}_{i,j} - (B^L)^p_{j-\frac{1}{2}} \Delta \bar{Q}_{i,j-1} \right] \right\} = \Delta \bar{Q}_{i,j}^* \quad (33)$$

where  $\Delta \bar{Q}$  is now defined as the iterative change in the cell averaged dependent variables,  $(\bar{Q}_{i,j}^{p+1} - \bar{Q}_{i,j}^p)$  rather than the time change and  $p$  denotes the iteration number. Ideally, all linearization errors are completely eliminated when the residual of equation 31 is driven to zero. However, in practice, convergence is defined short of this with minimal loss in accuracy, in order to reduce the number of iterations and hence the expense of the calculation.

**3.6 Axisymmetric Source Term.** The governing equations and numerical algorithm described so far are appropriate for 2-D planar problems. It is a simple matter to include axisymmetric effects by adding the source terms denoted by  $H$  and  $I$  to equation 32 where:

$$H = \frac{1}{r} \begin{bmatrix} \rho v \\ \rho uv \\ \rho v^2 \\ (e+p)v \end{bmatrix} \quad (34)$$

$$I = \frac{\partial H}{\partial Q} \quad (35)$$

Thus, equations 32 and 33 become:

$$\left\{ \Delta \bar{Q}_{i,j}^* + \frac{\Delta t}{V_{i,j}} \left[ (A^R)^p_{i+\frac{1}{2}} \Delta \bar{Q}_{i+1,j}^* + \{ (A^L)^p_{i+\frac{1}{2}} - (A^R)^p_{i-\frac{1}{2}} + I \} \Delta \bar{Q}_{i,j}^* - (A^L)^p_{i-\frac{1}{2}} \Delta \bar{Q}_{i-1,j}^* \right] \right\} \\ = - (\bar{Q}_{i,j}^p - \bar{Q}_{i,j}^n) - \frac{\Delta t}{V_{i,j}} \left[ (\hat{E}_{i+\frac{1}{2},j}^{2nd} - \hat{E}_{i-\frac{1}{2},j}^{2nd}) + (\hat{F}_{i,j+\frac{1}{2}}^{2nd} - \hat{F}_{i,j-\frac{1}{2}}^{2nd}) + H \right]^p \quad (36)$$

$$\left\{ \Delta \bar{Q}_{i,j} + \frac{\Delta t}{V_{i,j}} \left[ (B^R)^P_{j+\frac{1}{2}} \Delta \bar{Q}_{i,j+1} + \{ (B^L)^P_{j+\frac{1}{2}} - (B^R)^P_{j-\frac{1}{2}} + 1 \} \Delta \bar{Q}_{i,j} - (B^L)^P_{j-\frac{1}{2}} \Delta \bar{Q}_{i,j-1} \right] \right\} = \Delta \bar{Q}_{i,j}^* \quad (37)$$

3.7 Boundary Conditions. The inviscid boundary conditions are obtained by specifying an appropriate flux on the walls of the shock tube and at the symmetry boundary. Only half of the symmetrical shock tube is actually modeled to save computational expense. Then, the results are graphically reflected. At the walls and symmetry boundary, the normal component of velocity is zero, the tangential component of velocity is nonzero. The flux on these surfaces can then be represented as:

$$F = \begin{bmatrix} 0 \\ -y_{\xi} p \\ x_{\xi} p \\ 0 \end{bmatrix} \quad (38)$$

Only a value of pressure need be evaluated at the surface. As a first approximation, one might consider using the pressure of the cell directly above the surface. This translates into a zero-order approximation. However a first-order approximation of the surface flux can be made if a Riemann problem is set up on the surface. This is consistent with the interior scheme and would seem like the reasonable approach. The first-order Riemann solver is used between the first cell off the surface and a reflected cell. If the subscripts 1 and -1 denote the first cell off the surface and the reflected cell respectively, the surface flux can then be written as:

$$\hat{F}_s = 1/2 \left[ F_1 + F_{-1} + (A^- - A^+)_s (\bar{Q}_1 - \bar{Q}_{-1}) \right] \quad (39)$$

The dependent variables of the reflected cell are calculated using the following relations.

$$\begin{aligned}
 p_{-1} &= p_1 & p_{-1} &= p_1 \\
 u_{-1} &= \left[ \left( x_\xi^2 - y_\xi^2 \right) u_1 + 2x_\xi y_\xi v_1 \right] / \left[ x_\xi^2 + y_\xi^2 \right] \\
 v_{-1} &= \left[ \left( y_\xi^2 - x_\xi^2 \right) v_1 + 2x_\xi y_\xi u_1 \right] / \left[ x_\xi^2 + y_\xi^2 \right]
 \end{aligned} \tag{40}$$

The metrics in the above equations are those of the cell interface on the surface. A second order flux can be obtained by reflecting even another set of dependent variables with a subscript of -2.

#### 4. GEOMETRY, GRID, AND INITIAL CONDITIONS FOR LBS COMPUTATION

The geometry of the single-driver, 1/57 scale model LBS design concept is shown in Figure 2. The corners and sharp edges were smoothed out in the computational shock tube to simplify grid generation and to facilitate the use of an elliptic grid generator for the driver and converging-diverging nozzle portion of the tube. The elliptic grid generator produced grid cells that varied smoothly in regions of rapid change such as the converging-diverging nozzle. The grid generated for this configuration was 488 cells axially and 30 cells radially. The computational and experimental diaphragm and test station locations were the same as shown in Figure 2.

Five computations were performed for the LBS configuration with initial conditions that duplicated experimental runs. The initial conditions are summarized in the following table:

TABLE 1. 1/57 Scale Model LBS Initial Conditions

Shot #	P4/P1	Heated Driver	T4/T1	Overpressure kPa (psi)
2	16.0	no	1.0	34 ( 5)

12	136.0	no	1.0	175 (25)
85-11	68.6	yes	1.58	175 (25)
85-21	224.4	no	1.0	241 (35)
85-23	132.1	yes	1.84	241 (35)

## 5. RESULTS AND DISCUSSION

Computational results are presented in this section for the five initial conditions listed in Table 1. The five conditions represent possible lower and upper limits of blast simulation under consideration for the LB/TS. The 175 kPa and 241 kPa pressure levels are more difficult to computationally simulate than the 34 kPa level because of the increased complexity of the resulting flow gradients. Comparisons with experimental data are made where possible.

Data is presented in the form of overpressure and dynamic pressure versus time plots at station 7. Station 7 is located seven diameters downstream from the end of the diverging nozzle and is the primary test location. Also, density and pressure contour plots are presented. The density and pressure contour plots reveal the nature of the flow physics in the shock tube. In this study, efforts are concentrated on understanding two flow phenomena; one is the nozzle flow that results in the large blast thermal simulator, the second is the flow differences that result when the driver gas is heated versus when the driver gas is not heated.

The pressure versus time plots for the 34 kPa (5 psi) run are presented in Figure 5. An experimental dynamic pressure record was not available for this case, therefore, the stagnation pressure record was substituted. The experimental probe was positioned at one half the radius of the tube. The computational data sampled at one half the radius reveals excellent agreement while the computational data sampled at the centerline is in poor agreement. This implies that the stagnation pressure in the radial direction is nonuniform. The stagnation pressure versus time plot shows the importance of computationally sampling at the same spanwise position in the tube as the experiment.

The static overpressure plot shows a discrepancy between the experimental and computational data on the end of the positive phase duration (time when static overpressure goes negative). The experimental and computational data indicates the end of the positive phase duration at 26 and 18 ms respectively. The volume of the computational driver after grid generation was slightly smaller than the volume of the experimental driver, which could cause this discrepancy. Otherwise, the computational and experimental data on the pressure versus time plots are in excellent agreement. Note the computational data is taken at 1/4 diameter and at the centerline. The experimental data was taken by probes flush with the tube wall. This excellent comparison indicates that the static overpressure is radially uniform in the tube. In this paper, the computational and experimental comparison of static overpressure produced very good agreement at all shock overpressures.

The contour data for the 34 kPa (5 psi) run, Figures 6 through 8, reveal the formation of a complex shock system in the diverging nozzle. The contour data shows the primary shock, contact surface, and backward-facing shock developing in the diverging nozzle. The backward-facing shock is not a normal shock, but consists of two oblique shocks which terminate in a normal shock at the center of the tube. The intersection of the oblique and normal shock produces a reflected or an oblique transmitted shock which can also be seen in the contour plots, Figure 7. The complex structure of the backward-facing shock has been verified experimentally, as shown in a shadowgraph photograph by Amann(8), Figure 9.

The primary shock moves quickly through the diverging nozzle and proceeds downstream as a normal shock. The contact surface which separates the driver gas from driven gas can be distinguished as the clustered gradient present in the density plot and not present in the pressure plot. The contact surface moves downstream, maintaining a curved surface. Behind it, the driver gas resembles core flow. In Figure 8, the contact surface takes on a jetting appearance at the centerline boundary that may be an artifice of the code. Behind the contact surface, a complex system of oblique

shocks, rotational motion and slip surfaces develops in the core flow.

The oblique shocks are a result of the backward facing shock, which remains in the diverging nozzle, reflecting at the solid walls and symmetry boundary as oblique shocks. These reflections set up a shock diamond pattern that stretches downstream. This shock diamond pattern was discussed by Gottlieb(9), "If the conical expansion is too rapid, however, or boundary-layer effects are significant this upstream-facing shock wave would be a series of cells consisting of oblique shock waves. The spatial extent or length of such pseudo-shock patterns is very large compared to the thickness of a typical normal shock wave, and they can cover a duct length of many tube diameters". The computations presented here were inviscid, which implies the rapid expansion alone can produce the shock diamond pattern shown in the contour plots.

Even though this is an inviscid code, rotational motion can occur, as visible in Figure 8. Gradients in total enthalpy are caused by the unsteady nature of the shock. These gradients in entropy occur when some streamlines experience a higher entropy increase by going through the normal part of the recompression shock while other streamlines experience a lower entropy increase by going through the oblique part of the recompression shock. From Crocco's theorem we know that whenever gradients in total entalpy or gradients in entropy exist in the flow field, rotational motion occurs.

Figures 10 through 13 present pressure versus time results for the 175 kPa (25 psi) and 241 kPa (35 psi) unheated and heated runs. As stated before, the computational and experimental comparison of static pressure produced good agreement at all shock overpressures. However, it is very important for blast simulation to model not only static pressure but dynamic pressures as well.

Experimental dynamic pressure is not measured directly in the shock tube but is calculated from static and stagnation pressure records. The static pressure data was measured at the wall and the stagnation pressure data was measured at 1/4 diameter. To be rigorous, the static and stagnation probes



should be at the same location in order to calculate true local Mach number and thus true dynamic pressure. However, if the static pressure is radially uniform, then there is no need to have the probes at the same exact radial location. The code indicates static pressure is radially uniform, although this has not been confirmed experimentally by placing probes at different radial locations.

For the 175 kPa heated driver case, the experimental and computational comparison of dynamic pressure are in excellent agreement until the contact surface goes by at .008 seconds. After the contact surface, the computation at 1/4 diameter and the experimental record, based on a stagnation probe at 1/4 diameter are very similar except for one anomaly. The motivation for heating the driver gas can be seen in the experimental records for the 175 kPa unheated driver case.

For the 175 kPa unheated driver case, a much noisier experimental dynamic pressure record is indicated after the arrival of the contact surface. In the previous case, heating smoothed this region and produced a simulation closer to that of a decaying free field wave. Computationally, the comparison is good until the arrival of the contact surface. After the contact surface, the experiment shows a higher Mach number flow at the centerline.

The purpose of heating is to reduce the jump in dynamic pressure (Figures 10 and 12) which occurs across the contact surface for unheated cases. The jump in dynamic pressure increases with the shock overpressure.(2) When the diaphragm is opened, the driver gas is cooled by the passage of the rarefaction wave into the driver section. The driven gas is heated by the passage of the primary shock. At the contact surface, where the driver gas meets the driven gas, the difference in temperature of the driver and driven gas results in a difference in density which in turn is demonstrated as a jump in the dynamic pressure plots. By heating the driver gas to the proper level, the temperature on each side of the contact surface can be matched.

Furthermore, heating of the driver gas reduces the driver pressure required to obtain a given shock overpressure as shown by the initial conditions in Table 1. Heating also significantly reduces the spike activity in the stagnation and

dynamic pressure versus time records (Figures 11 and 13) and produces overpressure versus time records that more closely resemble a smoothly decaying blast overpressure wave shape.

Figures 14 through 19 present contour plots for the 175 kPa (25 psi) and 241 kPa (35 psi) unheated and heated runs. Another effect of heating, as shown in the last contour plots (Figures 16 and 19) available for the time simulated, is the backward-facing shock is eventually swallowed in the nozzle for the heated case, but remains outside the nozzle for the unheated case.

## VI. Conclusions

One-dimensional calculations(3,4) have had limited success for accurately predicting the flow through the rapid expansion of the LB/TS design because the flow in this region is multi-dimensional. Two-dimensional calculations with the upwind, TVD, finite-volume, implicit scheme in the BRL BLAST2D code were presented here which captured and revealed the nature of the flow physics in the 1/57 scale LBS. A complex system of shocks, vortices, and slip surfaces were revealed in contour plots.

Nozzle flow produces a complex recompression shock system which influences the flow behind the contact surface. The static pressure is uniform radially, however, the stagnation pressure and thus both the Mach number and dynamic pressure vary greatly. Because of this radial variation in flow it is very important to compare dynamic pressure computational and experimental records at the same radial location. Heating reduces the required driver pressure for a given shock overpressure and smooths the flow behind the contact surface, producing a dynamic pressure record closer to that of a free field wave.

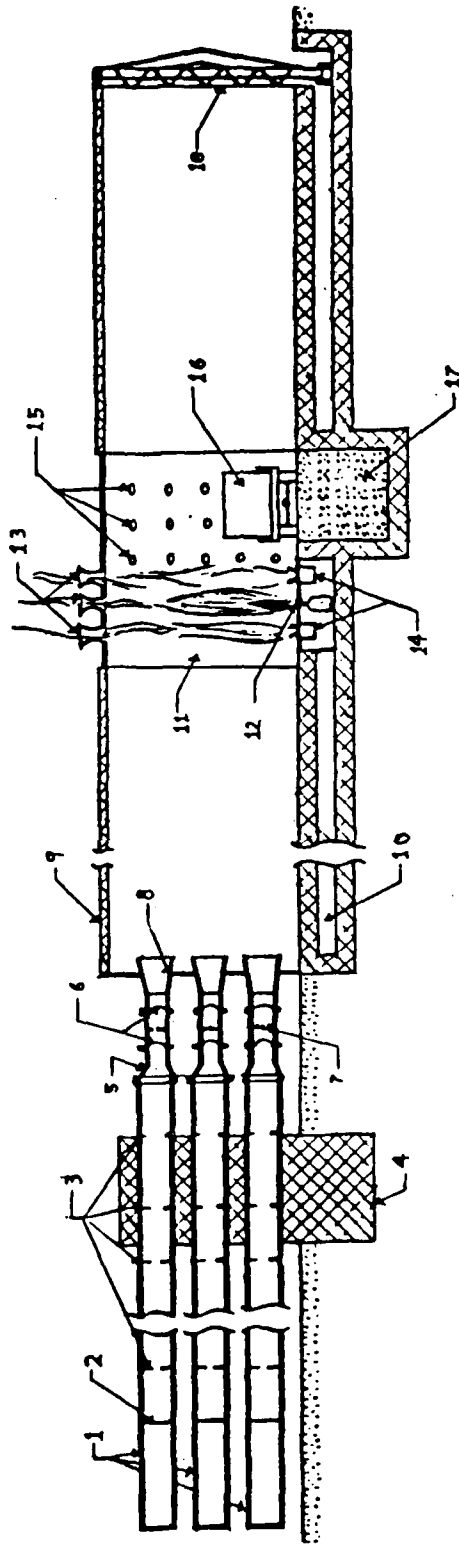
The BLAST2D code provides excellent modeling capability at low shock overpressures and good modeling capabilities at higher shock overpressures. The code simulates heated driver cases better than unheated driver cases for high shock overpressures. Future efforts will be concentrated on

including viscous effects in the simulations and better modeling and understanding of dynamic pressure at high shock overpressures.

## REFERENCES

1. G. A. Molvik, "Computation of Viscous Blast Wave Solutions with an Upwind Finite Volume Method", AIAA Paper 87-1290, Honolulu, HA, June 1987.
2. R. Pearson, K. Opalka, and D. Hisley, "Design Studies of Drivers for the US Large Blast/Thermal Simulator", Proceedings of the Ninth International Symposium on Military Applications of Blast Simulation (MABS9), Oxford, England, 23-27 September, Atomic Weapons Research Establishment, Foulness, Southend-on-Sea, Essex, England SS3 9XE.
3. E. Gion, D. Hisley and B. Bertrand, "Experimental and Theoretical Performance of Large Blast Simulator Models", Proceedings of the Ninth International Symposium on Military Applications of Blast Simulation (MABS9), Oxford, England, 23-27 September, Atomic Weapons Research Establishment, Foulness, Southend-on-Sea, Essex, England SS3 9XE.
4. K.O. Opalka and A. Mark, "The BRL-Q1D Code: A Tool for the Numerical Simulation of Flows in Shock Tubes with Variable Cross-Sectional Areas", BRL-TR-2763, US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, 21005, October 1986.
5. M. M. Rai, "An Implicit Form for the Osher Upwind Scheme", AIAA Paper 84-0088, Reno, NV, Jan. 1984.
6. S. R. Chakravarthy, "A New Class of High Accuracy TVD Schemes for Hyperbolic Conservation Laws", AIAA Paper, 85-0363, Reno, NV, Jan. 1985.
7. P. L. Roe, "Approximate Riemann Solvers, Parameter Vectors, and Difference Schemes", Journal of Computational Physics, Vol. 43, 1981, pp. 357-372.
8. Amann, in An Album of Fluid Motion, Van Dyke, ed., The Parabolic Press, Post Office Box 3032, Stanford, CA 94305, p. 171.
9. J. J. Gottlieb, "Random-Choice-Method Computations of LB/TS Design", Aerospace Engineering and Research Consultants Limited, 4925 Dufferin Street, Downsview, Ontario M3H 5T6, 29 March 1986.

CURRENT US LARGE BLAST/THERMAL SIMULATOR CONCEPT



- ☒ CONCRETE
- STEEL
- ▨ SOIL

- 1 - HEATED, STEEL DRIVER TUBES
- 2 - ADJUSTABLE END PLATES
- 3 - BAFFLES
- 4 - CONCRETE REACTION PIER
- 5 - CONVERGENT NOZZLE
- 6 - DIAPHRAGMS
- 7 - VALVES FOR VENTING
- 8 - DIVERGENT NOZZLE
- 9 - STRESS CONCRETE EXPANSION TUNNEL
- 10 - ACCESS TUNNEL
- 11 - STEEL TEST SECTION
- 12 - THERMAL RADIATION SOURCES
- 13 - TRS EJECTORS
- 14 - AIR CURTAIN PLENUM
- 15 - CAMERA AND LIGHT PORTS
- 16 - TARGET
- 17 - SOIL TANK
- 18 - ACTIVE RAREFACTION WAVE ELIMINATOR

Figure 1: Schematic of the Proposed US Large Blast/Thermal Simulator Facility 2

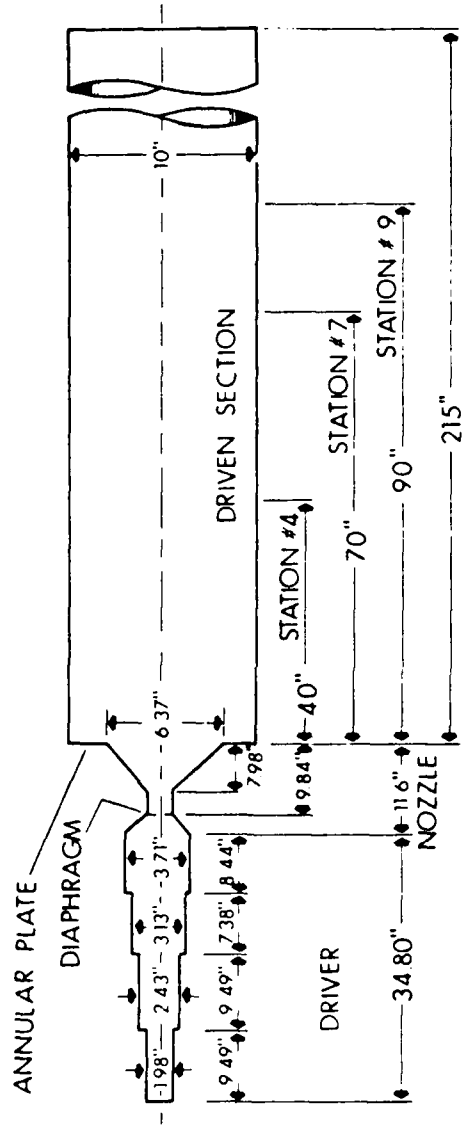


Figure 2: Single-driver 1/57 Scale Model of LBS Design Concept



Figure 3: Finite Volume Cell in Computational Space

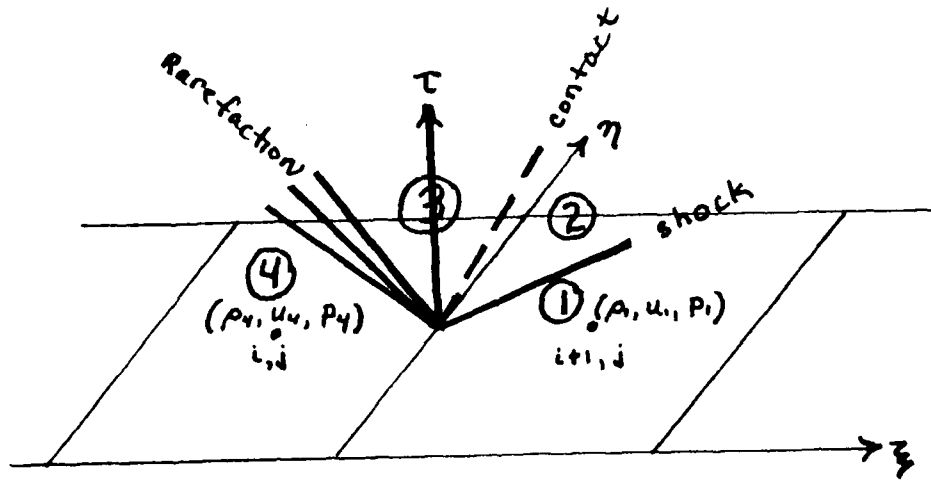


Figure 4: Riemann Problem

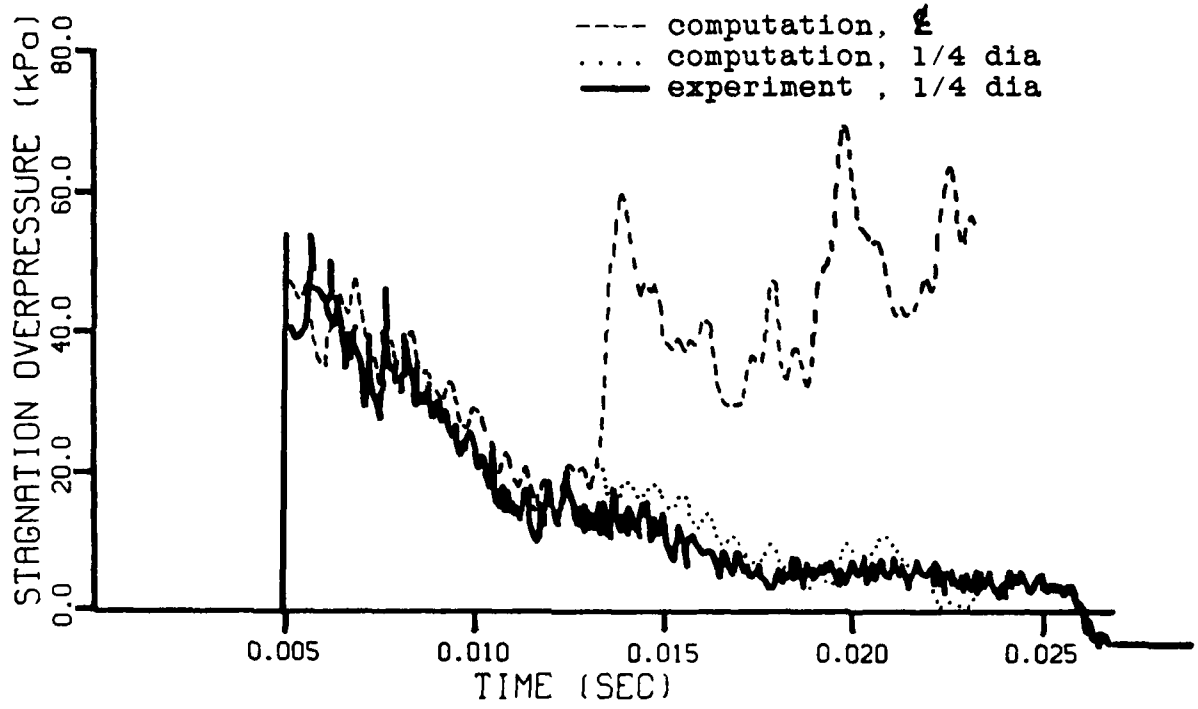
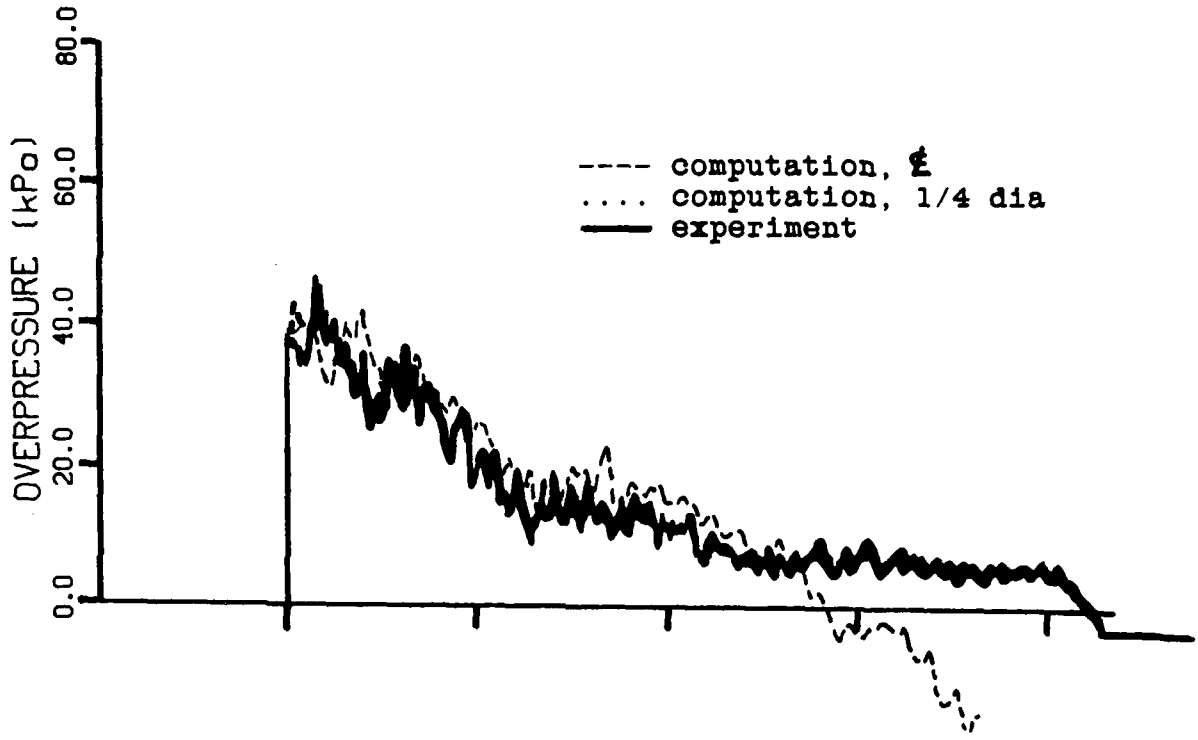
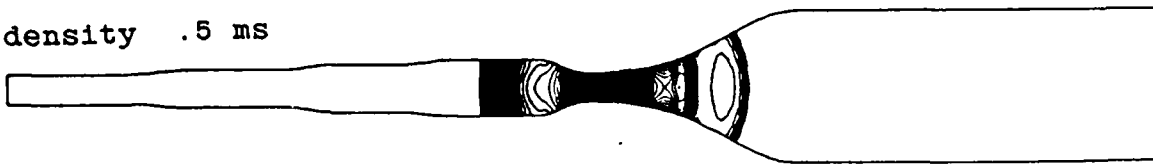


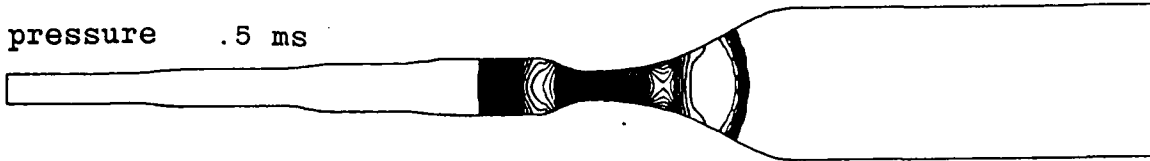
Figure 5: Pressure versus Time Plots, 35 kPa (5 psi)  
Peak Overpressure, Shot #2



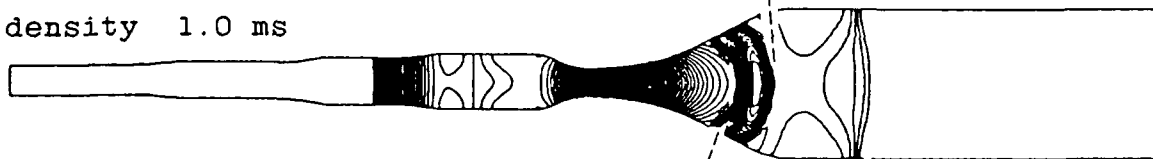
density .5 ms



pressure .5 ms



density 1.0 ms



Contact surface

Backward-facing shock

Primary shock

pressure 1.0 ms

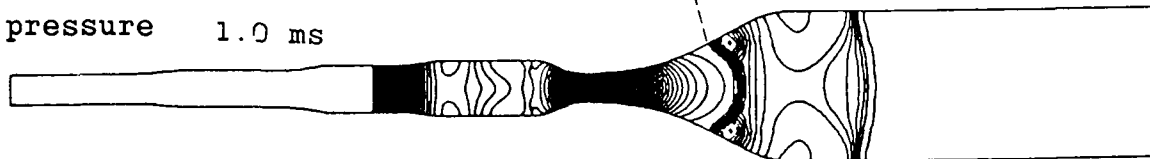


Figure 6: Contour Plots at .5 ms and 1.0 ms,  
34 kPa (5 psi) Peak Overpressure, Shot #2

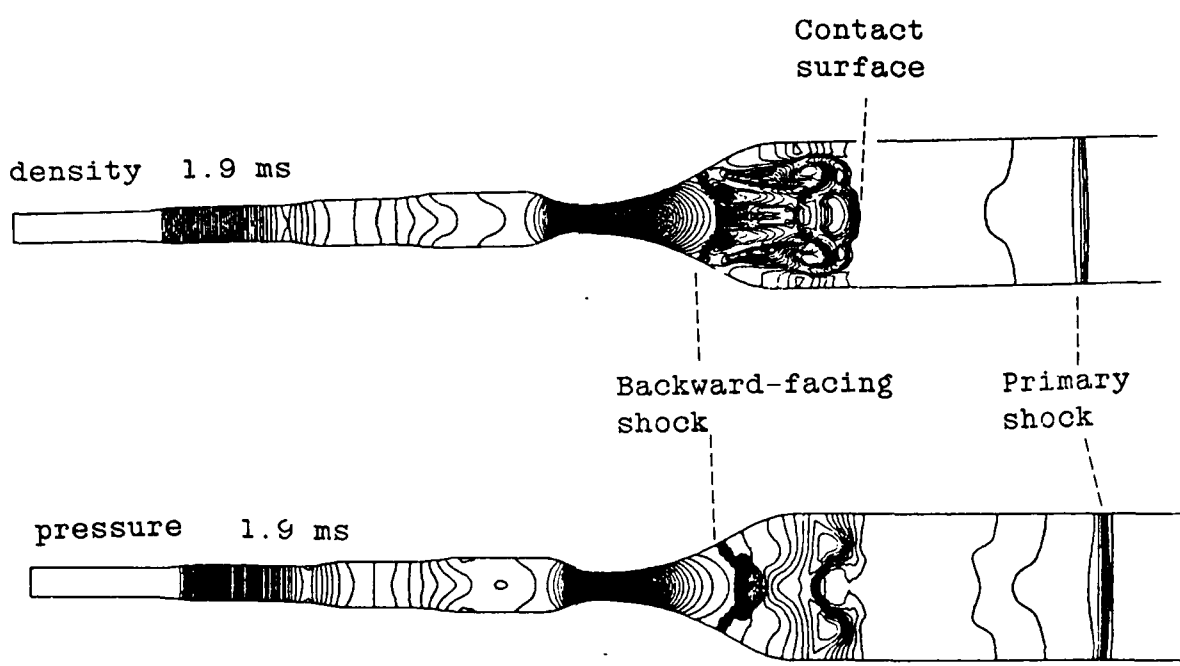
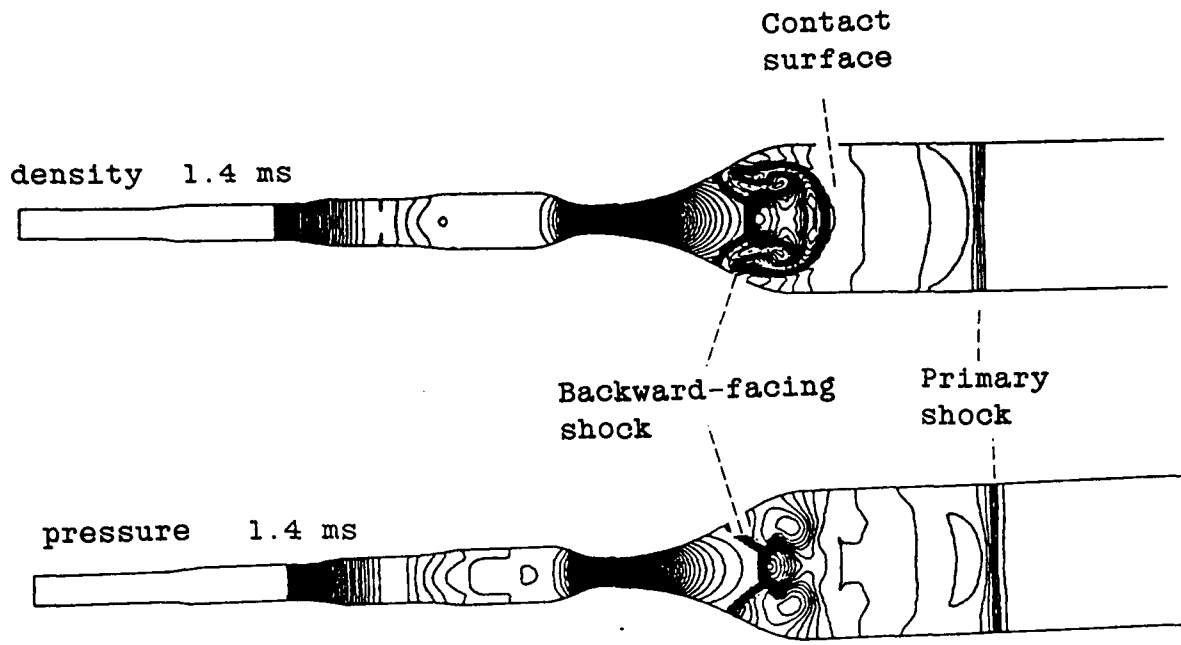
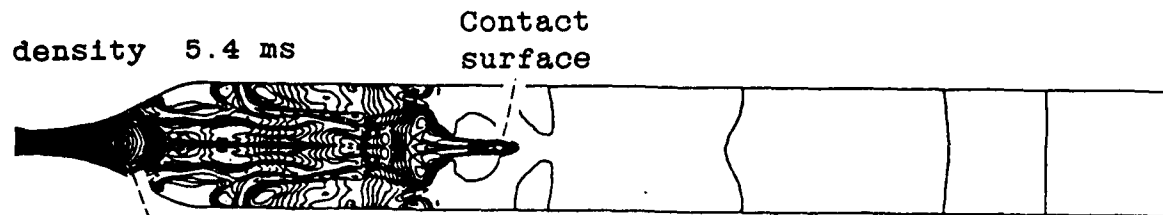
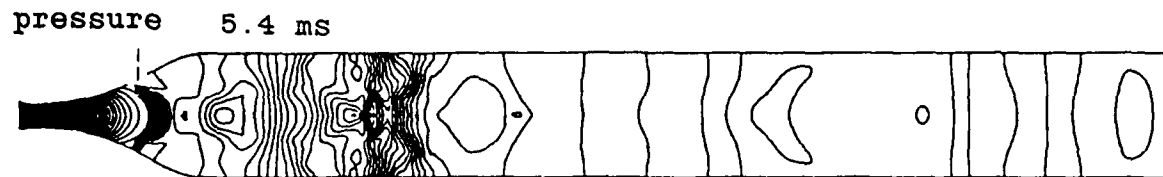


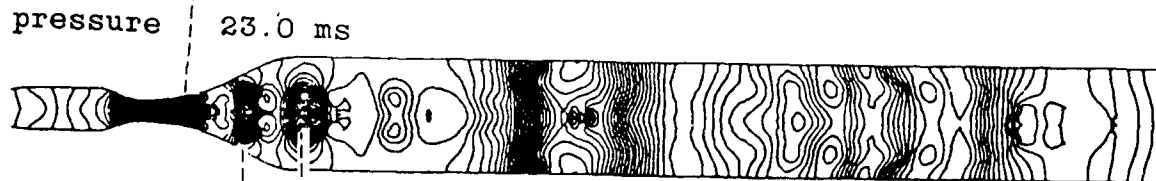
Figure 7: Contour Plots at 1.4 ms and 1.9 ms,  
34 kPa (5 psi) Peak Overpressure, Shot #2



Backward-facing shock

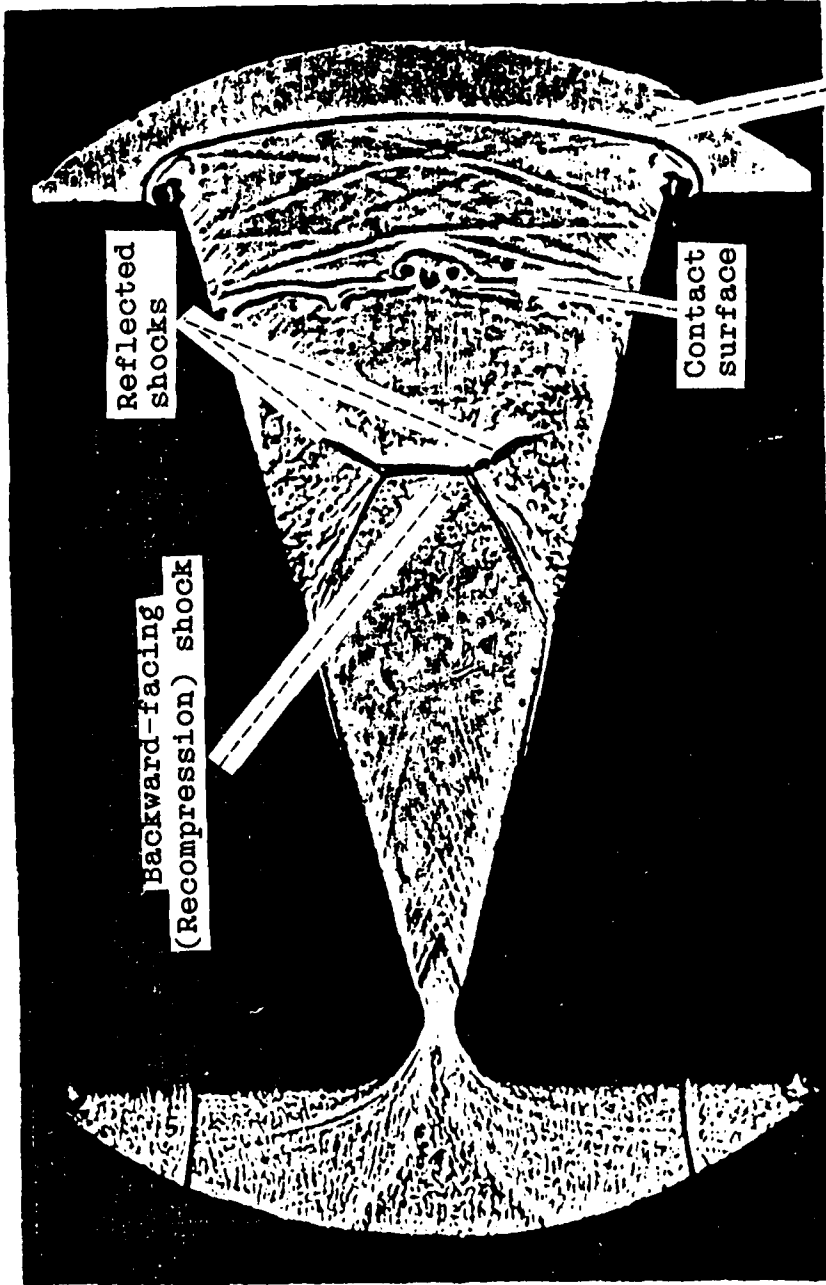


Backward-facing shock



Rotational flow

Figure 8: Contour Plots at 5.4 ms and 23.0 ms,  
34 kPa (5 psi) Peak Overpressure, Shot #2



Primary  
shock

Reflected  
shocks

Contact  
surface

Backward-facing  
(Recompression) shock

Figure 9: Development of Primary Shock, Contact, and Backward-facing Shock in Diverging Nozzle, Amann(8)

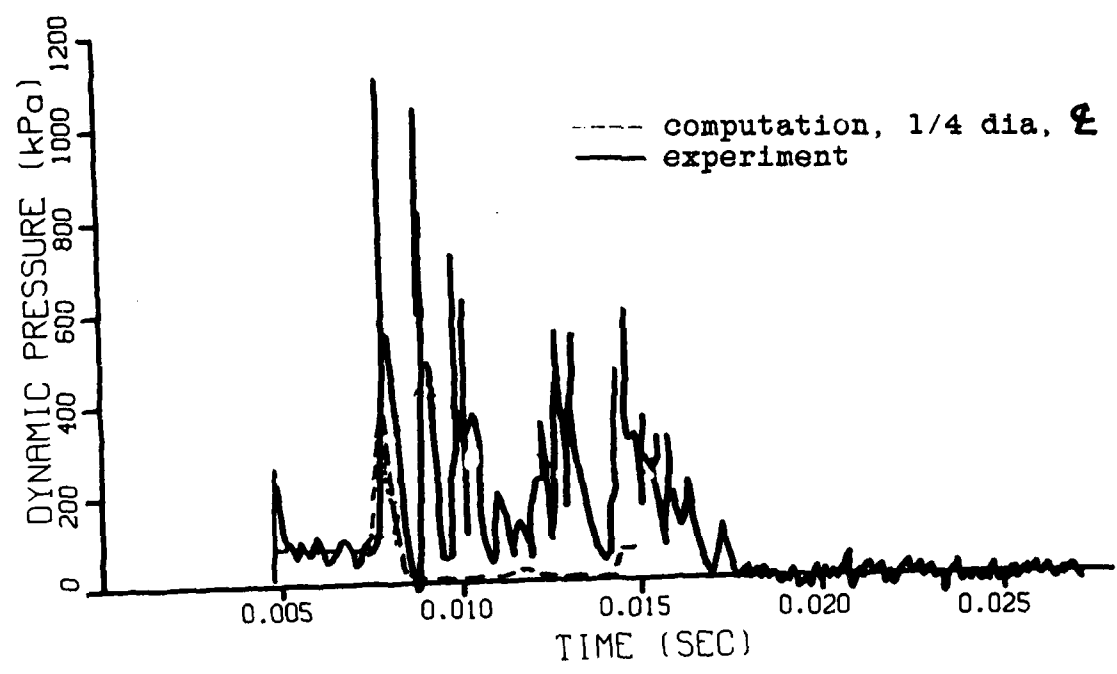
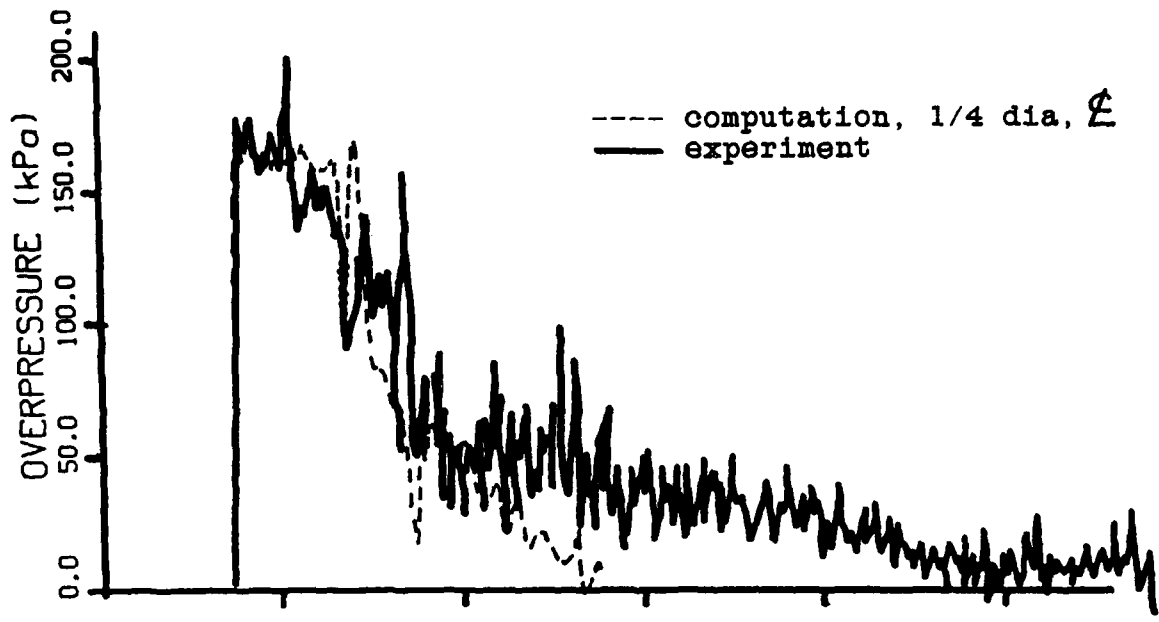


Figure 10: Pressure versus Time Plots, 175 kPa (25 psi)  
 Peak Overpressure, Unheated Driver, Shot #12

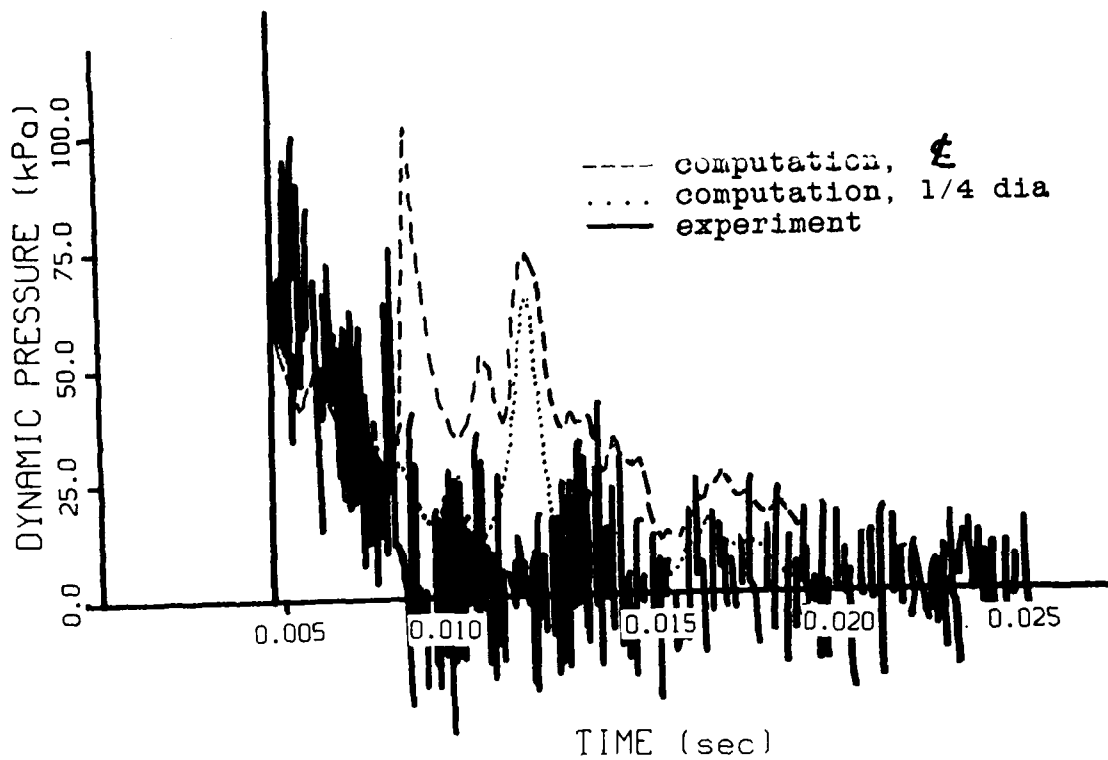
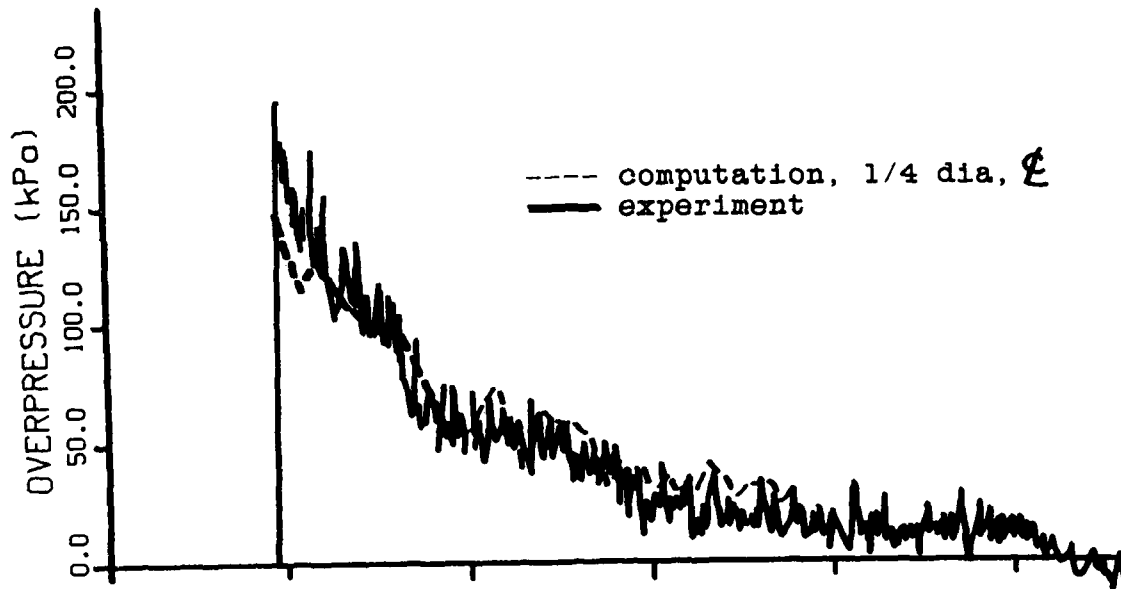


Figure 11: Pressure versus Time Plots, 175 kPa (25 psi)  
Peak Overpressure, Heated Driver, Shot #85-11

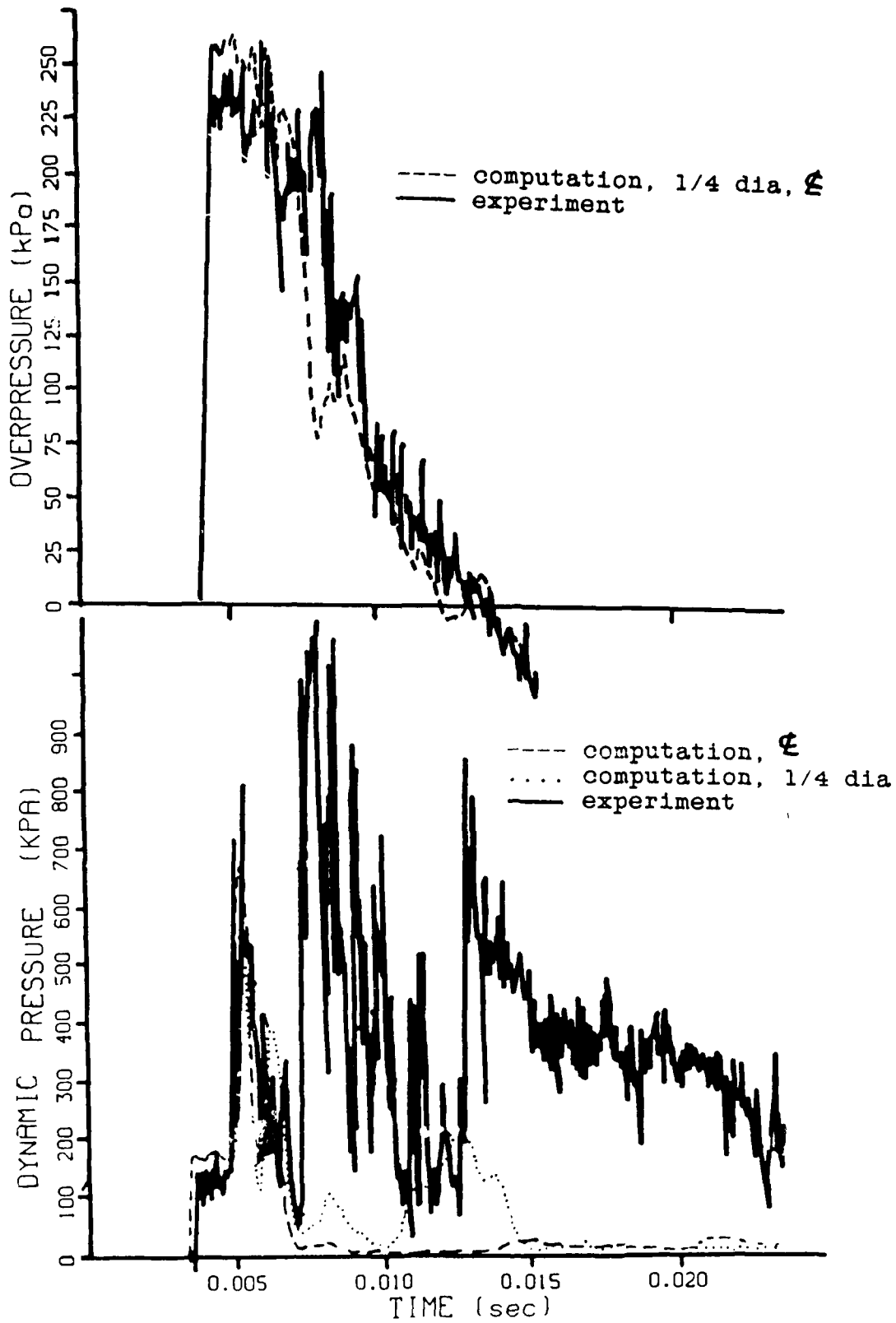


Figure 12: Pressure versus Time Plots, 245 kPa (35 psi)  
Peak Overpressure, Unheated Driver, Shot #85-21

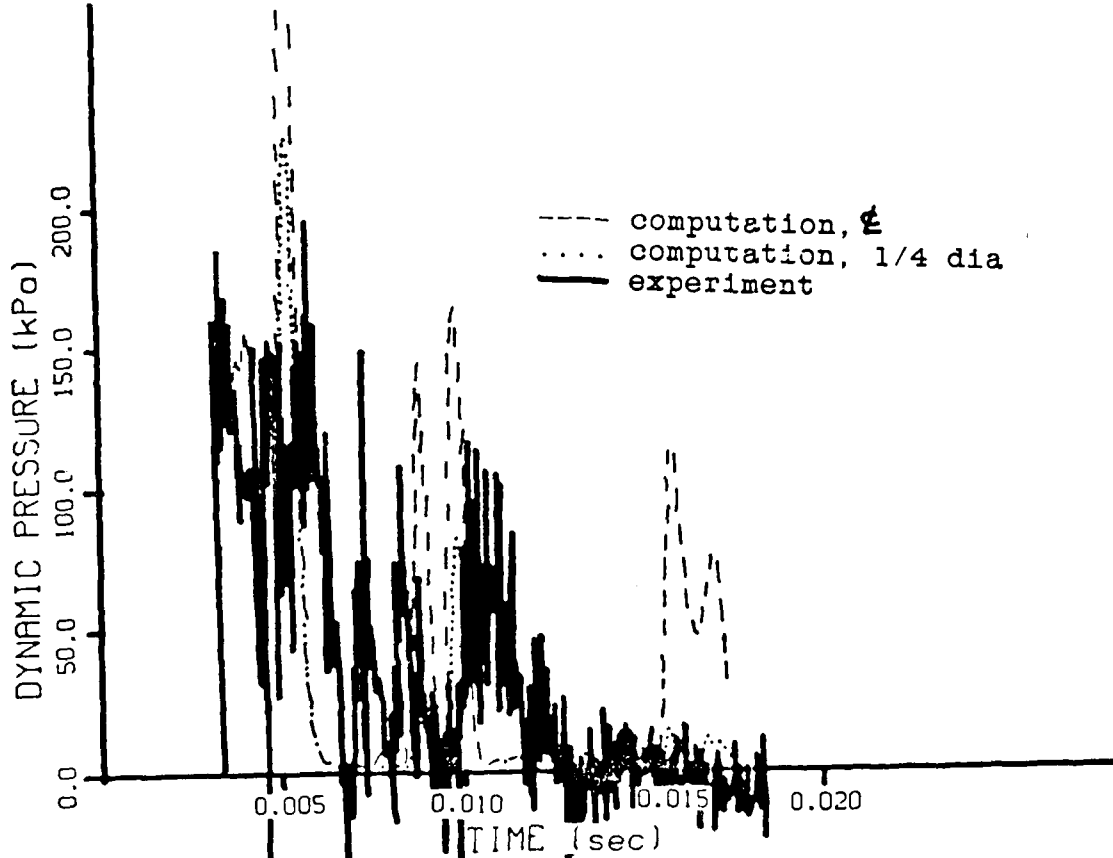
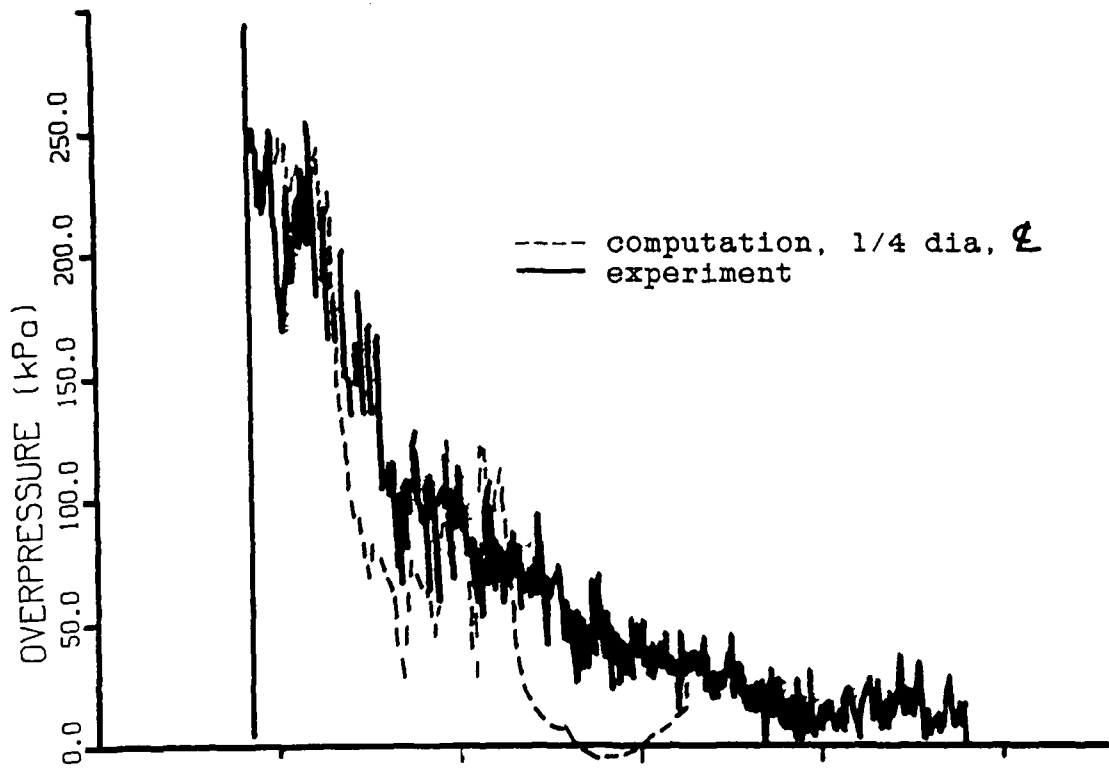


Figure 13: Pressure versus Time Plots, 245 kPa (35 psi)  
 Peak Overpressure, Heated Driver, Shot #85-23



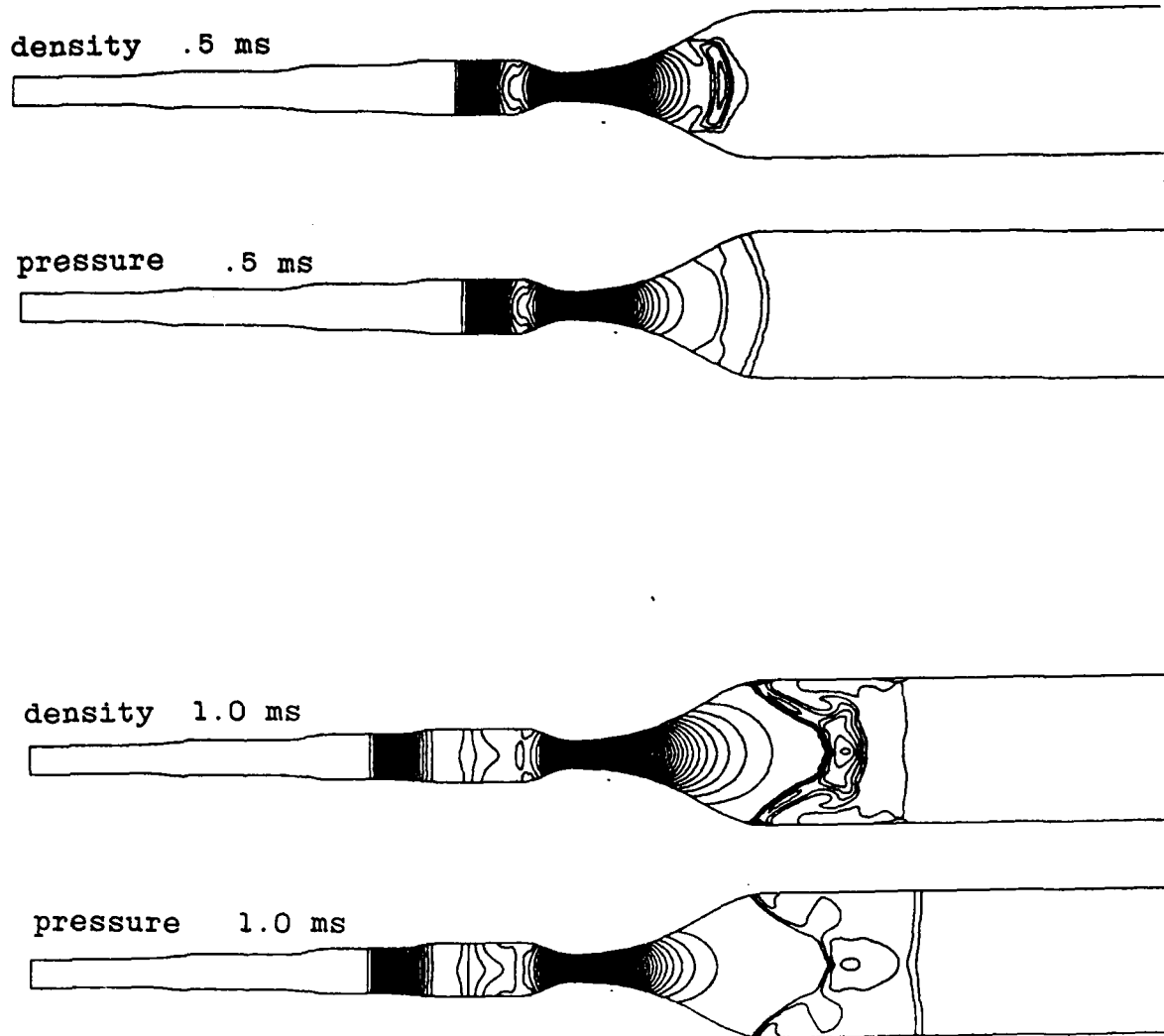
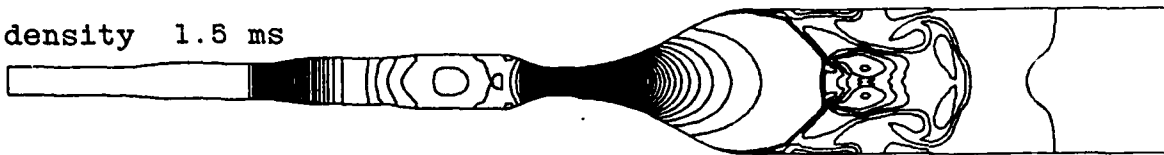
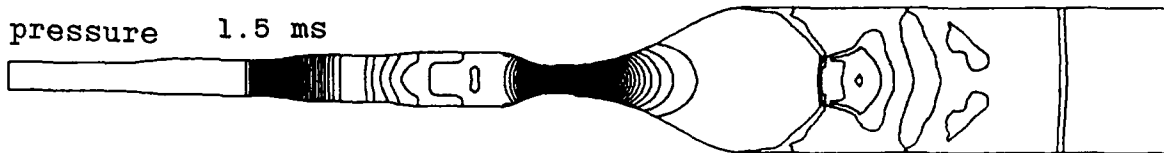


Figure 14: Contour Plots at .5 ms and 1.0 ms,  
241 kPa (35 psi) Peak Overpressure,  
Shot #85-21, Unheated Driver

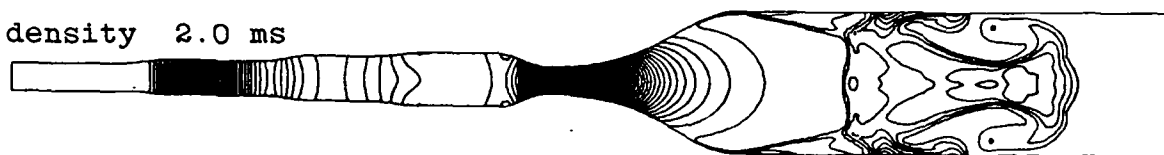
density 1.5 ms



pressure 1.5 ms



density 2.0 ms



pressure 2.0 ms

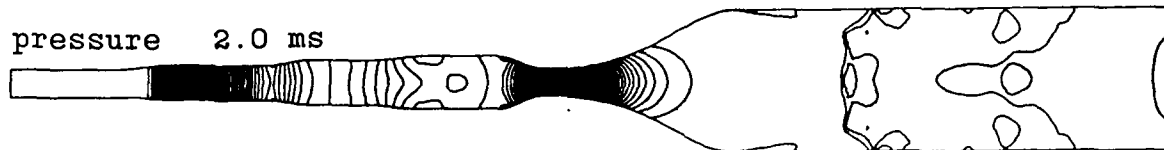
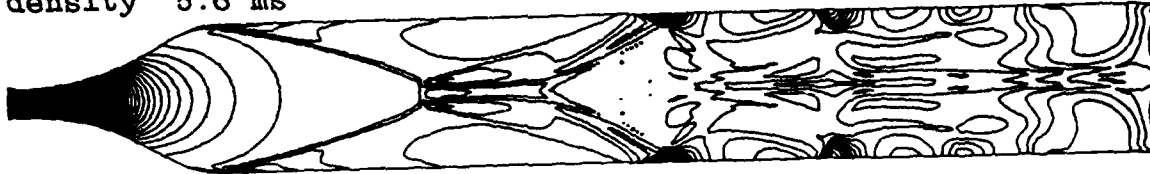


Figure 15: Contour Plots at 1.5 ms and 2.0 ms,  
241 kPa (35 psi) Peak Overpressure,  
Shot #85-21, Unheated Driver

density 5.6 ms



pressure 5.6 ms



density 23.4 ms

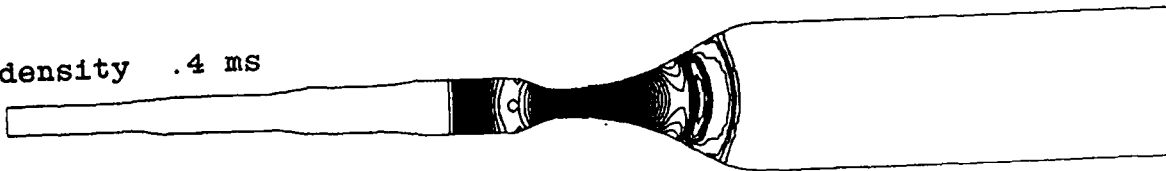


pressure 23.4 ms

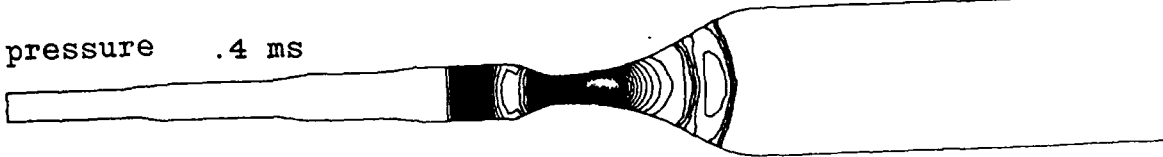


Figure 16: Contour Plots at 5.6 ms and 23.4 ms,  
241 kPa (35 psi) Peak Overpressure,  
Shot #85-21, Unheated Driver

density .4 ms



pressure .4 ms



density .7 ms



pressure .7 ms

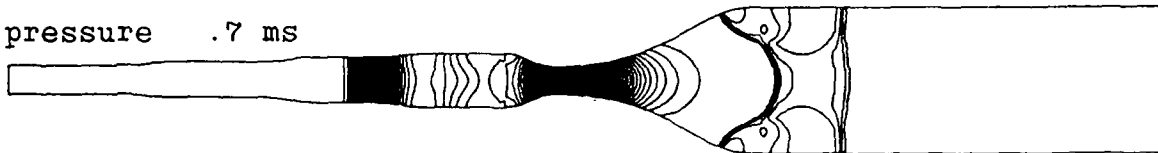


Figure 17: Contour Plots at .4 ms and .7 ms,  
241 kPa (35 psi) Peak Overpressure,  
Shot #85-23, Heated Driver

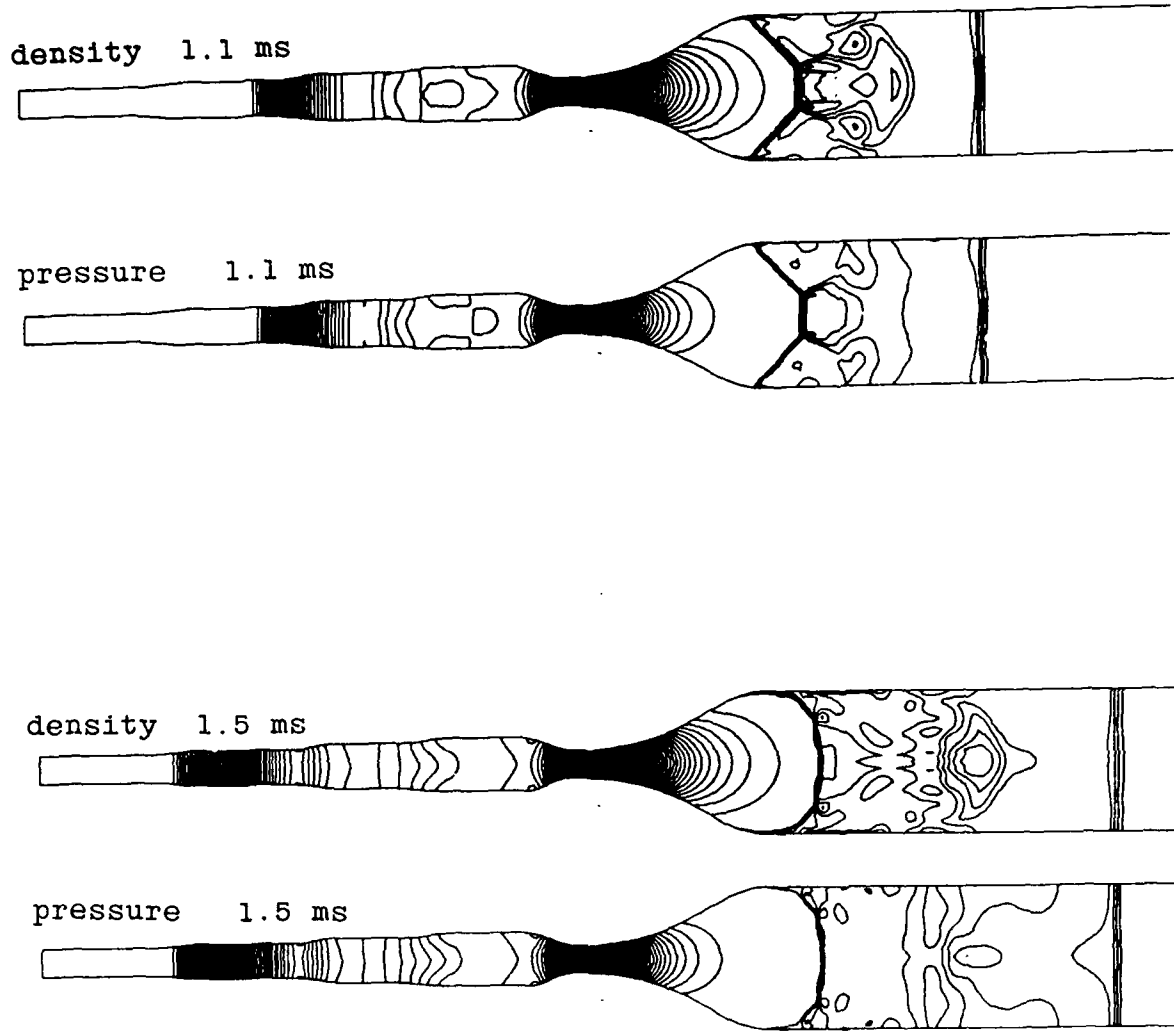
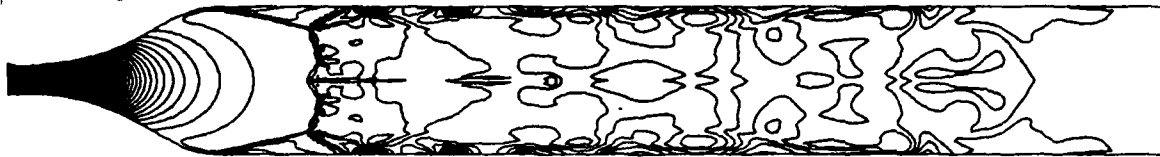
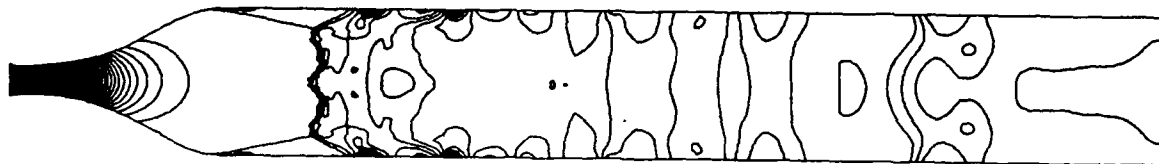


Figure 18: Contour Plots at 1.1 ms and 1.5 ms, 241 kPa (35 psi) Peak Overpressure, Shot #85-23, Heated Driver

density 4.1 ms



pressure 4.1 ms



density 17.3 ms



pressure 17.3 ms



Figure 19: Contour Plots at 4.1 ms and 17.3 ms,  
241 kPa (35 psi) Peak Overpressure,  
Shot #85-23, Heated Driver

DISTRIBUTION LIST

<u>No. of</u> <u>Copies</u>	<u>Organization</u>	<u>No. of</u> <u>Copies</u>	<u>Organization</u>
12	Administrator Defense Technical Information Center ATTN: DTIC-FDAC Cameron Station, Bldg 5 Alexandria, VA 22304-6145	9	Director Defense Nuclear Agency ATTN: DDST TIPL/Tech Lib SPSS/K. Goering SPTD/T. Kennedy SPAS/P.R. Rohr G. Ullrich STSP/COL Kovel NATD NATA Washington, DC 20305
1	Director of Defense Research & Engineering ATTN: DD/TWP Washington, DC 20301	2	Commander Field Command Defense Nuclear Agency ATTN: FCPR FCTMOF Kirtland AFB, NM 87115
1	Asst. to the Secretary of Defense (Atomic Energy) ATTN: Document Control Washington, DC 20301	1	Commander Field Command, DNA Livermore Branch ATTN: FCPRL P.O. Box 808 Livermore, CA 94550
1	Director Defense Advanced Research Projects Agency ATTN: Tech Lib 1400 Wilson Boulevard Arlington, VA 22209	1	HQDA (DAMA-ART-M) Washington, DC 20310
2	Director Federal Emergency Management Agency ATTN: D. A. Bettge Technical Library Washington, DC 20472	10	C.I.A. OIR/DB/Standard GE47 HQ Washington, D.C. 20505
1	Director Defense Intelligence Agency ATTN: DT-2/Wpns & Sys Div Washington, DC 20301	1	Program Manager US Army BMD Program Office ATTN: John Shea 5001 Eisenhower Avenue Alexandria, VA 22333
1	Director National Security Agency ATTN: E. F. Butala, R15 Ft. George G. Meade, MD 20755	2	Commander US Army BMD Advanced Technology Center ATTN: CRDABH-X CRDABH-S P.O. Box 1500 Huntsville, AL 35807
1	Director Joint Strategic Target Planning Staff JCS Offut AFB Omaha, NB 68113		

DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
1	Commander US Army BMD Command ATTN: BDMSC-TFN/N.J. Hurst P.O. Box 1500 Huntsville, AL 35807	1	U.S. Army Armament, Munitions and Chemical Command ATTN: AMSMC-IMP-L Rock Island, IL 61299-7300
1	Commander US Army Engineer Division ATTN: HNDED-FD P.O. Box 1500 Huntsville, AL 35807	1	Commander US AMCCOM ARDEC CCAC Benet Weapons Laboratory ATTN: SMCAR-CCB-TL Watervliet, NY 12189-4050
2	Deputy Chief of Staff for Operations and Plans ATTN: Technical Library Director of Chemical & Nuc Operations Department of the Army Washington, DC 20310	1	Commander U.S. Army Aviation Systems Command ATTN: AMSAV-ES 4300 Goodfellow Blvd. St. Louis, MO 63120-1798
3	Director US Army Engineer Waterways Experiment Station ATTN: Technical Library Jim Watt Jim Ingram P.O. Box 631 Vicksburg, MS 39180-0631	1	Director U.S. Army Aviation Research and Technology Activity Ames Research Center Moffett Field, CA 94035-1099
1	Commander US Army Materiel Command ATTN: AMCDRA-ST 5001 Eisenhower Avenue Alexandria, VA 22333-0001	1	Commander US Army Communications - Electronics Command ATTN: AMSEL-ED Fort Monmouth, NJ 07703-5301
1	Commander US Army Armament Research, Development and Engineering Center ATTN: SMCAR-MSI Dover, NJ 07801-5001	1	Commander US Army Communications Rsch and Development Command ATTN: DRSEL-ATDD Fort Monmouth, NJ 07703
1	Commander US Army Armament Research, Development and Engineering Center ATTN: SMCAR-TDC Dover, NJ 07801	1	Commander CECOM R&D Technical Library ATTN: AMSEL-IM-L (Reports Section) B.2700 Fort Monmouth, NJ 07703-5301
		2	Commander US Army Electronics Research and Development Command ATTN: DELEW-E, W. S. McAfee DELSD-EI, J. Roma Fort Monmouth, NJ 07703-5301



DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
6	Director US Army Harry Diamond Labs ATTN: Mr. James Gaul Mr. L. Belliveau Mr. J. Meszaros Mr. J. Gwaltney Mr. Bill Vault Mr. R. J. Bostak 2800 Powder Mill Road Adelphi, MD 20783-1197	1	Commander US Army Logistics Management Center ATTN: ATCL-O, Mr. Robert Cameron Fort Lee, VA 23801
4	Director US Army Harry Diamond Labs ATTN: SLCHD-TA-L DRXDO-TI/002 DRXDO-NP SLCHD-RBA/J. Rosado 2800 Powder Mill Road Adelphi, MD 20783-1197	2	Commander US Army Materials Technology Laboratory ATTN: AMXMR-ATL Eugene de Luca Watertown, MA 02172-0001
1	Commander US Army Missile Command ATTN: AMSMI-RD Redstone Arsenal, AL 35898-5245	1	Commander US Army Research Office ATTN: SLCRO-D P.O. Box 12211 Research Triangle Park NC 27709-2211
1	Director US Army Missile and Space Intelligence Center ATTN: AIAMS-YDL Redstone Arsenal, AL 35898-5500	4	Commander US Army Nuclear & Chemical Agency ATTN: ACTA-NAW MONA-WE Technical Library LTC Finno 7500 Backlick Rd, Bldg. 2073 Springfield, VA 22150
2	Commander US Army Natick Research and Development Center ATTN: AMDNA-D/Dr. D. Sieling STRNC-UE/J. Calligeros Natick, MA 01762	1	Commander US Army TRADOC ATTN: DCST&E Fort Monroe, VA 23651
1	Commander US Army Tank-Automotive Command ATTN: AMSTA-TSL Warren, MI 48397-5000	2	Director US Army TRADOC Systems Analysis Activity ATTN: LTC John Hesse ATOR-TSL White Sands Missile Range, NM 88002-5502
1	Commander US Army Foreign Science and Technology Center ATTN: Research and Data Br 220 7th Street, NE Charlottesville, VA 22901	2	Commandant U.S. Army Infantry School ATTN: ATSH-CD-CS-OR Fort Benning, GA 31905-5400

DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
1	Commander U.S. Army Development and Employment Agency ATTN: MODE-ORO Fort Lewis, WA 98433-5000	1	Commander Naval Sea Systems Command ATTN: Code SEA-62R Department of the Navy Washington, DC 20362-5101
1	Commandant Interservice Nuclear Weapons School ATTN: Technical Library Kirtland AFB, NM 87115	3	Officer-in-Charge(Code L31) Civil Engineering Laboratory Naval Construction Battalion Center ATTN: Stan Takahashi R. J. Odello Technical Library Port Hueneme, CA 93041
1	Chief of Naval Material ATTN: MAT 0323 Department of the Navy Arlington, VA 22217	1	Commander David W. Taylor Naval Ship Research & Development Command ATTN: Lib Div, Code 522 Bethesda, MD 20084-5000
2	Chief of Naval Operations ATTN: OP-03EG OP-985F Department of the Navy Washington, DC 20350	1	Commander Naval Surface Weapons Center ATTN: DX-21, Library Br. Dahlgren, VA 22448-5000
1	Chief of Naval Research ATTN: N. Perrone Department of the Navy Arlington, VA 22217	2	Commander Naval Surface Weapons Center ATTN: Code WA501/Navy Nuclear Programs Office Code WX21/Tech Library Silver Spring, MD 20902-5000
1	Director Strategic Systems Projects Ofc ATTN: NSP-43, Tech Library Department of the Navy Washington, DC 20360	1	Commander Naval Weapons Center ATTN: Code 533, Tech Lib China Lake, CA 93555-6001
1	Commander Naval Electronic Systems Com ATTN: PME 117-21A Washington, DC 20360	1	Commander Naval Weapons Evaluation Fac ATTN: Document Control Kirtland AFB, NM 87117
1	Commander Naval Facilities Engineering Command Washington, DC 20360	1	Commander Naval Research Laboratory ATTN: Code 2027, Tech Lib Washington, DC 20375

DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
1	Superintendent Naval Postgraduate School ATTN: Code 2124, Technical Reports Library Monterey, CA 93940	1	Director Lawrence Livermore Lab. ATTN: Tech Info Dept L-3 P.O. Box 808 Livermore, CA 94550
1	AFSC/SDOA Andrews Air Force Base MD 20334	2	Director Los Alamos Scientific Lab. ATTN: Doc Control for Rpts Lib P.O. Box 1663 Los Alamos, NM 87545
1	AFWL/SUL Kirtland AFB, NM 87117	2	Director Sandia National Laboratories ATTN: Doc Control for 3141 Sandia Rpt Collection L. J. Vortman P.O. Box 5800 Albuquerque, NM 87185-5800
1	AFATL/DOIL (Tech Info Center) Eglin AFB, FL 32542-5438	1	Director Sandia Laboratories Livermore Laboratory ATTN: Doc Control for Technical Library P.O. Box 969 Livermore, CA 94550
1	AFESC/RDCS ATTN: Paul Rosengren Tyndall AFB, FL 32403	1	Director National Aeronautics and Space Administration Scientific & Tech Info Fac P.O. Box 8757 Baltimore/Washington International Airport MD 21240
1	AFATL (DLYV) Eglin AFB, FL 32542-5438	1	Director NASA-Ames Research Center Applied Computational Aerodynamics Branch MS 202-14, Dr. T. Holtz Moffett Field, CA 94035
1	RADC (EMTLD/Docu Library) Griffiss AFB, NY 13441		
1	AFWL/NTES, R. Henny Kirtland AFB, NM 87117-6008		
1	AFWL/NTED, J. W. Aubrey Kirtland AFB, NM 87117-6008		
2	Commander-in-Chief Strategic Air Command ATTN: NRI-STINFO Lib Offutt AFB, NB 68113		
1	AFIT (Lib Bldg. 640, Area B) Wright-Patterson AFB Ohio 45433		
1	FTD/NIIS Wright-Patterson AFB Ohio 45433		

DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
3	Aberdeen Research Center ATTN: N.H. Ethridge J. Keefer Library P.O. Box 548 30 Diamond Street Aberdeen, MD 21001	1	Goodyear Aerospace Corp ATTN: R. M. Brown, Bldg 1 Shelter Engineering Litchfield Park, AZ 85340
1	Aerospace Corporation ATTN: Tech Info Services P.O. Box 92957 Los Angeles, CA 90009	6	Kaman Avidyne ATTN: Dr. R. Reutenick (4 cys) Mr. S. Criscione Mr. R. Milligan 83 Second Avenue Northwest Industrial Park Burlington, MA 01830
1	Agbabian Associates ATTN: M. Agbabian 250 North Nash Street El Segundo, CA 90245	3	Kaman Sciences Corporation ATTN: Library P. A. Ellis F. H. Shelton 1500 Garden of the Gods Road Colorado Springs, CO 80907
1	The BDM Corporation ATTN: Richard Hensley P.O. Box 9274 Albuquerque International Albuquerque, NM 87119	2	Kaman-TEMPO ATTN: DASIAC Don Sachs P.O. Drawer QQ 816 State Street Santa Barbara, CA 93102
1	The Boeing Company ATTN: Aerospace Library P.O. Box 3707 Seattle, WA 98124	1	Lockheed Missiles & Space Co. ATTN: J. J. Murphy, Dept. 81-11, Bldg. 154 P.O. Box 504 Sunnyvale, CA 94086
1	California Research and Technology ATTN: F. Sauer Suite B 130 11875 Dublin Blvd Dublin, CA 94568	1	Martin Marietta Aerospace Orlando Division ATTN: G. Fotieo P.O. Box 5837 Orlando, FL 32805
1	California Research & Technology, Inc. ATTN: M. Rosenblatt 20943 Devonshire Street Chatsworth, CA 91311	2	McDonnell Douglas Astronautics Corporation ATTN: Robert W. Halprin K.A. Heinly 5301 Bolsa Avenue Huntington Beach, CA 92647
1	Carpenter Research Corporation ATTN: H. Jerry Carpenter Suite 424 904 Silver Spur Road Rolling Hills Estates, CA 90274		

DISTRIBUTION LIST

<u>No. of Copies</u>	<u>Organization</u>	<u>No. of Copies</u>	<u>Organization</u>
1	New Mexico Engineering Research Institute (CERF) ATTN: J. Leigh P.O. Box 25 UNM Albuquerque, NM 87131	1	Texas Engineering Experiment Station ATTN: Dr. D. Anderson 301 Engineering Research Center College Station, TX 77843
2	Physics International Corp 2700 Merced Street San Leandro, CA 94577	2	TRW Systems Group ATTN: Benjamin Sussholtz Stanton Fink One Space Park Redondo Beach, CA 90278
2	R&D Associates ATTN: Technical Library Allan Kuhl P.O. Box 9695 Marina del Rey, CA 90291	1	Battelle Memorial Institute ATTN: Technical Library 505 King Avenue Columbus, OH 43201
1	R&D Associates ATTN: G.P. Ganong P.O. Box 9335 Albuquerque, NM 87119	1	California Inst of Tech ATTN: T. J. Ahrens 1201 E. California Blvd. Pasadena, CA 91109
2	Science Applications, Inc. ATTN: W. Layson John Cockayne PO BOX 1303 1710 Goodridge Drive McLean, VA 22102	2	Denver Research Institute University of Denver ATTN: Mr. J. Wisotski Technical Library PO Box 10127 Denver, CO 80210
1	Science Applications, Inc. ATTN: Technical Library 1250 Prospect Plaza La Jolla, CA 92037	1	TRW Ballistic Missile Division ATTN: H. Korman, Mail Station 526/614 P.O. Box 1310 San Bernadino, CA 92402
2	Systems, Science and Software ATTN: C. E. Needham Lynn Kennedy PO Box 8243 Albuquerque, NM 87198	1	Massachusetts Institute of Technology Aeroelastic and Structures Research Laboratory ATTN: Dr. E. A. Witmer Cambridge, MA 02139
3	Systems, Science and Software ATTN: Technical Library R. Duff K. Pyatt PO Box 1620 La Jolla, CA 92037	2	Southwest Research Institute ATTN: Dr. W. E. Baker A. B. Wenzel 8500 Culebra Road San Antonio, TX 78228

DISTRIBUTION LIST

No. of  
Copies

Organization

- 1 SRI International  
ATTN: Dr. G. R.  
Abrahamson  
333 Ravenswood Avenue  
Menlo Park, CA 94025
- 1 Stanford University  
ATTN: Dr. D. Bershader  
Durand Laboratory  
Stanford, CA 94305

Aberdeen Proving Ground

Dir, USAMSAA  
ATTN: AMXSY-D  
AMXSY-MP, H. Cohen

Cdr, USATECOM  
ATTN: AMSTE-SI-F

Cdr, CRDC, AMCCOM  
ATTN: SMCCR-RSP-A  
SMCCR-MU  
SMCCR-SPS-IL

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. BRL Report Number \_\_\_\_\_ Date of Report \_\_\_\_\_

2. Date Report Received \_\_\_\_\_

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

4. How specifically, is the report being used? (Information source, design data, procedure, source of ideas, etc.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided or efficiencies achieved, etc? If so, please elaborate. \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

CURRENT ADDRESS      \_\_\_\_\_  
Name  
\_\_\_\_\_ Organization  
\_\_\_\_\_ Address  
\_\_\_\_\_ City, State, Zip

7. If indicating a Change of Address or Address Correction, please provide the New or Correct Address in Block 6 above and the Old or Incorrect address below.

OLD ADDRESS      \_\_\_\_\_  
Name  
\_\_\_\_\_ Organization  
\_\_\_\_\_ Address  
\_\_\_\_\_ City, State, Zip

(Remove this sheet, fold as indicated, staple or tape closed, and mail.)

FOLD HERE

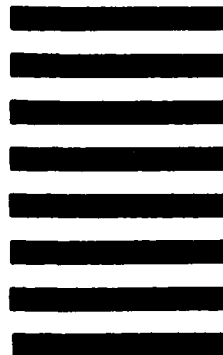
Director  
U.S. Army Ballistic Research Laboratory  
ATTN: SLCBR-DD-T  
Aberdeen Proving Ground, MD 21005-5066



NO POSTAGE  
NECESSARY  
IF MAILED  
IN THE  
UNITED STATES

OFFICIAL BUSINESS  
PENALTY FOR PRIVATE USE, \$300

**BUSINESS REPLY MAIL**  
FIRST CLASS PERMIT NO 12062 WASHINGTON, DC  
POSTAGE WILL BE PAID BY DEPARTMENT OF THE ARMY



Director  
U.S. Army Ballistic Research Laboratory  
ATTN: SLCBR-DD-T  
Aberdeen Proving Ground, MD 21005-9989

FOLD HERE