Best Available Copy

AD-A279 277

ARMY RESEARCH LABORATORY

ARL

Electrothermal-Chemical Modeling Workshop, 12–13 May 1993— Volume I

Gloria P. Wren
William F. Oberle
CONTRIBUTING EDITORS

ARL-SR-10

May 1994

[illegible]

NOTICES

Destroy this report when it is no longer needed. DO NOT return it to the originator.

Additional copies of this report may be obtained from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The use of trade names or manufacturers' names in this report does not constitute indorsement of any commercial product.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
May 1994

3. REPORT TYPE AND DATES COVERED
Final, 12–13 May 1993

4. TITLE AND SUBTITLE
Electrothermal-Chemical Modeling Workshop, 12–13 May 1993—Volume I

5. FUNDING NUMBERS
PR: 1L162618AH80

6. AUTHOR(S)
Gloria P. Wren and William F. Oberle - Contributing Editors

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-WT-PA
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-OP-AP-L
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARL-SR-10

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

This compilation contains presentations presented at the Electrothermal-Chemical (ETC) Modeling Workshop held at the U.S. Army Research Laboratory, APG, MD in May 1993. Also included is a summary of ongoing modeling efforts and experimental data which could enhance ETC model development.

14. SUBJECT TERMS
electrothermal-chemical, workshops, interior ballistics, liquid gun propellants

15. NUMBER OF PAGES
293

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

INTENTIONALLY LEFT BLANK.

TABLE OF CONTENTS

Page

Page

INTRODUCTION

An Electrothermal-Chemical (ETC) Gun Modeling Workshop was held at the Weapons Technology Directorate (WTD), U.S. Army Research Laboratory (ARL)(formerly the Ballistic Research Laboratory (BRL)) on 12–13 May 1993. The workshop was specifically focused on technical aspects of ETC gun modeling and was sponsored by the WTD/ARL. Thus, the meeting was not as broad in scope as an earlier meeting held at BRL under the sponsorship of the JANNAF Combustion Subcommittee on 9–11 July 1991.

The objectives of the workshop were to: (a) assess the current state of ETC modeling; (b) determine the class of problems currently being addressed by various organizations; (c) encourage exchange of ideas and modeling techniques among participants; and (d) provide recommendations for future work, particularly in view of declining research funds.

The following compilation contains: (1) the meeting agenda; (2) a list of current known U.S. ETC modeling activities; (3) diagnostics measurements desired by ETC modelers as summarized by the group; (4) presentations by organizations attending the workshop; and (5) a list of participants. The workshop benefitted greatly from the participation of university, industry, and government (Army, DNA, Navy) personnel and contractors who all worked toward the common goal of understanding ETC processes through modeling.

We would like to thank Ms. Sharon Richardson for her excellent administering of the workshop; each participant for their active roles during the workshop; each author and funding agency for allowing work to be reprinted in this compilation (note that there are unclassified/unlimited and unclassified/government & contractors only sections)—and Army, DNA and Navy personnel in many different agencies for their cooperation and support in this endeavor. The modeling community has made significant advances in understanding ETC gun interior ballistics over the past several years and continues to impact gun cartridge design. It is hoped that this compilation will convey the development of state-of-the-art models for ETC guns.

Gloria Wren
Bill Oberle
Weapons Technology Directorate
Army Research Laboratory

Electrothermal-Chemical (ETC) Gun Modeling Workshop AGENDA
Weapons Technology Directorate, U.S. Army Research Laboratory

Wednesday, May 12, 1993

8:15	Administrative Remarks Sharon Richardson
8:30	Science Applications International Corporation, San Diego, CA C.-C. Hsiao, Fred Su
9:30	General Dynamics Land System/GT-Devices Niels Winsor
10:30	Break
10:45	Science Applications International Corporation, Ft. Washington, PA Sandy Dash
11:45	Lunch
1:00	Sandia National Laboratories, Albuquerque, NM Steve Kempka
2:00	FMC Corporation, Minneapolis, MN Patrick Janke
3:00	Break
3:15	U.S. Army Armament Research, Development, and Engineering Center Lee Harris
4:15	Pennsylvania State University F. Cheung
5:00	Adjourn
7:00	No-host dinner at Tidewater Grille, Havre de Grace

Thursday, May 13

8:30	U.S. Army Research Laboratory Gloria Wren
9:00	Olin Corporation Hugh McElroy
10:00	California Research and Technology Phil Hookham
11:00	Group discussion and wrap-up
12:00	Adjourn

Current ETC Modeling Activities in the U.S. (May 1993)

Organization	Program Funding	Current Activities
1. ARDEC	Army	1. 0D*
2. ARL	Army	2. 1D Plasma, 0D, End - to - end (Power Plasma, IB)
3. Eli Freedman & Associate	Army	3. Thermochemistry (BLAKE - ETC)
4. FMC	IR & D, Services	4. 0D*,1D,2D (Finite Difference),End-to-end,Inverse Ballistic Model
5. GDLS	IR & D , Services	5. 0D*, 1D*, 2D (Finite Element)
6. LLNL	DNA	6. 2D/3D, AMR code
7. NC State University	Army, IR & D	7. 1D Plasma
8. Olin Corporation	IR & D	8. 0D*, 1D*, 1 1/2 D*
9. Paul Gough Associates	Army	9. 0D, 1D
10. Penn State University	IR & D, Army	10. 2D (2 phase, multiple sites, detailed droplet shedding)
11. SAIC, Atlanta	Army, DNA	11. 1D Plasma, 0D*, End - to - end
12. SAIC, Ft. Washington	Army	12. 2D /3D (Upwind/Implicit)
13. SAIC, San Diego	DNA	13. 0D*, 2D (FCT), 3D potential
14. S-Cubed, Maxwell Labs	DNA	14. 0D/1D
15. Sandia National Labs	Army, DoD/DOE MOU	15. 2D Plasma
16. CRT	DNA	16. 2D (TVD-Adaptive Grid), 3D potential

Note: * ARL model extension

Diagnostic Measurements Desired by ETC Modelers

Measurement	Status	Organization Addressing
*1. Degree of burning rate augmentation of SP by plasma or intense radiation source in local contact with plasma	1. Now doing; With solid propellant and with proposed alternate ETC propellants	1. ARL, Penn State, NC State
*2. SP burning rate law with plasma compared to conventional for bulk propellant	2. Some data is available	2. ARL, FMC
*3. Effects of plasmas on burning rate of liquids, gels & solids	3. Need data, will soon be doing	3. ARL, ARDEC
*4. Burning rate and/or mass generation effects in two - component systems for slurries (mixtures of liquid and solid propellant)	4. Need data; efforts starting at ARL & ongoing at Penn State	4. ARL, Penn State, FMC
5. Location of reaction front in bulk homogeneous energetic liquid vs. two phase	5. Important; no ongoing efforts directly addressing issue, but feasibility is an issue	5. N/A
6. Effects of changes in plasma mass on mixing (Thermal energy vs. momentum)	6. SNLA experiments have not yet shown a significant influence	6. SNLA
7. Analysis of closed bomb experimental data via fluid dynamic models	7. Can be done (GTD)	7. ARL will share closed bomb data with GTD

Diagnostic Measurements Desired by ETC Modelers

Measurement	Status	Organization Addressing
8. Rates of droplet formation in liquid propellant ETC designs	8. Penn State can perform diagnostics	8. None
9. Plasma pressure, exit velocity, ablation rates, species composition, temperature	9. Pressure, temperature and ablation rates have been measured in some low power diagnostic fixtures. Other measurements extremely difficult.	9. SNLA, ARL, NC State
10. "Benchmarch experiments" for community model validation	10. Needed, but time consuming. Experimentalists could all supply carefully obtained data sets for model validations.	10. Groundrules need to be worked out for study

INTENTIONALLY LEFT BLANK.

ARL WORKSHOP ON ETC MODELING

RESULTS, METHODS AND PLANS FOR 0, 1 AND 2-DIMENSIONAL ETC MODELING AT GT-DEVICES

Niels Winsor, Bob Greig
Jon Earnhart and Dave Hurlburt

12-13 MAY 1993

Work performed under: DAAA15-90-C-1061, DAAA15-92-C-0017 and GDLS IR&D.

MANY THANKS!

The assistance of many Government, Olin and other personnel is gratefully acknowledged. In particular, Ron Anderson, Joe Buzzett, Paul Gough, Arpad Juhasz, George Keller, Ed Lilliott, Hugh McElroy, Dennis Worthington and Gloria Wren contributed either directly or by helping with codes or documentation.

ETC MODELING WORK

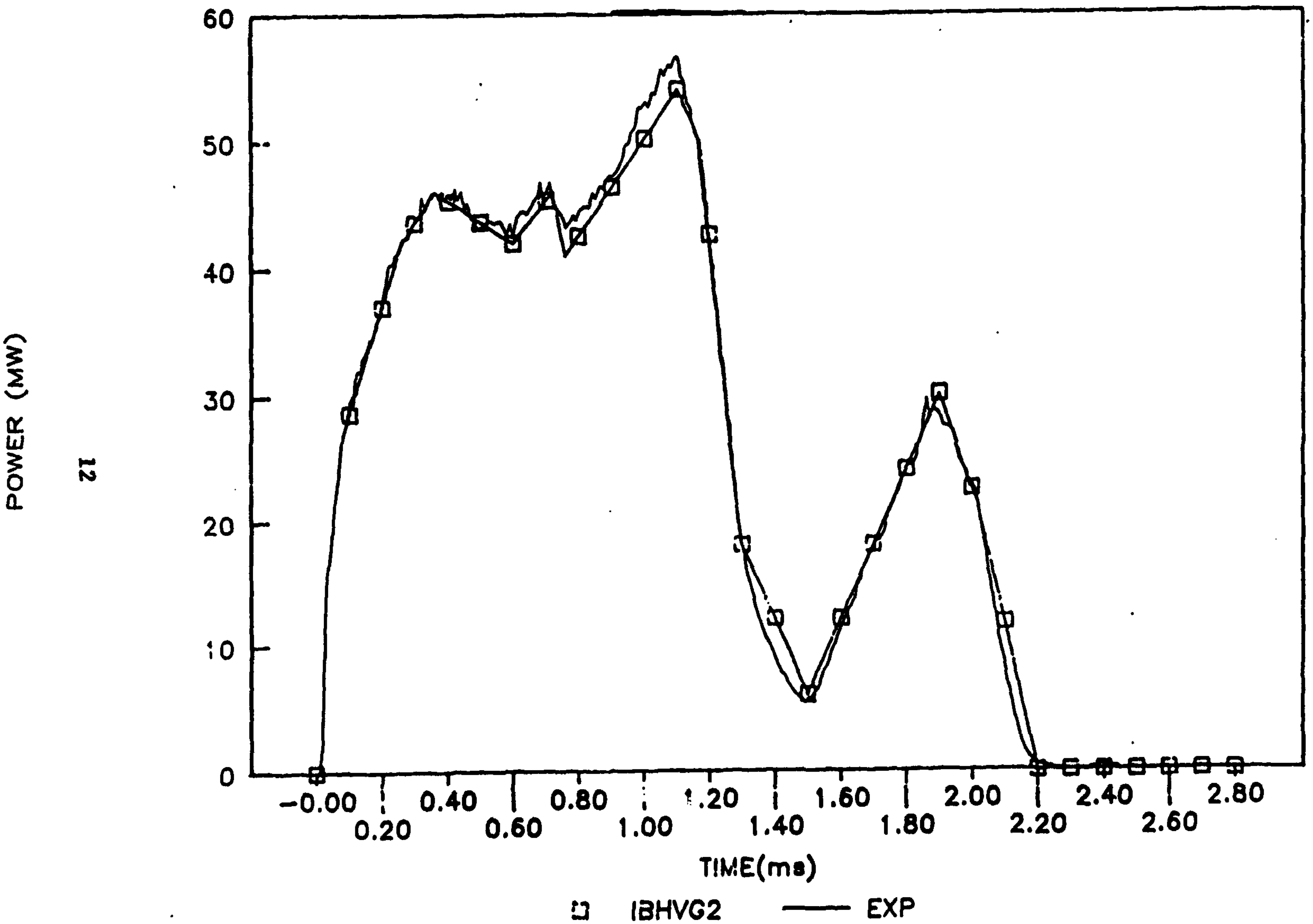
- IBHVG2 ENHANCEMENTS & DOC
- XNOVAKTC COMPUTATIONS
- FETC EXPERIMENTS
- FUTURE SIMULATION PLANS

IBHVG2 UPDATES

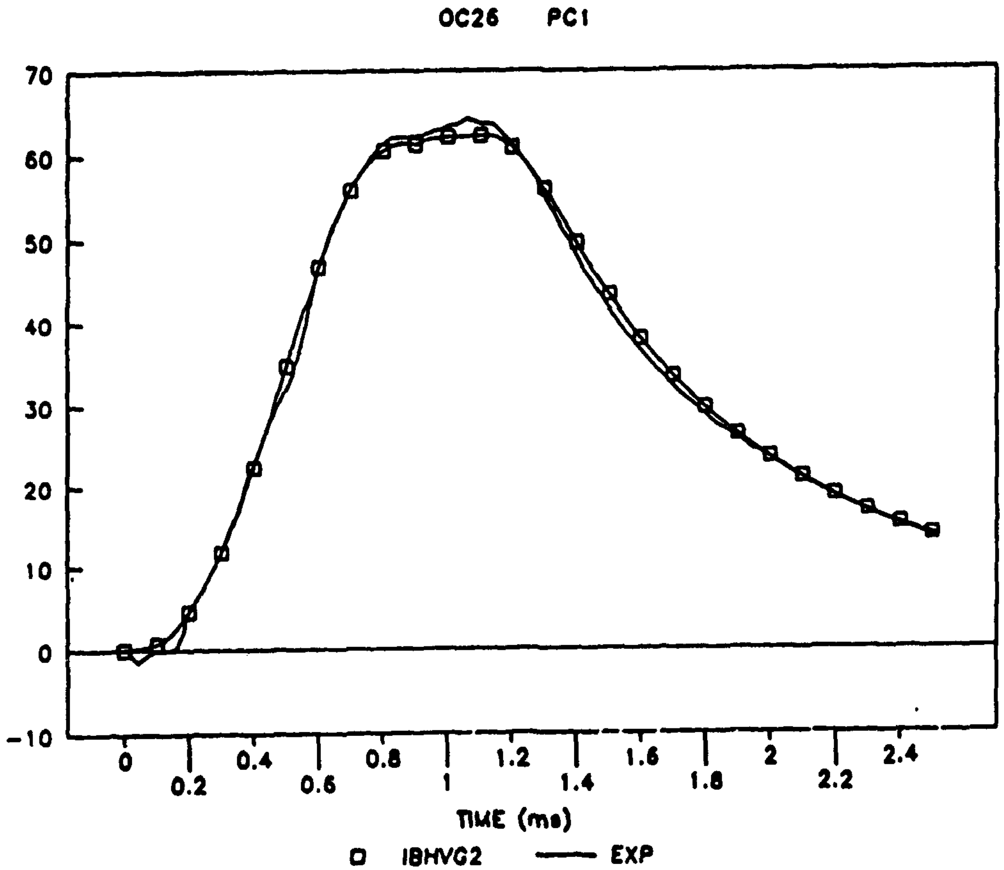
- ETC ENHANCEMENTS
- ETC TUTORIAL
- GENERAL DOCUMENTATION
- COORDINATION WITH OLIN

ETC ENHANCEMENTS

- ELECTRIC POWER INPUT
- ENERGY EQUATION MODS
- BURN RATE CONTROL
- ETC OUTPUT DATA

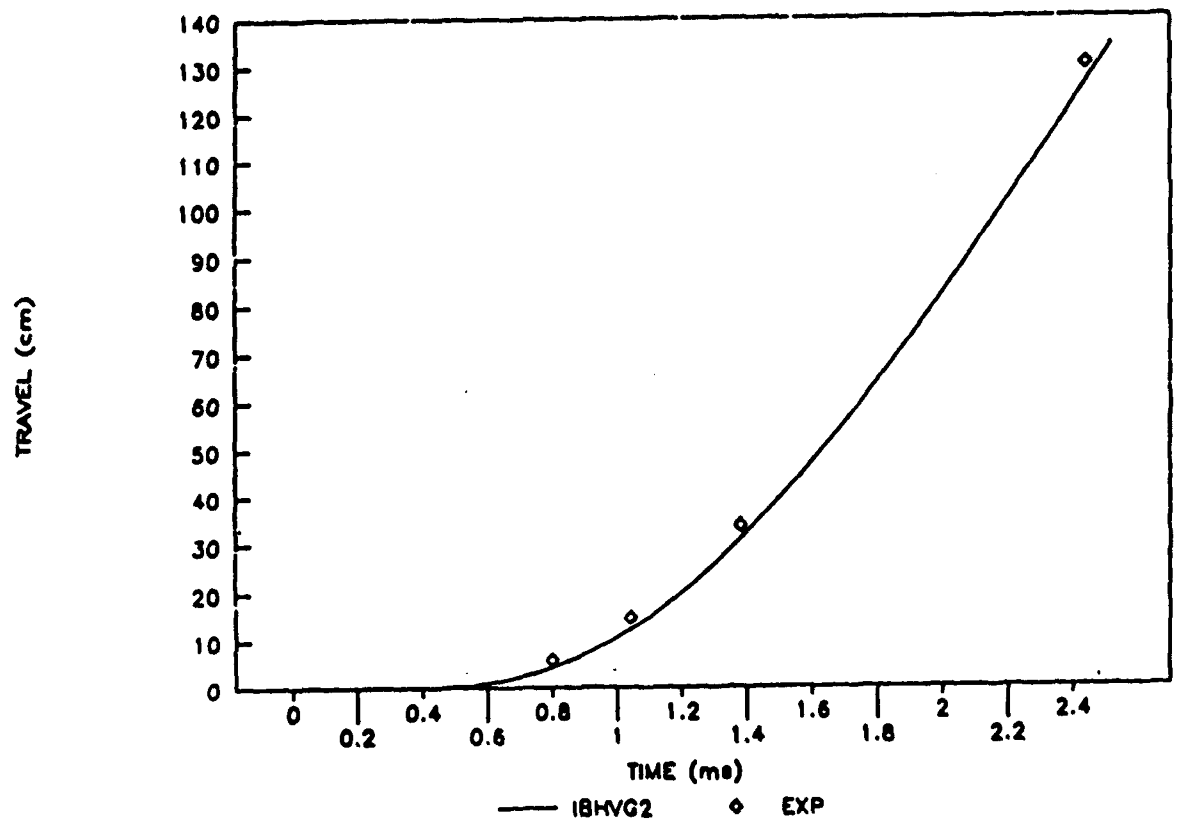

POWER (MW)
60
50
40
30
20
10
0
-0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
2.20
2.40
2.60
2.80
TIME(ms)
IBHVG2
EXP

30mm OLIN EXP. DATA vs. CODE RESULTS



CODE AND EXP. PROJECTILE TRAVEL

OC26



ETC TUTORIAL

- FEB 92 DRAFT TR-2829 + TUTOR
- MAR 93 REISSUE -> PICATINNY
- TUTORIAL IN PROCESS AT ARL

XNOVAKTC TRIALS

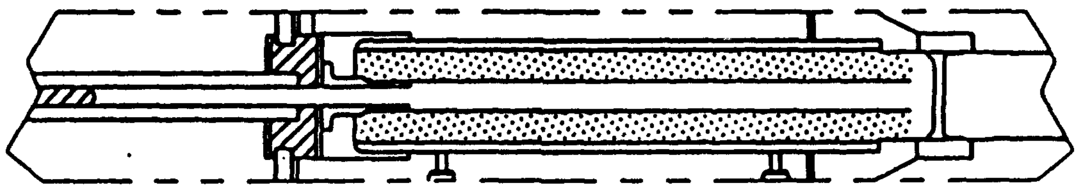
- AXIAL WAVE EXPERIMENTS
- POSTPROCESSOR CHANGES
- PROPELLANT ISSUES
- DOCUMENTATION STATUS

AXIAL WAVES

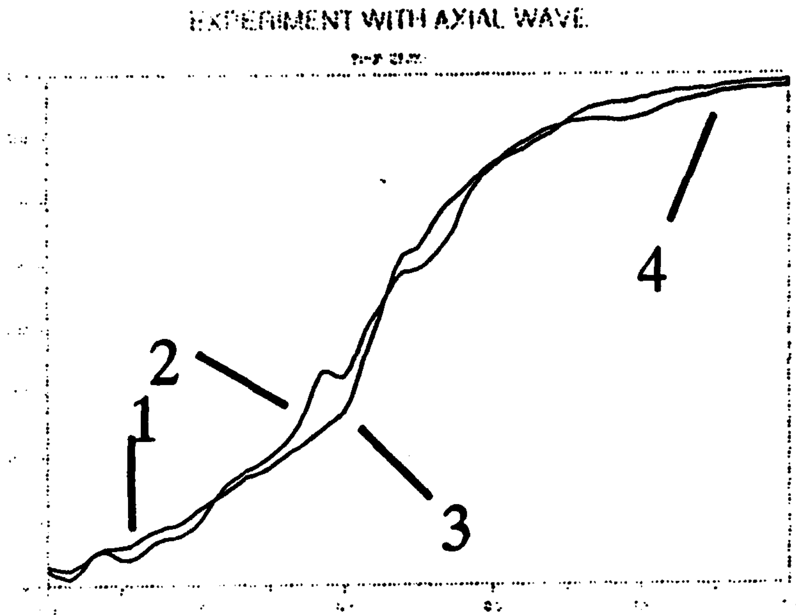
- EXPERIMENTAL GEOMETRY
- BREECH IGNITION
- XNOVAKTC APPROXIMATIONS
- COMPARISON WITH EXPERIMENT

LOADING GEOMETRY

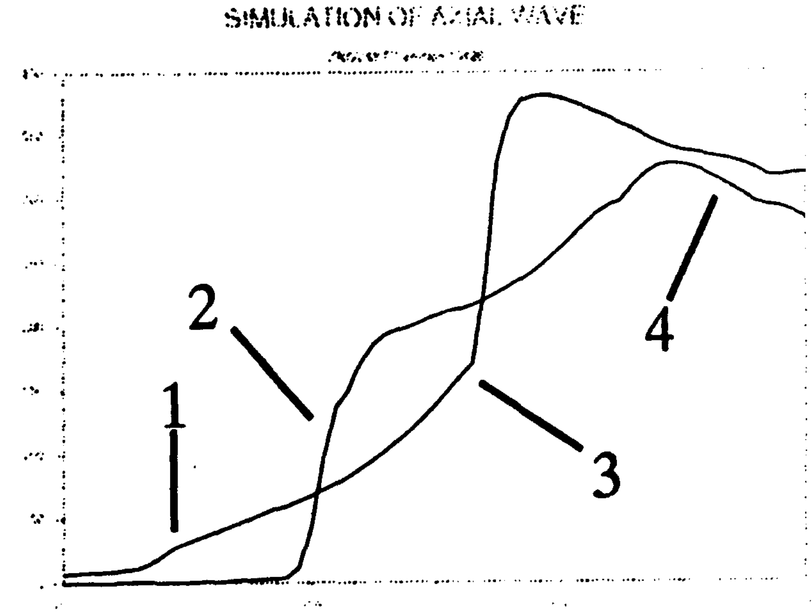
OC26



EARLY BREECH IGNITION CAUSES AXIAL WAVE



EXPERIMENT



COMPUTATION

1. Breech overpressure
2. Shock reaches front
3. Reflection reaches breech
4. Waves decay

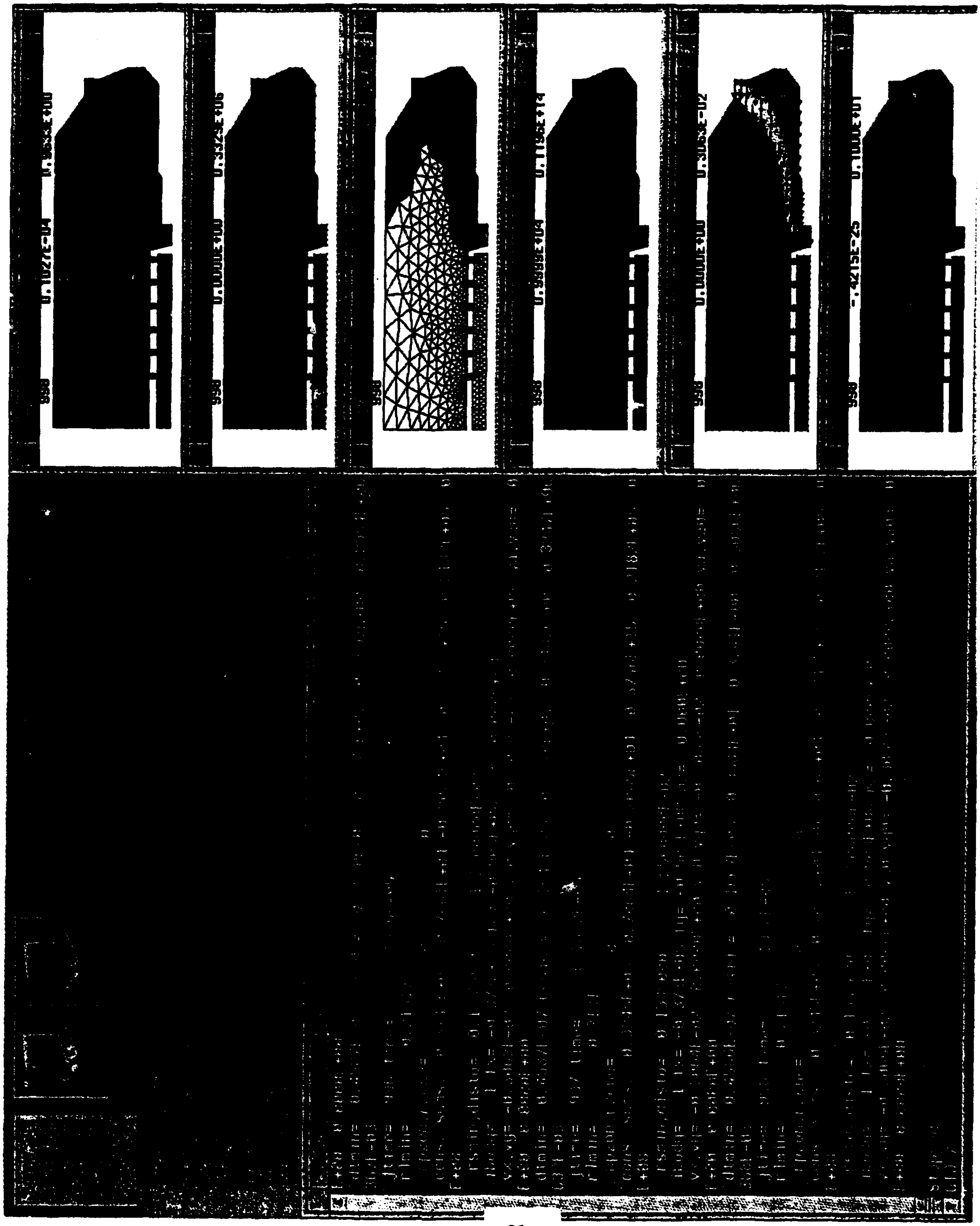
A. Breech ignition drives waves.

B. Wave steepens to shock during bed transit.

C. Wave decays after 2 transits.

FETC EXPERIMENTS

- MODEL EXTENSIONS
- PLASMA CHANNEL STABILITY
- CHANNEL WALL STRENGTH
- BASIC BALLISTIC LAUNCH

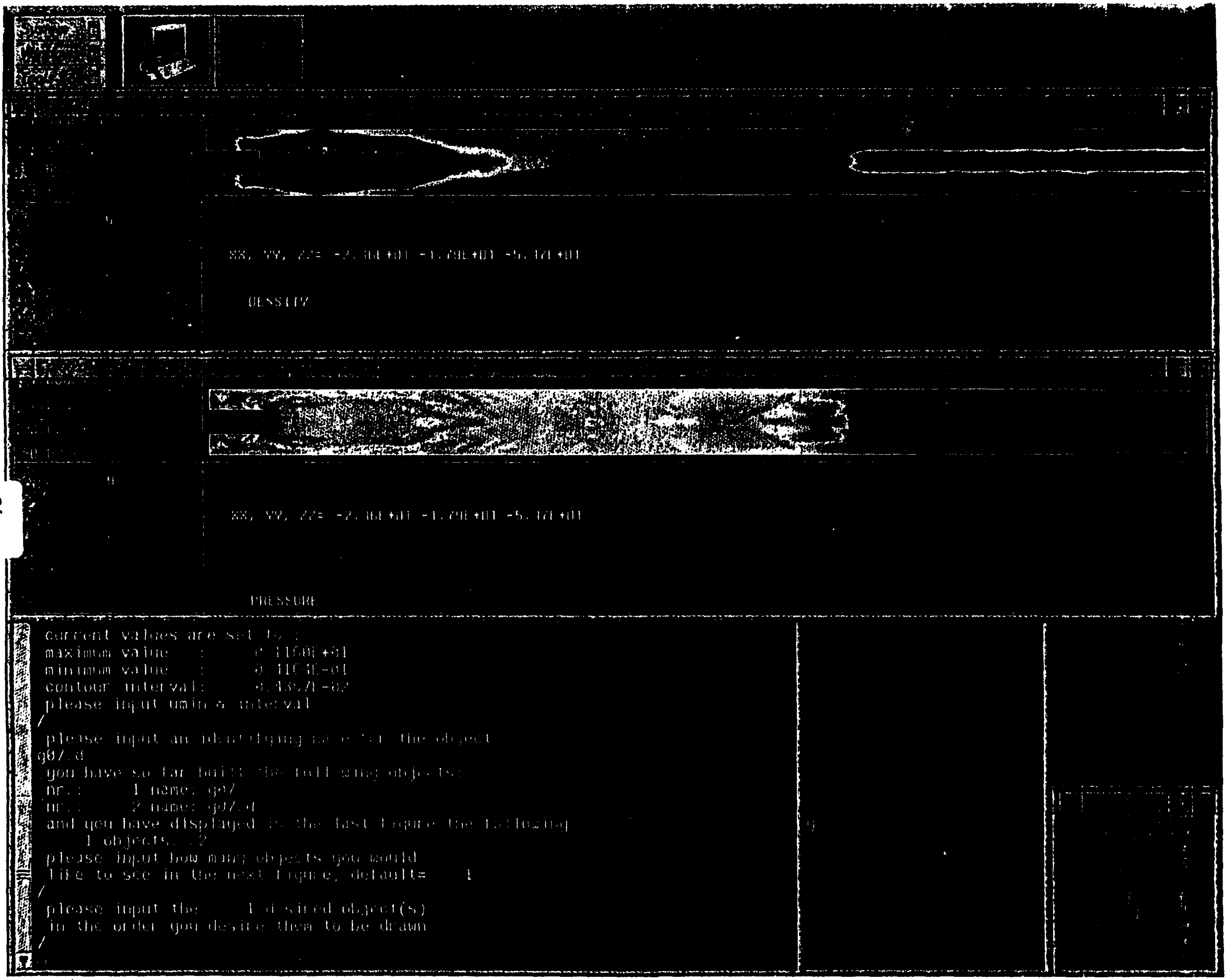


FETC EXTENSIONS

- LONG, THIN FINITE ELEMENTS
- RIGID, FRANGIBLE MEMBRANES
- MORE COMPLETE CHEMISTRY
- IGNITION MODELS

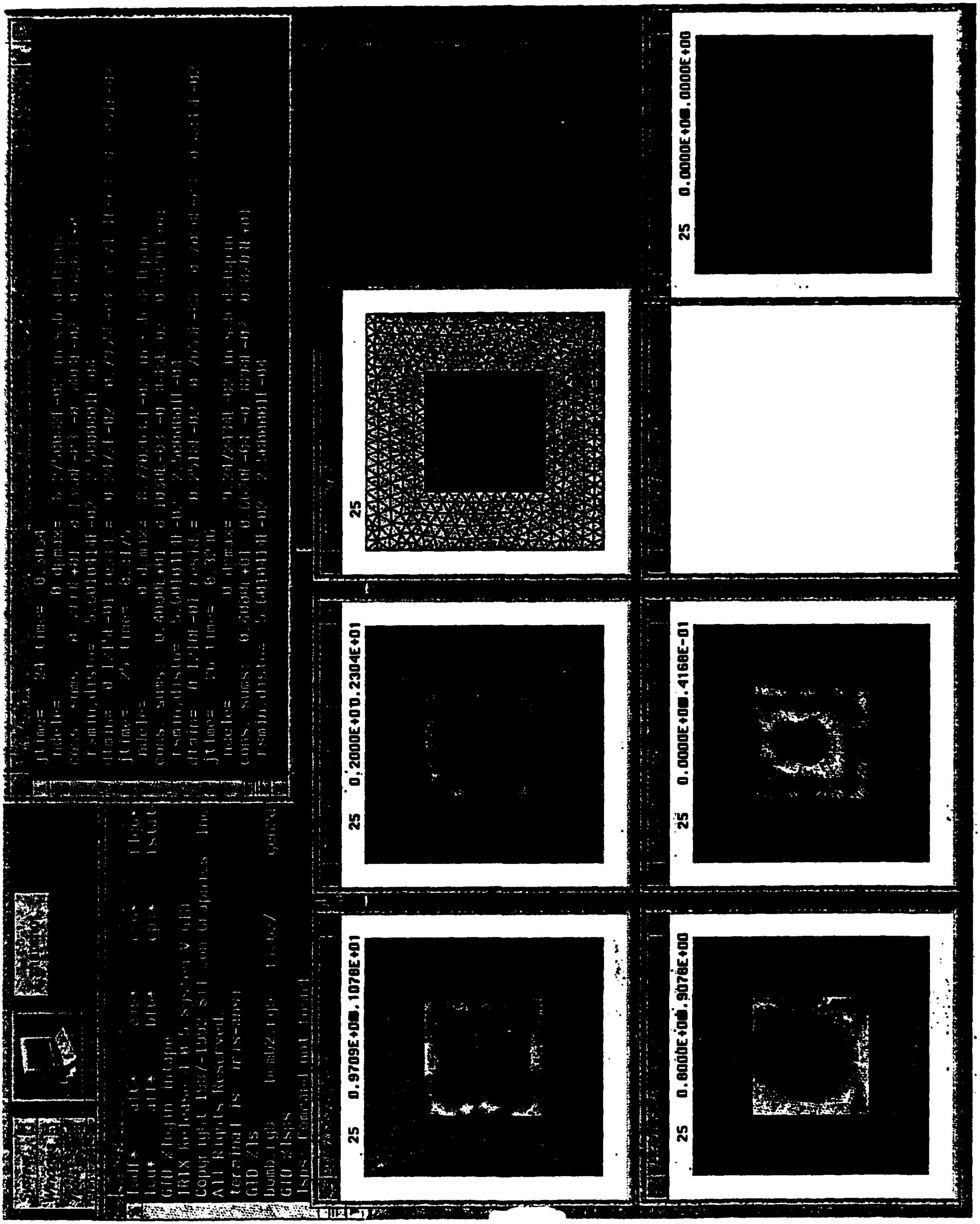
PLASMA CHANNEL

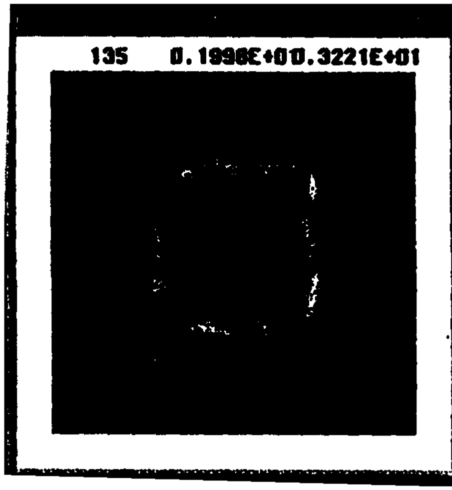
- MULTIFLUID TRANSPORT
- FCT BOUNDARY MAINTENANCE
- DISSIMILAR SOUND SPEEDS
- PHYSICAL IMPLICATIONS

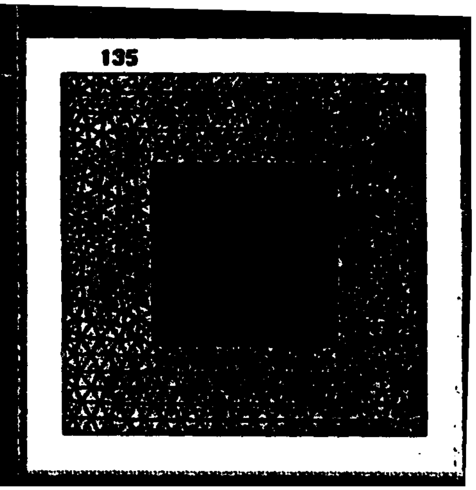

DENSITY
PRESSURE
current values are set to :
maximum value :
minimum value :
contour interval:
please input umin & interval
/
please input an identifying name for the object
g07.d
you have so far built the following objects:
nr.: 1 name: g07
nr.: 2 name: g07.d
and you have displayed in the last figure the following
1 objects. 2
please input how many objects you would
like to see in the next figure, default= 1
/
please input the 1 desired object(s)
in the order you desire them to be drawn
/

CHANNEL WALL

- FLUID-SOLID BOUNDARY
- DELTA-PRESSURE BREAKS
- CLOSED-BOMB TEST




135
0.1998E+01 0.3221E+01


135

BALLISTIC LAUNCH

- FULL 120 MM GUN TUBE
- ROD, SABOT, IGNITER
- IGNITION FLAMESPREAD
- PROJECTILE LAUNCH

FUTURE WORK

- 120 MM ETC ANALYSIS
- IBHVG2 POST-PROCESSING
- XKTC ETC INCORPORATION
- FETC CHEMISTRY MATCHING

PRODUCTS MENTIONED

IBHVG2, VERSION 5.04, WITH ETC EXTENSIONS
SEE GLORIA WREN FOR DETAILS OR COPIES

XNOVAKTC, VERSION 10426
SEE GEORGE KELLER FOR INFORMATION

CASEVision/Toolworks VERSION 1.1.1
SEE SILICON GRAPHICS UN-EXPRESS
1-800-800-7441 Cost $1500 for 1-user Indigo

FORTRAN LINT, Version 2.90
SEE IPT CORP, 1-800-944-5468, $3900 / 1-user

INTENTIONALLY LEFT BLANK.

SAIC/FW TP-268

MULTI-DIMENSIONAL SIMULATION OF LIQUID AND SOLID PROPELLANT ETC GUN INTERIOR BALLISTIC FLOWFIELDS

S. M. Dash, A. Hosangadi and N. Sinha
Science Applications International Corporation
Propulsive Sciences Division
501 Office Center Drive, Suite 420
Fort Washington, PA 19034-3211
Phone: 215/542-1200 Fax: 215/542-8567

MAY 12 & 13, 1993

Presentation at:

ETC MODELING WORKSHOP
U.S. Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

TOPICS

- CRAFT FINITE-VOLUME UPWIND/IMPLICIT CODE
  - Brief Overview of Numerics
  - Requirements for ETC Gun Simulation
- BASIC CRAFT UPGRADES FOR ETC GUN SIMULATION
  - Gridding: Dynamic/Blanking/Embedding
  - Thermochemistry: Liquid EOS/Virial EOS
  - Plasma Code Coupling/Quasi-Steady
- PROGRESS TOWARDS DEVELOPMENT OF CRAFT/LP-ETC MODEL
  - Gas/Liquid Equilibrated Formulation
  - Comparisons with Coffee LPG Code Predictions
  - Comparisons with FMC Shots
  - LES Turbulence Modeling/Subscale Terms
- PROGRESS TOWARDS DEVELOPMENT OF CRAFT/SP-ETC MODEL
  - Solid Propellant Burn Formulation and Integration into CRAFT
  - Comparisons with GDLS Shots
- FUTURE DIRECTION/MULTI-PHASE FLOW UPGRADES
  - Eulerian Solver/Volumetric Effects/Droplet Formation at G/L Interface — LP-ETC
  - Lagrangian Solver/Discrete Particle Combustion/Erosion of Particles from Surface — SP-ETC
  - Plasma Upgrades/Unsteady + Use of CRAFT Numerics

ETC MODELING PHILOSOPHY

- USE OF ADVANCED STATE-OF-THE-ART NUMERICS AND RESOLVED GRIDS

    - Minimize errors associated with numerical dissipation, etc. for adequate simulation of instabilities and turbulent/vortical structure

- INCORPORATE WELL-ESTABLISHED MODELS AND DATA SETS FOR PROCESSES WELL UNDERSTOOD, e.g., BALL PROPELLANT COMBUSTION

- INCORPORATE SIMPLEST PLAUSIBLE MODELS FOR PROCESSES NOT WELL UNDERSTOOD, e.g., LIQUID/PLASMA INTERFACE

- PERFORM SENSITIVITY STUDIES TO UNDERSTAND INFLUENCE OF MODEL MODIFICATIONS/UPGRADES, e.g., SUBSCALE LES MODELS FOR LP/ETC

- SYSTEMATIC MODELING UPGRADES AS REQUIRED BASED ON SHOT DATA COMPARISONS

    - Understanding processes emphasized

ETC GUN MODELING REQUIREMENTS

PHYSICS

- PLASMA COUPLING
- LES TURBULENCE
- PROJECTILE AERO

THERMO

- VIRIAL EOS
- LIQUID/SOLID EOS

NUMERICAL FRAMEWORK

- CONSERVATIVE, HIGHER-ORDER, NON-DISSIPATIVE
  - INSTABILITIES
- STRONGLY-COUPLED/IMPLICIT TREATMENT OF NONEQUILIBRIUM SOURCE TERMS
- DYNAMIC GRIDDING, GENERALIZED BC

CHEMISTRY

- GAS-PHASE
- LIQUID/DROPLET
- SOLID/BED-PARTICLE

MULTI-PHASE

- EQUILIBRATED MIXTURES
- G/P,D NONEQUILIBRIUM
  - EULERIAN
  - LAGRANGIAN
- DROPLET FORMATION/ PARTICLE EROSION

CRAFT CODE FEATURES FOR PROPULSIVE FLOWFIELD SIMULATION

NUMERICS	• 1D/2D/AXI/3D Finite-Volume Discretization
	• Implicit, Higher-Order Upwind (Roe/TVD) Formulation
	• Fully Implicit Source Terms/Boundary Conditions
GRID FEATURES	• Grid Dynamics to Account for Moving Boundaries
	• Grid Patching/Blanking for Complex Geometries
	• Solution-Adaptive Gridding
	• Hybrid Structured/Unstructured Formulation for Multi-Body Problems
THERMOCHEMISTRY	• Real Gas Mixtures (Calorically and Thermally Imperfect/JANNAF Thermo Tables/Virial EOS)
	• Finite-Rate Chemistry/Arbitrary Number of Species and Reactions
	• Fully Implicit Source Term Linearization
MULTI-PHASE FLOW	• Nonequilibrium Particle/Droplet Solvers (Eulerian and Lagrangian Formulations)
	• Gas/Liquid Equilibrium Formulation
	• Grain/Ablative Coupling Including Surface Recession and Interior Burning
TURBULENCE	• k-ε Formulation with Compressibility/Vortical Upgrades and Several Low Re Near-Wall Formulations
	• LES Subgrid Scale Models of Menon and Madabhushi
	• Particle Dispersion Formulations
APPLICATIONS	• Electrothermal Chemical (ETC) Gun
	• Regenerative Liquid Propellant Gun (RLPG)
	• Ram Accelerator
	• Solid /Liquid Propellant Rocket Motors/Exhausts
	• Ducted Rocket
	• Vertical Launcher Interactions
	• Turbulence/Multi-Phase Jet Research

CURRENT PROGRAMS UTILIZING CRAFT CODE

SPONSOR	PROGRAM	CODE	APPLICATIONS/FEATURES
NASA/LaRC	Jet Research	CRAFT/JR	• Jet structure, steady & unsteady • RS & LES turbulence models
MICOM	Tactical Missile Interactions	CRAFT/TM	• Missile propulsive/aero interactions • Nonequilibrium metallic oxide particles (Al_2O_3,...)
ARL	ETC	CRAFT/LP-ETC	• Liquid propellant ETC - gas/liquid equilibrated mixture ---> droplet combustion
		CRAFT/SP-ETC	• Solid propellant ETC - fixed bed combustion ---> fluidized bed/particle combustion
NSWC	VLS Interactions	CRAFT/TM	• Vertical launcher interactions including particle erosion/ablation • Nonequilibrium particles
MICOM	Advanced Technology	CRAFT/*	• Multiple body problems • Hybrid structured/unstructured solver
AFOSR	Ram Accelerator	CRAFT/RAM	• Ram accelerator simulation • Turbulence/combustion research
MICOM	Ducted Rocket	CRAFT/DR	• Ducted rocket • Carbon particulate combustion/dense loadings
ARL	LPG	CRAFT/LP	• Liquid propellant gun simulation • Vortex shedding/LES research

OVERVIEW OF BASIC NUMERICS

- **FINITE-VOLUME DESCRETIZATION**

$$\frac{\partial}{\partial t}\iiint Q\,dV + \iint (E_{i+1/2} - E_{i-1/2})\,d\eta\,d\zeta + \iint (F_{j+1/2} - F_{j-1/2})\,d\xi\,d\zeta + \iint (G_{k+1/2} - G_{k-1/2})\,d\xi\,d\eta$$

$$= \frac{1}{Re}\iint (R_{i+1/2} - R_{i-1/2})\,d\eta\,d\zeta + \iint (S_{j+1/2} - S_{j-1/2})\,d\xi\,d\zeta + \frac{1}{Re}\iint (T_{k+1/2} - T_{k-1/2})\,d\xi\,d\eta + \iiint D\,dV$$

- **CONSERVATIVE/IMPLICIT METHODOLOGY REQUIRES TIME LINEARIZATION OF FLUX VECTORS E, F, etc. WITH REPEAT TO Q**

$$Q^{n+1} = Q^{n} + \Delta Q,\ E^{n+1} = E^{n} + [A]\,\Delta Q,\ F^{n+1} = F^{n} + [B]\Delta Q$$

$$Q = (\rho, \rho u, \rho v, \rho w, e, \alpha_1, \alpha_2, \ldots);\ n \text{ variables}$$

A, B, C, etc. — n x n block non-sparse matrices

– VISCOUS AND SOURCE TERMS ALSO LINEARIZED AND INTEGRATED IN A STRONGLY COUPLED FASHION

DISCRETIZED FORM IS:

$$[I + \delta_\xi A - W][I - W]^{-1}[I - \delta_v B - w][I - W]^{-1}[I + \delta_\zeta C - W] = R.H.S.$$

- **FLUX EVALUATION ($E_{i+1/2}$, $E_{i-1/2}$, etc.) USING UPWIND Roe/TVD DIFFERENCING**

SAIC
Science Applications International Corporation
Propulsive Sciences Division

JACOBIAN OF THE FLUX VECTORS

$$
\hat{\mathbf{A}} = \begin{bmatrix}
0 & l_x & l_y & l_z & 0 & 0 & 0 & \cdots & 0 \\
-Uu + l_x \frac{\partial p}{\partial \rho} & U + l_x u + l_x \frac{\partial p}{\partial \rho u} & l_y u + l_x \frac{\partial p}{\partial \rho v} & l_z u + l_x \frac{\partial p}{\partial \rho w} & l_x \frac{\partial p}{\partial e} & l_x \frac{\partial p}{\partial \rho_1} & l_x \frac{\partial p}{\partial \rho_2} & \cdots & l_x \frac{\partial p}{\partial \rho_{n-1}} \\
-Uv + l_y \frac{\partial p}{\partial \rho} & l_x v + l_y \frac{\partial p}{\partial \rho u} & U + l_y v + l_y \frac{\partial p}{\partial \rho v} & l_z v + l_y \frac{\partial p}{\partial \rho w} & l_y \frac{\partial p}{\partial e} & l_y \frac{\partial p}{\partial \rho_1} & l_y \frac{\partial p}{\partial \rho_2} & \cdots & l_y \frac{\partial p}{\partial \rho_{n-1}} \\
-Uw + l_z \frac{\partial p}{\partial \rho} & l_x w + l_z \frac{\partial p}{\partial \rho u} & l_y w + l_z \frac{\partial p}{\partial \rho v} & U + l_z w + l_z \frac{\partial p}{\partial \rho w} & l_z \frac{\partial p}{\partial e} & l_z \frac{\partial p}{\partial \rho_1} & l_z \frac{\partial p}{\partial \rho_2} & \cdots & l_z \frac{\partial p}{\partial \rho_{n-1}} \\
-UH + \frac{\partial p}{\partial \rho} U & l_x H + U \frac{\partial p}{\partial \rho u} & l_y H + U \frac{\partial p}{\partial \rho v} & l_z H + U \frac{\partial p}{\partial \rho w} & (1 + \frac{\partial p}{\partial e}) U & \frac{\partial p}{\partial \rho_1} U & \frac{\partial p}{\partial \rho_2} U & \cdots & \frac{\partial p}{\partial \rho_{n-1}} U \\
-c_1 U & c_1 l_x & c_1 l_y & c_1 l_z & 0 & U & 0 & \cdots & 0 \\
c_2 U & c_2 l_x & c_2 l_y & c_2 l_z & 0 & 0 & U & \cdots & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
-c_{n-1} U & c_{n-1} l_x & c_{n-1} l_y & c_{n-1} l_z & 0 & 0 & 0 & \cdots & U
\end{bmatrix}
$$

NEED TO EVALUATE THE PRESSURE DERIVATIVES

$$\frac{\partial P}{\partial \rho}, \frac{\partial P}{\partial \rho U}, \ldots \frac{\partial P}{\partial e}, \ldots, \text{etc.}$$

UPWIND NUMERICAL FLUX CALCULATION

- **NUMERICAL FLUX AT CELL INTERFACE IS EVALUATED IN AN UPWIND FASHION**
- **FLUX DIFFERENCES ARE BASED UPON THE SIGN OF THE EIGENVALUE**
- **FLUX AT THE CELL INTERFACE $E_{i+1/2}$ IS GIVEN BY**

$$E_{i+1/2} = \frac{1}{2}\left[E_i + E_{i+1} + E^-_{i+1/2} - E^+_{i+1/2}\right] + \textit{higher order fluxes}$$

$E^-_{i+1/2}$ = **contribution of waves travelling in negative direction**

$E^+_{i+1/2}$ = **contribution of waves travelling in positive direction**

with

$$E^{\pm}_{j+1/2} = \frac{1}{2}\left[R_{j+1/2}(\Lambda \pm |\Lambda|)_{j+1/2} L_{j+1/2}\right](Q_{j+1} - Q_j)$$

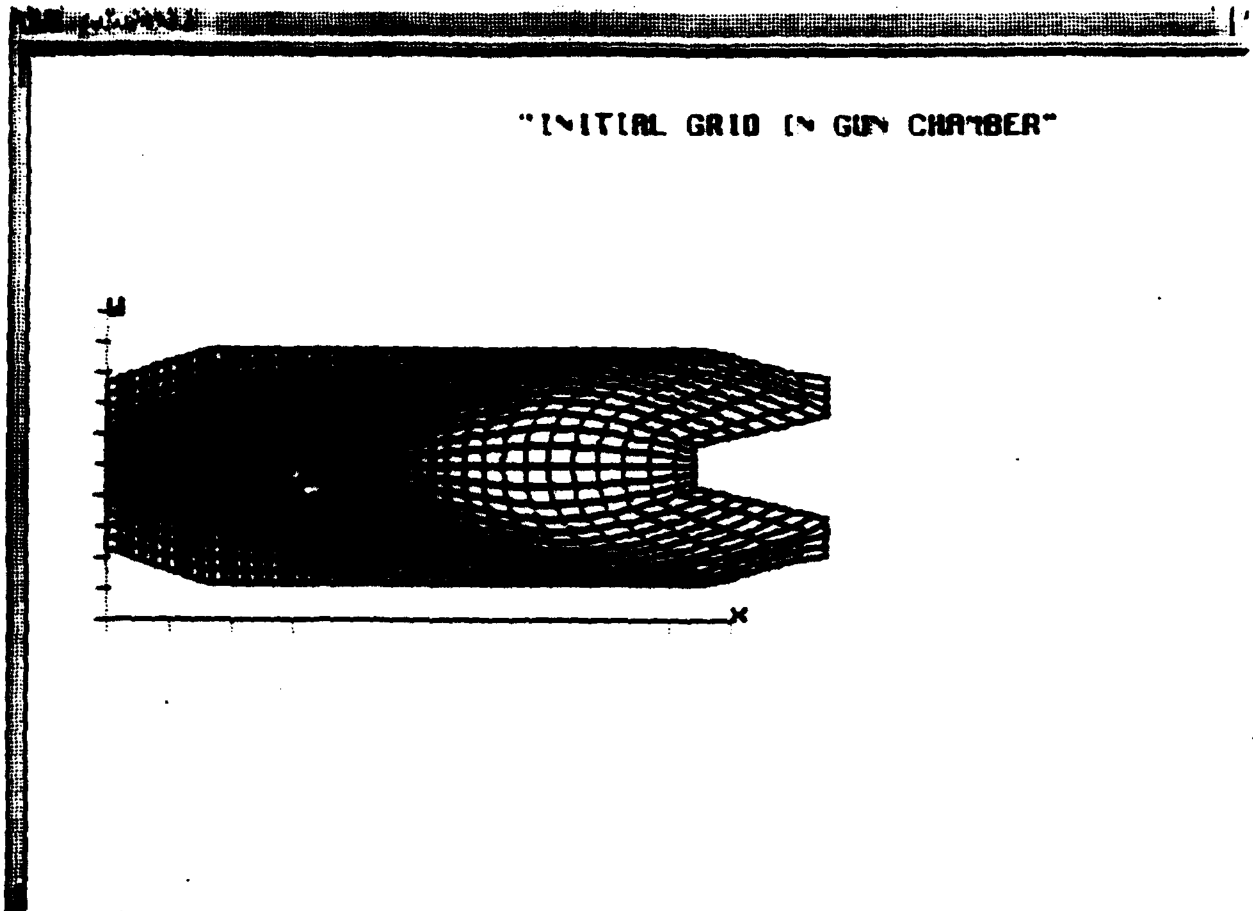
R and L are n x n block matrices containing the right and left eigenvectors, respectively.

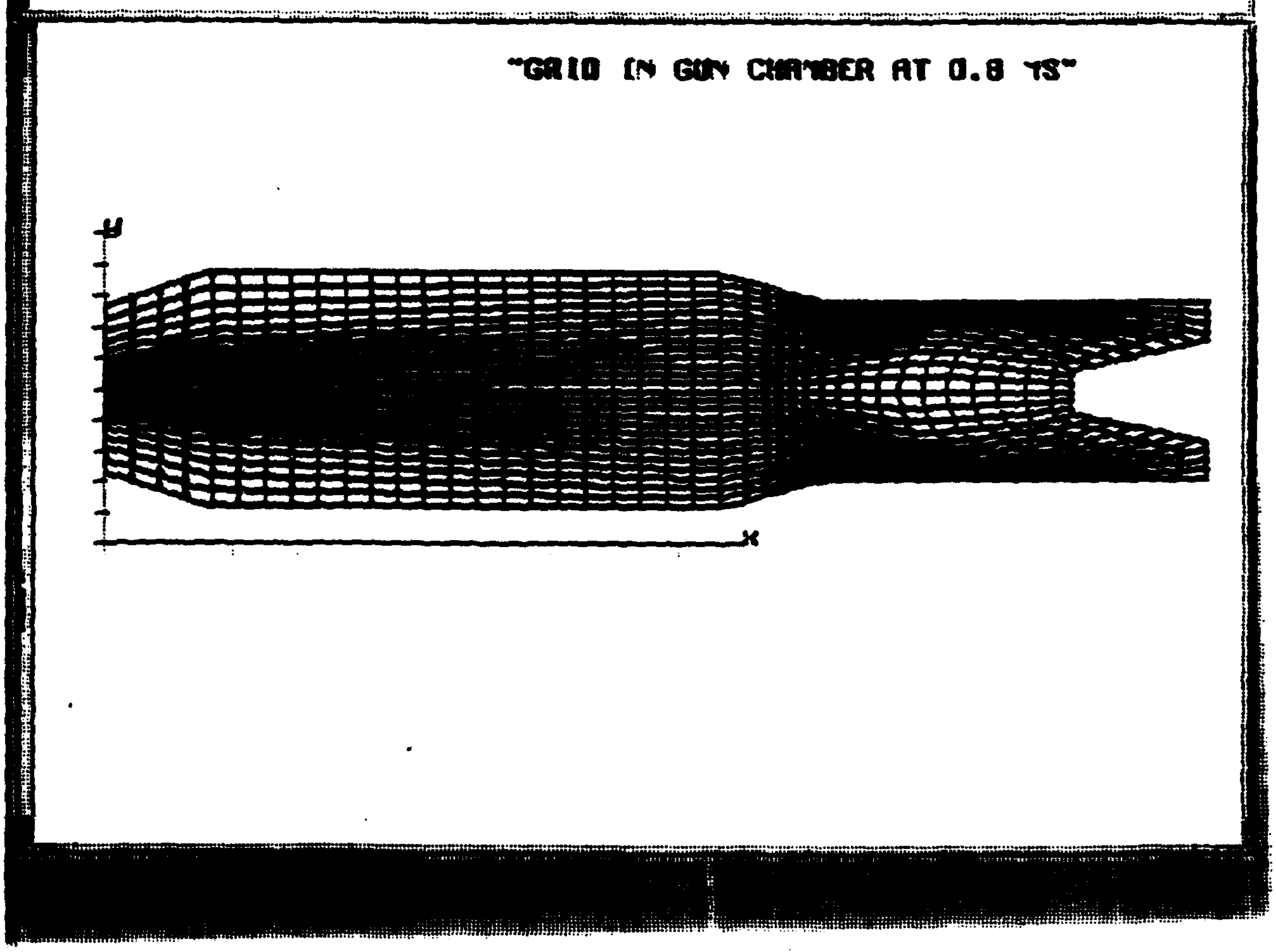
CPMI
5

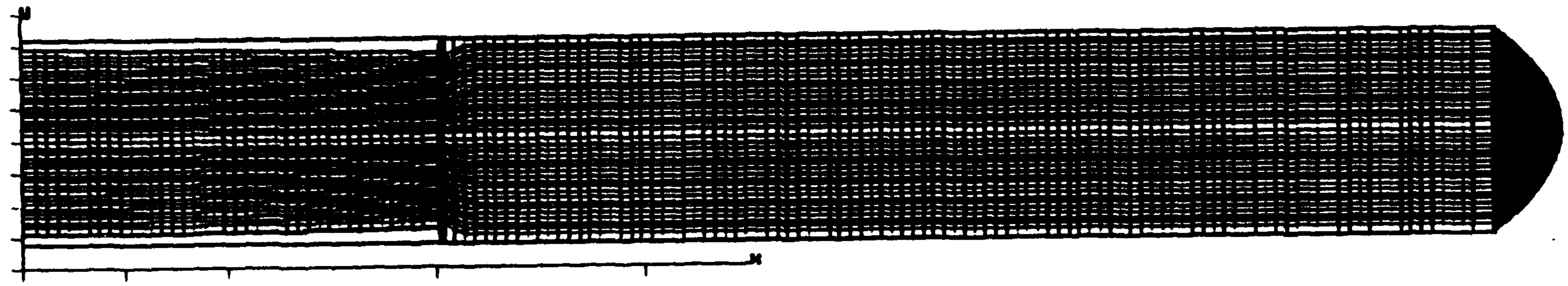
DYNAMIC GRID COMPUTATIONS

EQUATIONS	$\int_{t_2} Q dv - \int_{t_1} Q dv + \int_{t_1}^{t_2} \oint_{S(t)} \vec{n} \cdot \vec{f} \, ds dt = \int_{t_1}^{t_2} \int_{V(t)} \Phi dv dt$ Term I Term II Term III **Term I:** PRIMARY CONSERVED VARIABLES **Term II:** FLUX TERMS **Term III:** SOURCE TERMS **V(t):** TIME VARYING VOLUME
METHODOLOGY	• TREAT GRID AS PURELY GEOMETRIC QUANTITY, i.e., DEFINITION OF CONTRAVARIANT VELOCITY UN-CHANGED • EVALUATE FLUX TERM BY ASSUMING GRID IS HELD CONSTANT AT TIME-AVERAGED VALUE • INCLUDE ADDITIONAL FLUX ARISING FROM CELL FACE MOTION • EVALUATE SOURCE TERM FOR THE GRID AT THE NEW TIME LEVEL, THUS GIVING: $\left(\frac{Q^{n+1} - Q^n}{\Delta t}\right) V^{n+1} + Q^n \left(\frac{V^{n+1} - V^n}{\Delta t}\right) + F_n^{n+1} \bar{S} \Delta t = \Phi^{n+1} V^{n+1}$ $F_n = \vec{n} \cdot \vec{F}$, and $\bar{S}$ is the time averaged metric
NUMERICS	• SPECIFY GRID MOVEMENT AS A FUNCTION OF TIME • EVALUATE F_n AS A THIRD-ORDER UPWIND BIASED FLUX • SOLVE LINEARIZED IMPLICIT OPERATOR USING ADI PROCEDURE • USE NEWTON ITERATION FOR HIGHER ORDER ACCU-RACY IN TIME

CPM 1


"INITIAL GRID IN GUN CHAMBER"
y
x


"GRID IN GUN CHAMBER AT 0.8 MS"
y
x

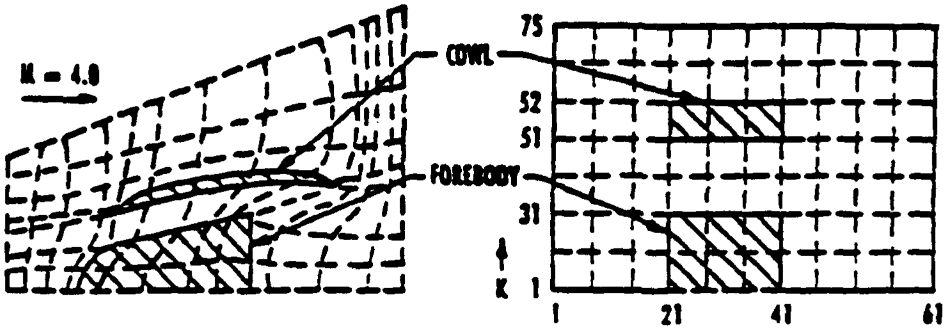


"LOG TEMPERATURE LEVELS AT 1.485 ms "

"Sp ETC SHOT #5 "

PATCHED GRIDDING IN PARCH (FROM PARC)

- SIMPLE GRIDS/COMPLEX GEOMETRY
- SINGLE DOMAIN/NO BLOCKING INEFFICIENCY

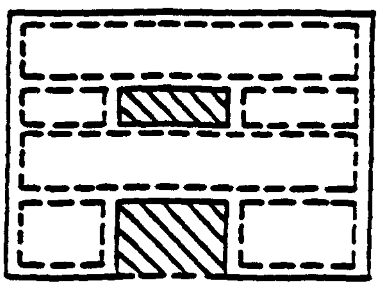


PHYSICAL DOMAIN

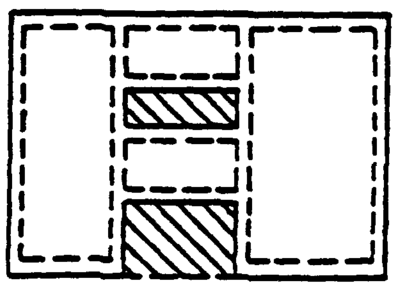
COMPUTATIONAL DOMAIN

J-Constant Index Class				
Segment Number	J Index	K-Indices		Sign of Normal
		Min	Max.	
1	1	1	75	1
2	21	1	31	-1
3	41	1	30	1
4	61	22	74	-1

K-Constant Index Class				
Segment Number	K Index	J-Indices		Sign of Normal
		Min	Max.	
1	1	1	20	1
2	1	42	61	1
3	75	2	61	-1
4	31	22	41	1
5	51	21	41	-1
6	52	21	41	1



J-PATCHES



K-PATCHES

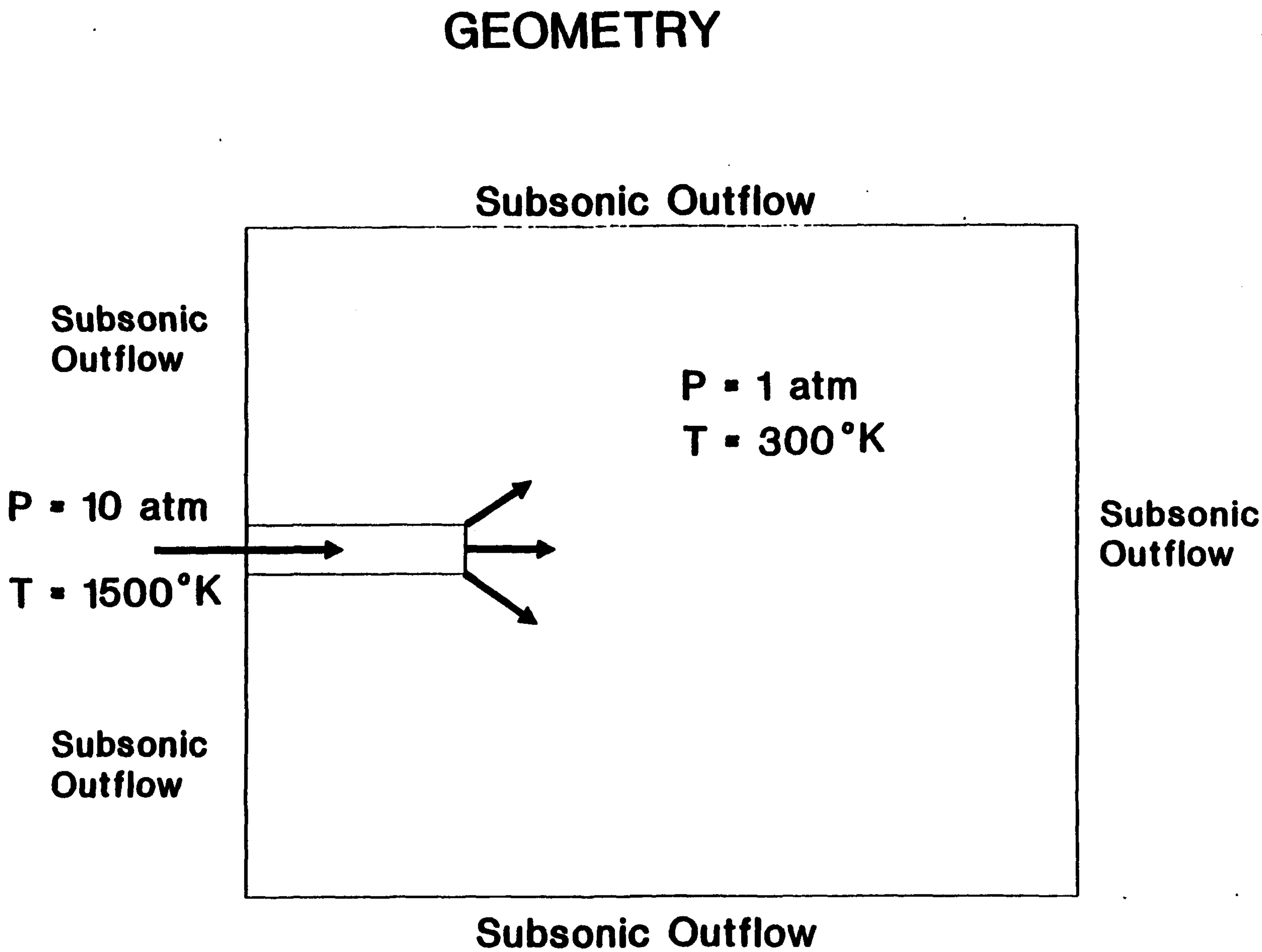


Figure 1. Schematic of Coupled Two-Dimensional Model Problem.

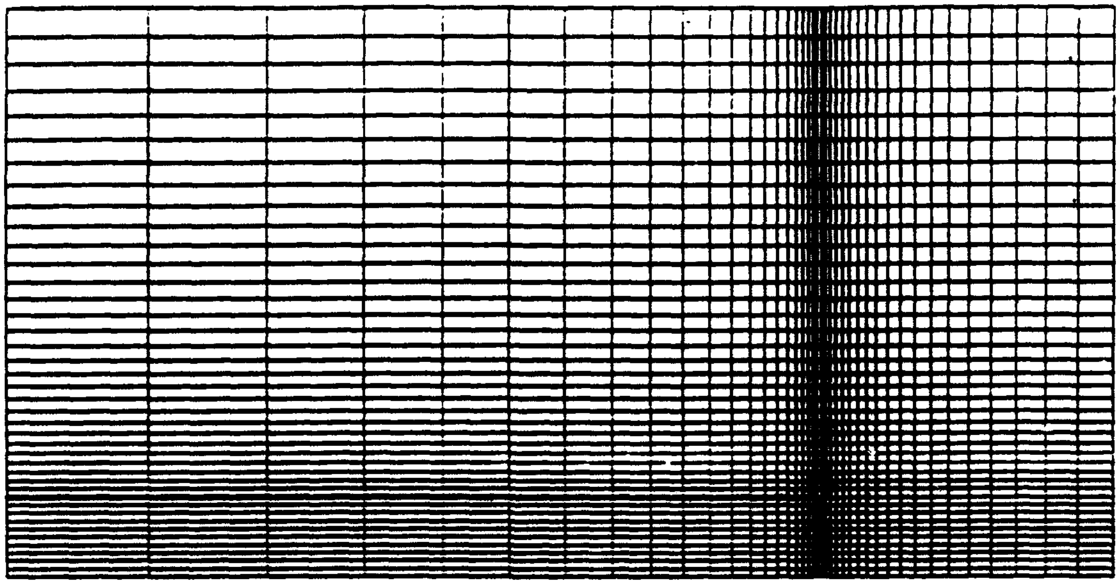


Figure 2a. Numerical Grid for Two-Dimensional Model Problem.

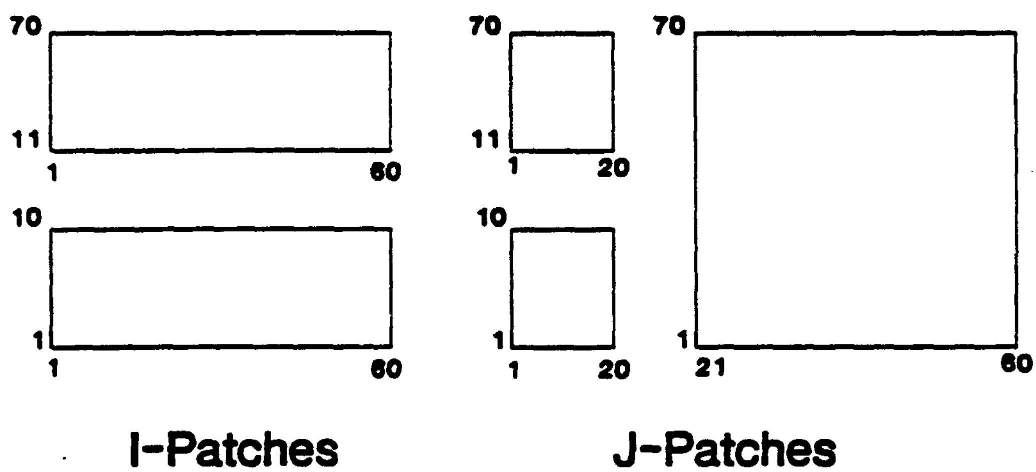
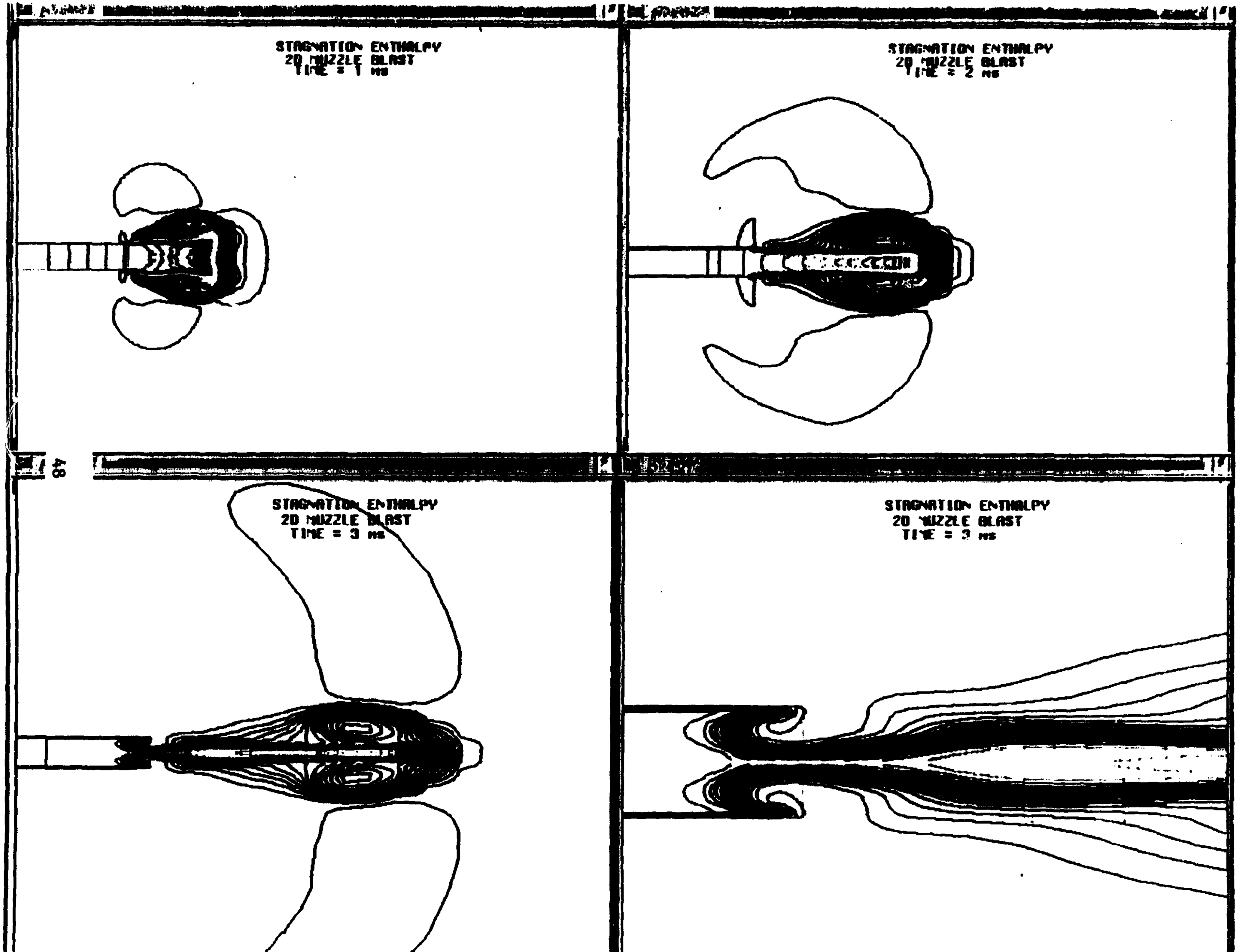


Figure 2b. Grid Patches Employed for Flux Calculation.


STAGNATION ENTHALPY
2D MUZZLE BLAST
TIME = 1 ms
STAGNATION ENTHALPY
2D MUZZLE BLAST
TIME = 2 ms
STAGNATION ENTHALPY
2D MUZZLE BLAST
TIME = 3 ms
STAGNATION ENTHALPY
2D MUZZLE BLAST
TIME = 3 ms

DENSE-GAS MODELING CAPABILITIES

- REAL GAS EFFECTS AT HIGH PRESSURES AND TEMPERATURES ARE MODELED BY INCORPORATING THE VIRIAL EOS

- THE VIRIAL EQUATION OF STATE FOR A MULTI-COMPONENT GAS MIXTURE IS GIVEN BY:

$$P = \bar{R}T \sum_n \frac{\rho_I}{W_I} \left[1 + B_m(T) \sum_n \rho_I + C_m(T) \sum_n (\rho_I)^2 \right]$$

THE SECOND AND THIRD VIRIAL COEFFICIENTS FOR THE MIXTURE ARE RELATED TO THE INDIVIDUAL SPECIES VIRIAL COEFFICIENTS.
IN GENERAL

$$B_m(T) = \sum_{IJ} B_{IJ} X_I X_J$$

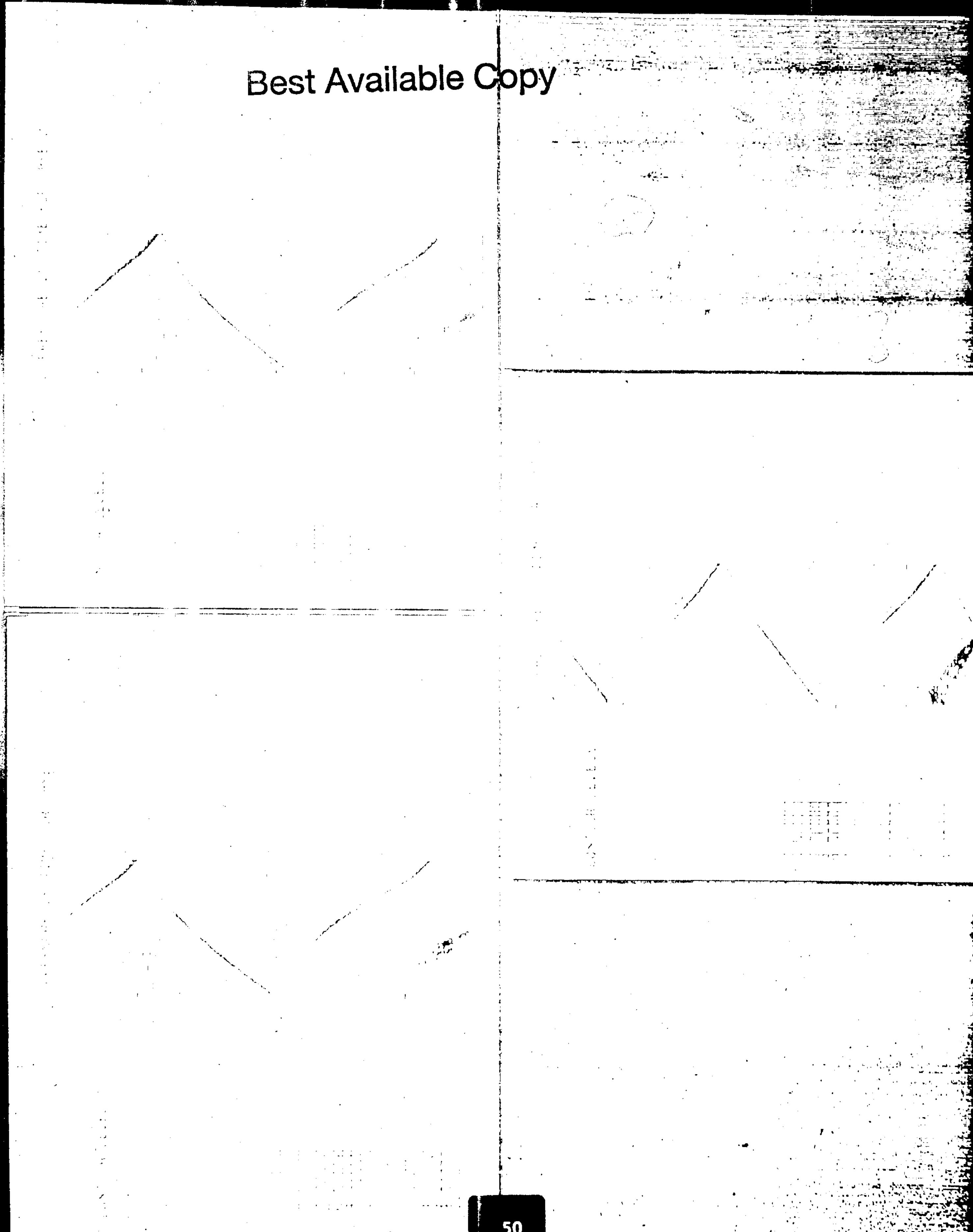
HOWEVER, IF DATA IS UNAVAILABLE FOR CROSS COEFFICIENTS SUCH AS B_{ij}, WE APPROXIMATE THE RELATIONSHIP BY

$$B_m(T) = \sum_I B_I Y_I$$ {suggested by Eli Freedman}

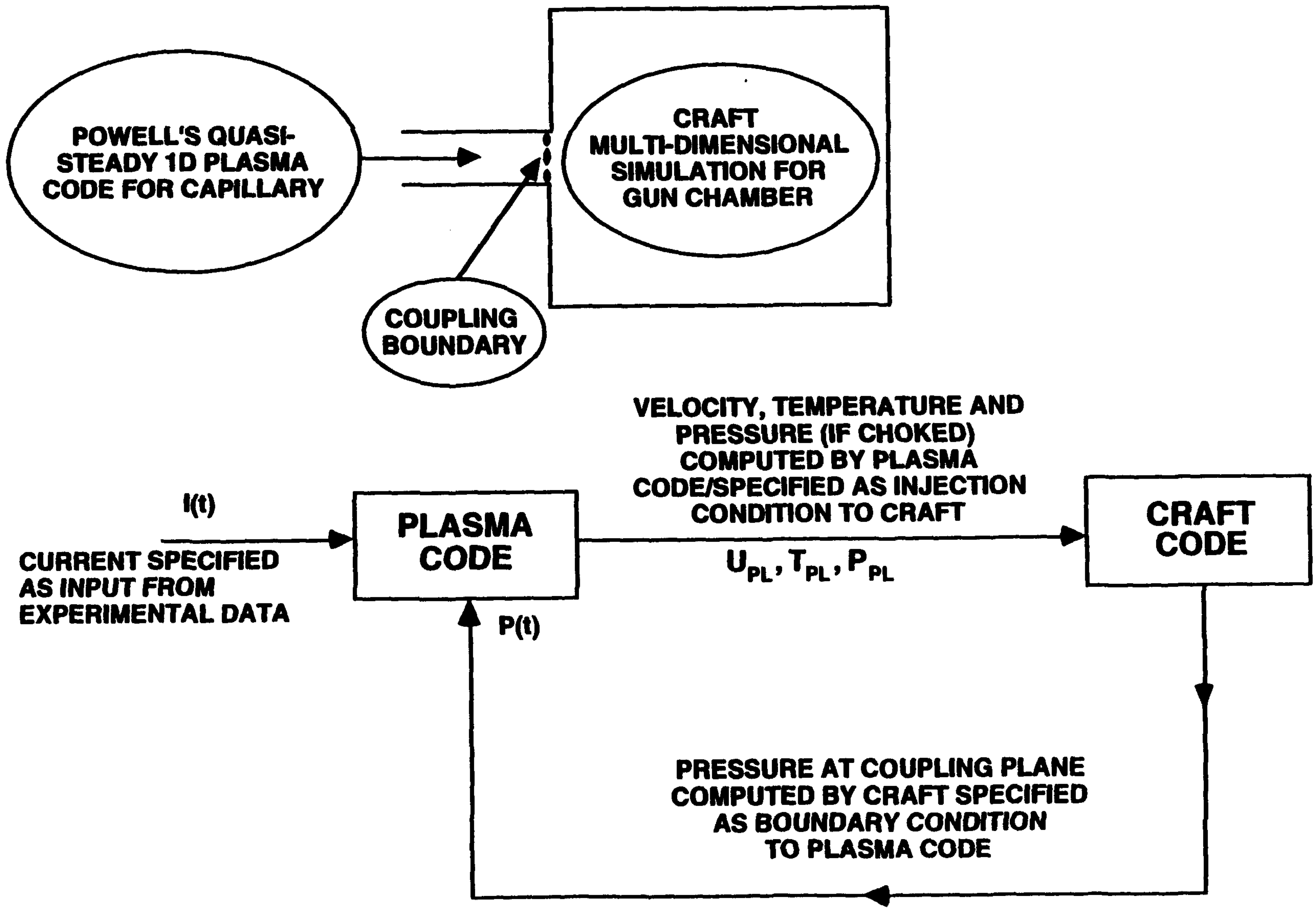
WHERE y_I IS THE MASS FRACTION.

THE VIRIAL COEFFICIENTS FOR EACH INDIVIDUAL COMPONENT CAN BE SPECIFIED IN TABULAR FORM AS A FUNCTION OF TEMPERATURE

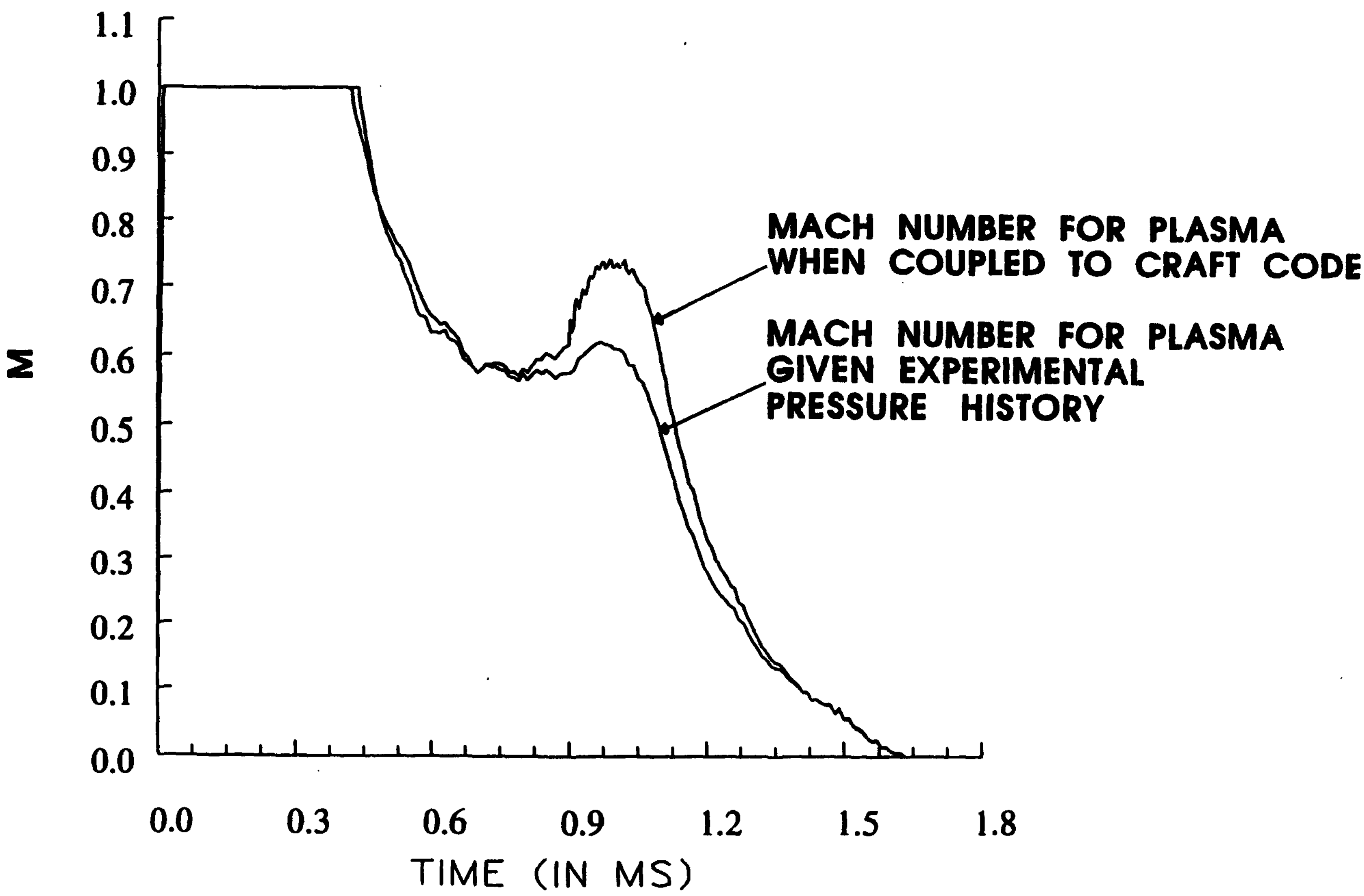
- TEST CASES: HIGH PRESSURE SHOCK TUBE STUDIES



PLASMA COUPLING PROCEDURE

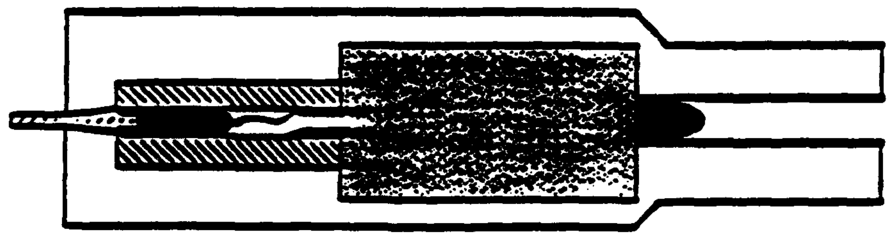


INFLOW MACH NUMBER HISTORY FOR PLASMA

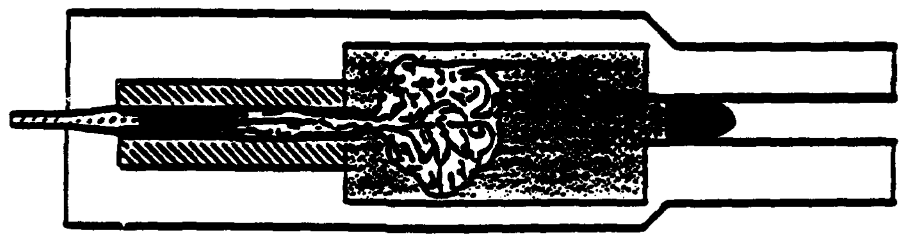


ETC PROCESS

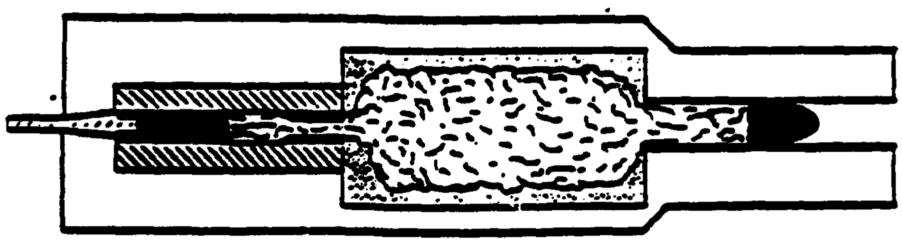
- Initial Configuration



- Initiation of Plasma into Working Fluid



- Interaction/ Combustion/ Vaporization of Plasma and Working Fluid



SAIC
An Employee-Owned Company

GAS-LIQUID EQUILIBRIUM FORMULATION

$P_L, \vec{U}_L, T_L, V_L$ *LIQUID*
GAS $P_G, \vec{U}_G, T_G, V_G$

- TWO-PHASE MIXTURE IS GOVERNED BY *AMAGAT'S LAW*

  TOTAL VOLUME = SUM OF PARTIAL VOLUMES

  $$\phi_G + \phi_L = 1$$

  PRESSURE IS IDENTICAL IN BOTH PHASES

  $$P_G = P_L$$

- GAS AND LIQUID PHASES TAKEN TO BE IN EQUILIBRIUM

  $$\vec{U}_G = \vec{U}_L$$

  $$T_G = T_L$$

THIS ALLOWS US TO FORMULATE GLOBAL CONSERVATION EQUATIONS FOR THE MIXTURE RATHER THAN SEPARATE EQUATIONS FOR EACH PHASE

TWO-PHASE EQUATIONS IN CRAFT

$$\frac{\partial Q}{\partial t} + \frac{\partial E}{\partial \xi} + \frac{\partial F}{\partial \eta} + \frac{\partial G}{\partial \zeta} = \text{VISCOUS} + \text{SOURCE TERMS}$$

$$Q = \left[\underbrace{\rho_m, \rho_m u, \rho_m v, \rho_m w, e}_{\text{global conservation equations}}, \underbrace{\rho_g \phi_g, \ldots\ldots}_{\text{species mass conservation}}\right]^T$$

$$E = \left[\overbrace{\rho_m \hat{U}, \rho_m \hat{U} u + \ell_x P, \rho_m \hat{U} v + \ell_y P, \rho_m \hat{U} w + \ell_z P, (e+P)\hat{U}}^{\text{global conservation equations}}, \overbrace{\rho_g \phi_g \hat{U}, \ldots\ldots}^{\text{species mass conservation}}\right]^T$$

LIQUID MASS IS OBTAINED FROM

$$\rho_m = \rho_g \phi_g + \rho_L (1 - \phi_g)$$

$$\therefore \rho_L (1 - \phi_g) = \rho_m - \rho_g \phi_g$$

$$\phi_g = \frac{V_g}{V_g + V_L}$$

CRAFT
10

HOW DO WE OBTAIN THE DERIVATIVES OF THE PRESSURE TERM?

THE GAS AND LIQUID PRESSURES ARE FUNCTIONS OF THREE VALUES:

$$P_G = f(\hat{\rho}_g,\ T,\ \phi_g)\ ,\ P_L = f(\hat{\rho}_L,\ T,\ (1 - \phi_g))$$

$$dP_g = f(d\hat{\rho}_g,\ dT,\ d\phi_g)$$

$$dP_L = f(d\hat{\rho}_L,\ dt,\ d(1 - \phi_g))$$

SINCE WE DO NOT SOLVE DIRECTLY FOR ϕ_g, WE ELIMINATE THE $d\phi_g$ TERM BY EVALUATING $dP_g = dP_L$ AND GETTING AN EXPRESSION FOR $d\phi_g$.

USING THIS RELATIONSHIP FOR $d\phi_g$, IT IS STRAIGHTFORWARD TO DERIVE THE DERIVATIVES OF THE PRESSURE

SAIC

SPEED OF SOUND IN TWO-PHASE SYSTEM

- **CALCULATE EIGENVALUES OF THE FLUX JACOBIAN A:**

$$A - \lambda I = 0$$

- **EIGENVALUES OF A ARE EVALUATED TO BE:**

$$\Lambda = \left[\hat{U} + k_\xi C, \hat{U} - k_\xi C, \hat{U}, \hat{U}, \ldots \hat{U}\right]^T \quad \left\{k_\xi = \left[\tilde{\xi}_x^2 + \tilde{\xi}_y^2 + \tilde{\xi}_z^2\right]^{1/2}\right\}$$

WHERE, C, THE SPEED OF SOUND IN THE MIXTURE IS:

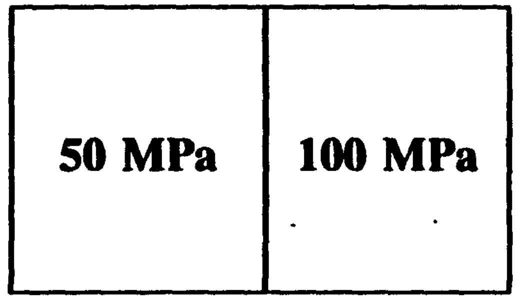
$$C_m = \left\{\frac{\tilde{\gamma}}{\rho_m}\left[\frac{\phi_g}{\rho_g C_g^2} + \frac{1 - \phi_g}{\rho_L C_L^2}\right]^{-1}\right\}^{1/2}$$

C_g = **<u>Isothermal</u> Speed of Sound in Gas** = $\left(\frac{\partial P_g}{\partial \rho_g}\right)_T^{1/2}$

C_L = **<u>Isothermal</u> Speed of Sound in Liquid** = $\left(\frac{\partial P_L}{\partial \rho_L}\right)_T^{1/2}$

VALIDATION STUDIES FOR GAS-LIQUID FORMULATION

- SOLUTIONS FOR TWO-PHASE 1-D SHOCK TUBES WERE COMPARED WITH TERRY COFFEE'S COMPUTATIONS



<u>CASE I</u> LIQUID – HIGH PRESSURE SIDE
GAS – LOW PRESSURE SIDE

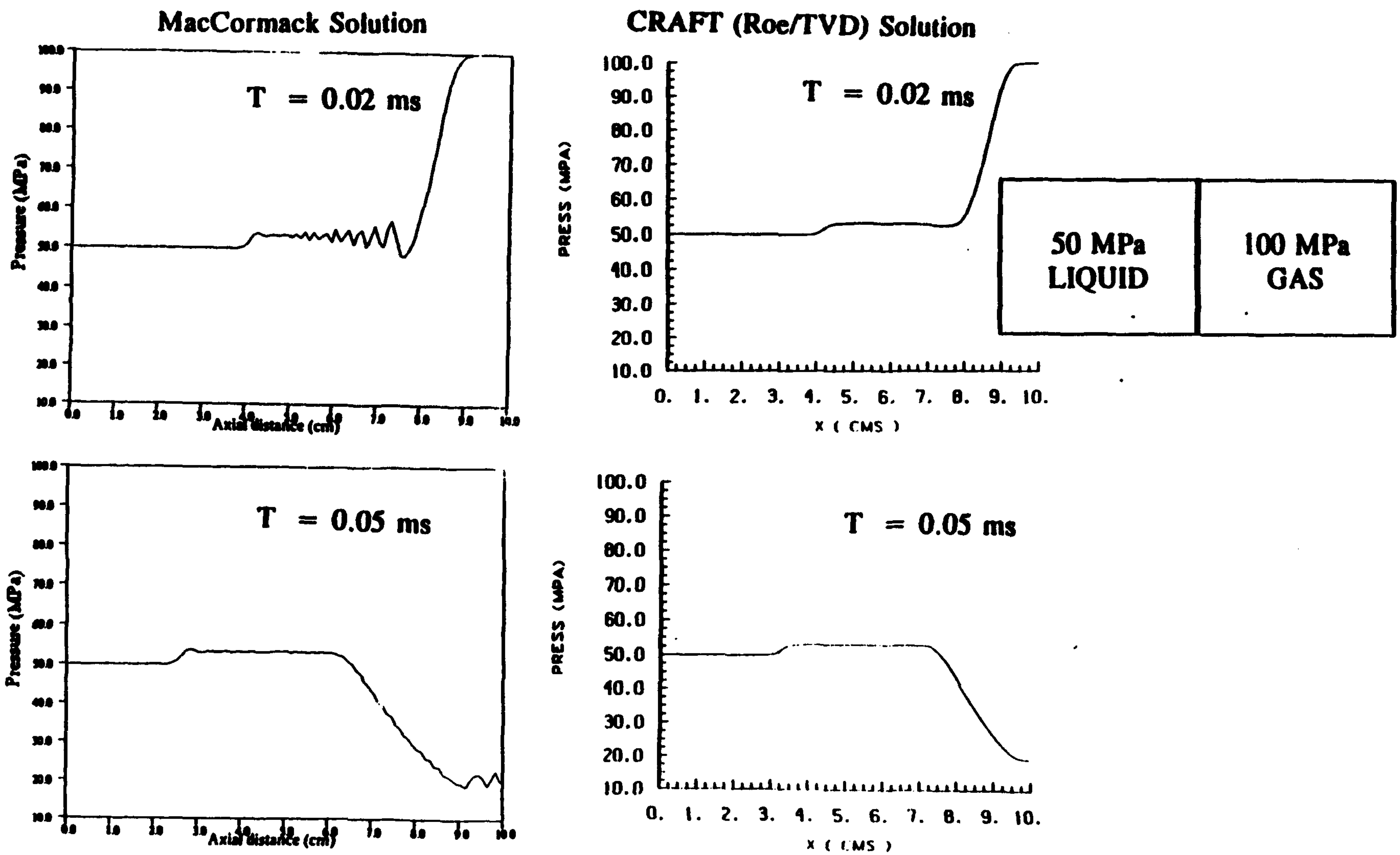
<u>CASE II</u> LIQUID – LOW PRESSURE SIDE
GAS – HIGH PRESSURE SIDE

<u>CASE III</u> UNIFORM MIXTURE OF GAS AND LIQUID ON BOTH SIDES

<u>CASE IV</u> RADIAL SHOCK TUBE – UNIFORM MIXTURE WITH HIGH PRESSURE AT CORE

PRESSURE PROFILES FOR A TWO-PHASE SHOCK TUBE

Gas = High Pressure Side and Liquid = Low Pressure Side

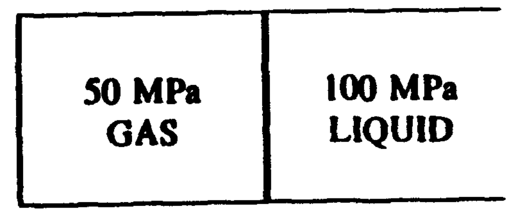


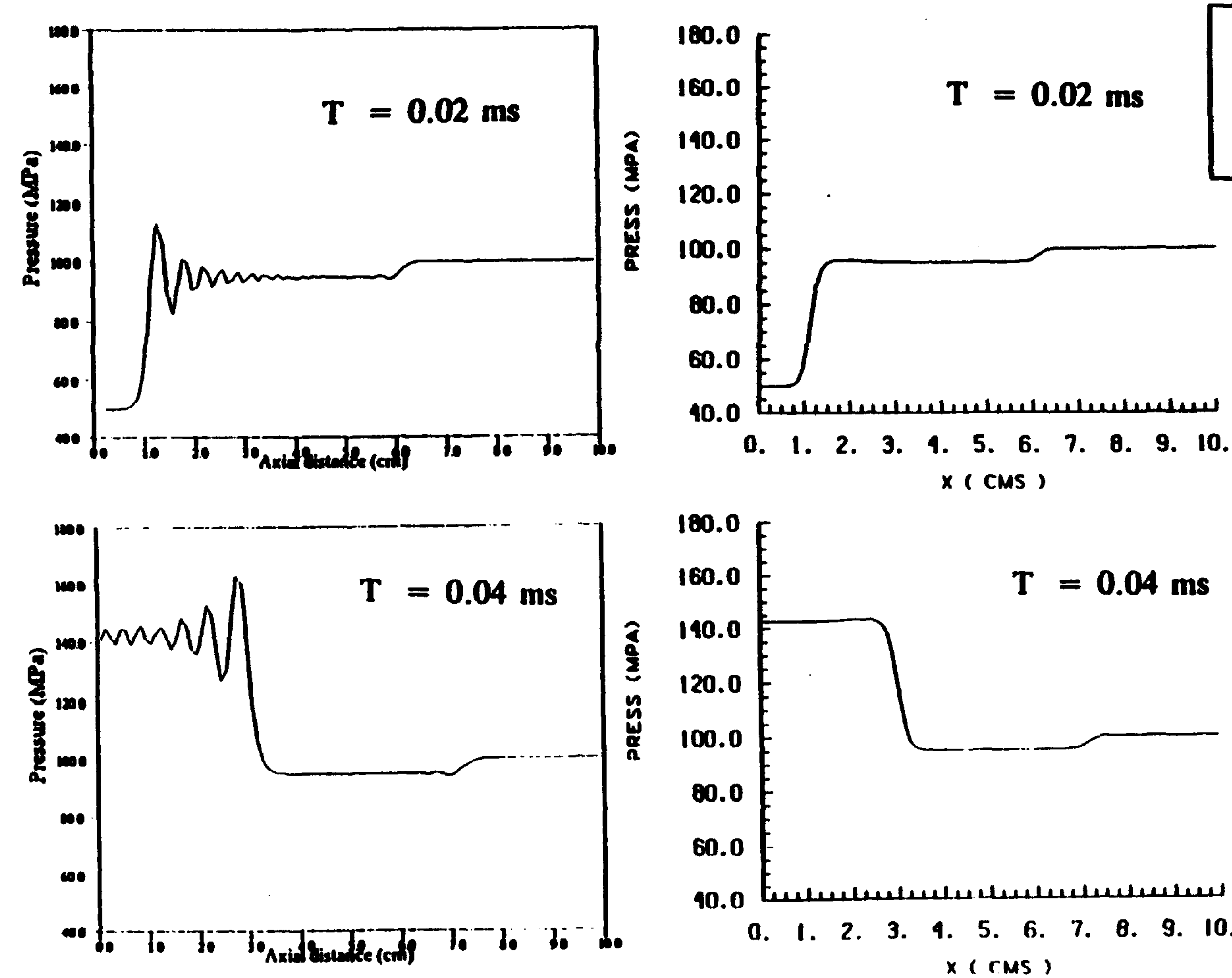
PRESSURE PROFILES FOR A TWO-PHASE SHOCK TUBE

Gas = Low Pressure Side and Liquid = High Pressure Side

MacCormack Solution

CRAFT (Roe/TVD) Solution

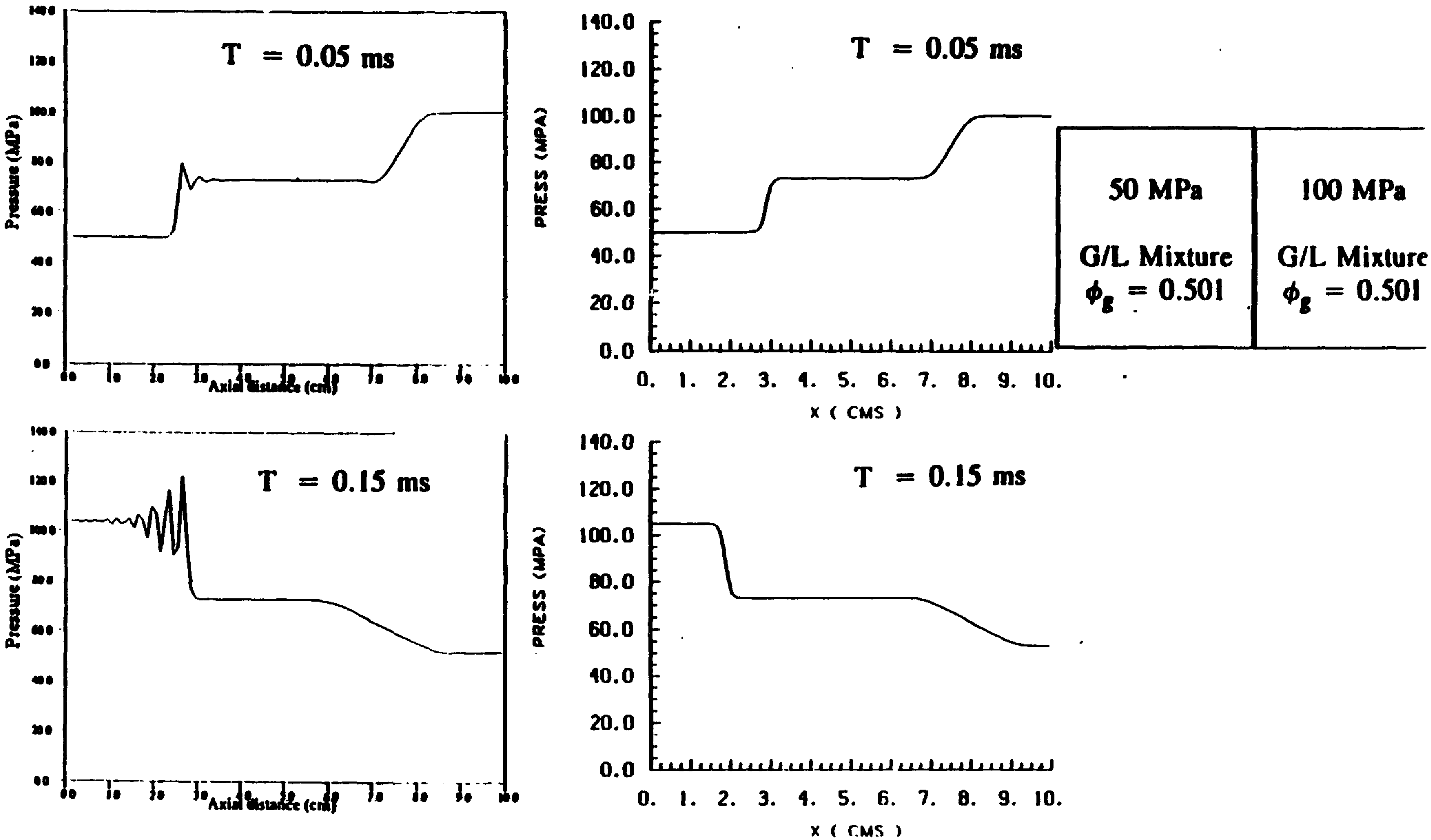




PRESSURE PROFILES FOR A TWO-PHASE SHOCK TUBE

Uniform Gas/Liquid Mixture

MacCormack Solution | CRAFT (Roe/TVD) Solution



PRESSURE HISTORY ON WALL OF TWO-PHASE SHOCK TUBE

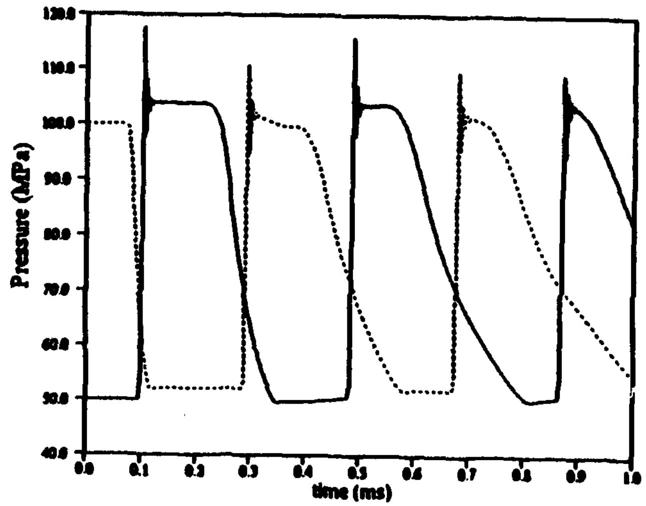
Uniform Gas/Liquid Mixture

50 MPa	100 MPa
G/L Mixture $\phi_g = 0.501$	G/L Mixture $\phi_g = 0.501$

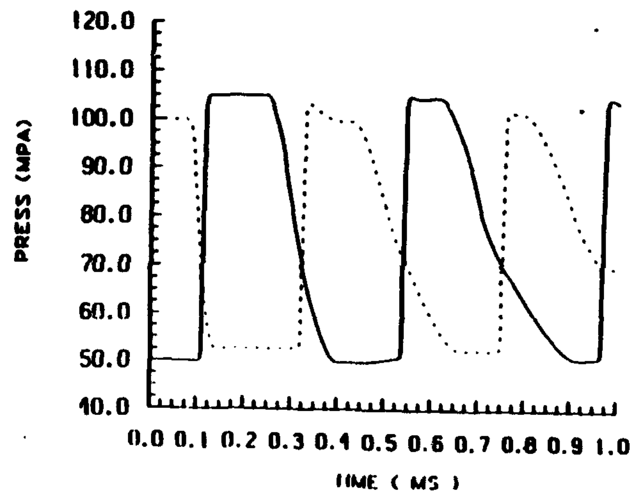
——— Left Wall

- - - - - Right Wall

MacCormack Solution

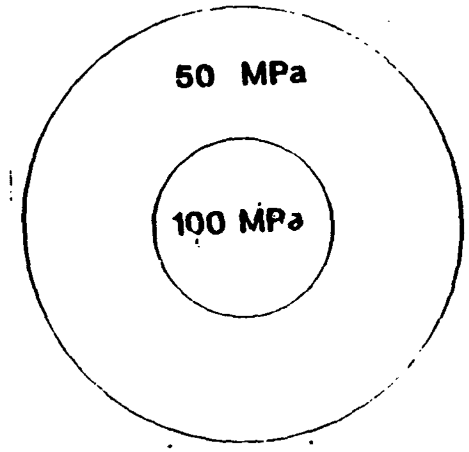


CRAFT (Roe/TVD) Solution

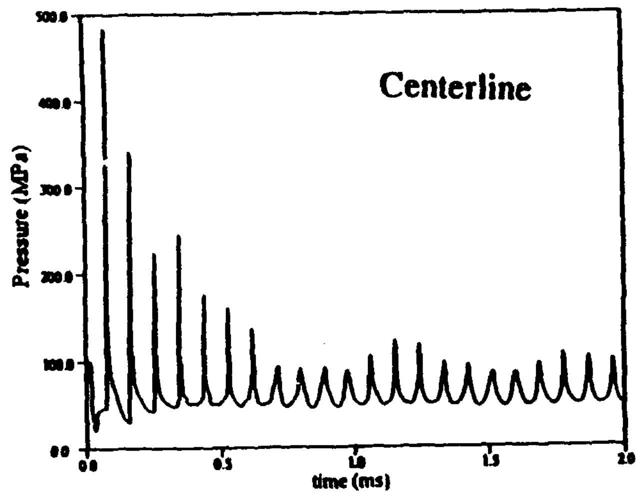


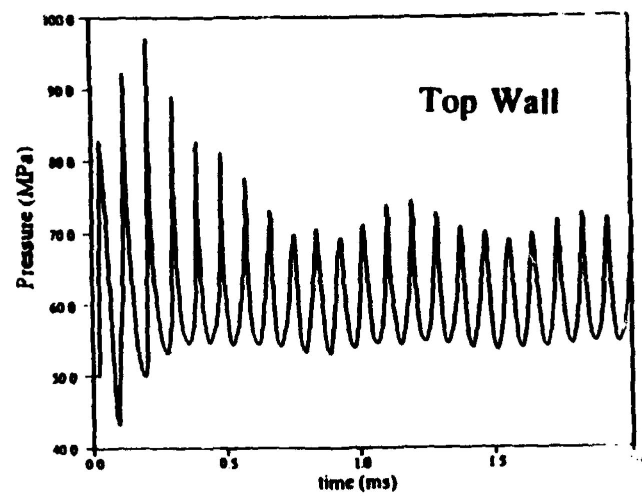
PRESSURE HISTORY FOR A RADIAL TWO-PHASE SHOCK TUBE

Uniform Gas/Liquid Mixture

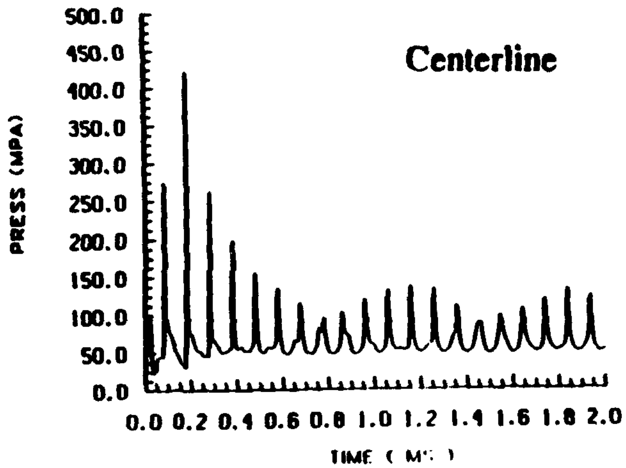


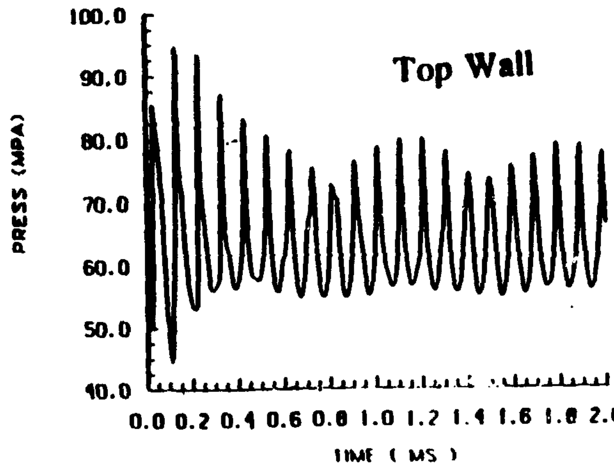
MacCormack Solution





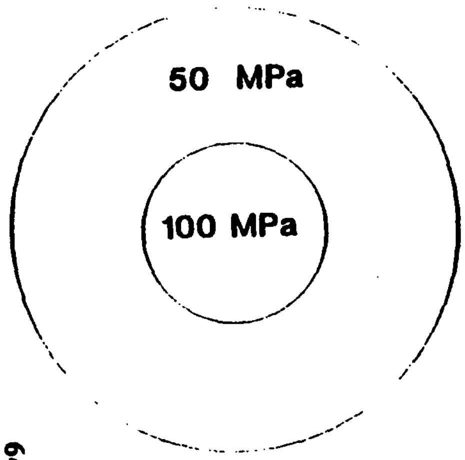
CRAFT (Roe/TVD) Solution

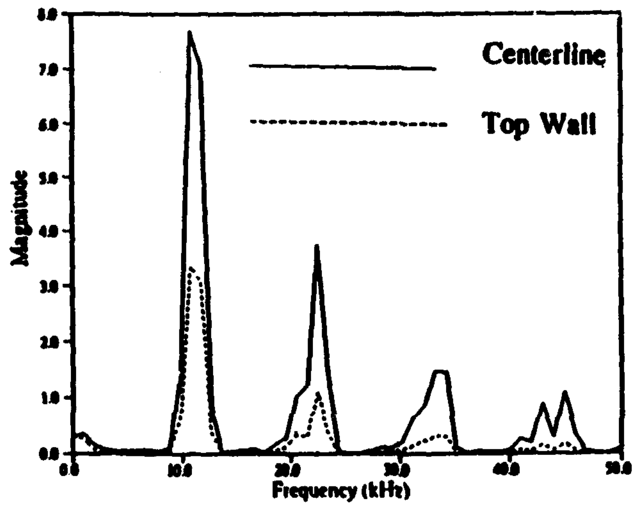




FREQUENCY SPECTRA FOR A RADIAL TWO-PHASE SHOCK TUBE

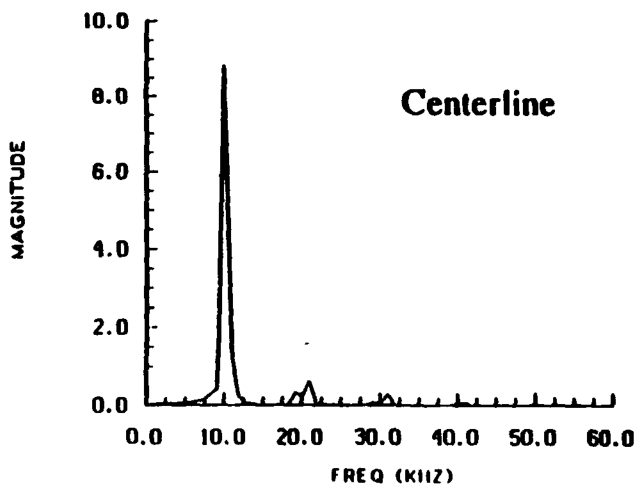
Uniform Gas/Liquid Mixture

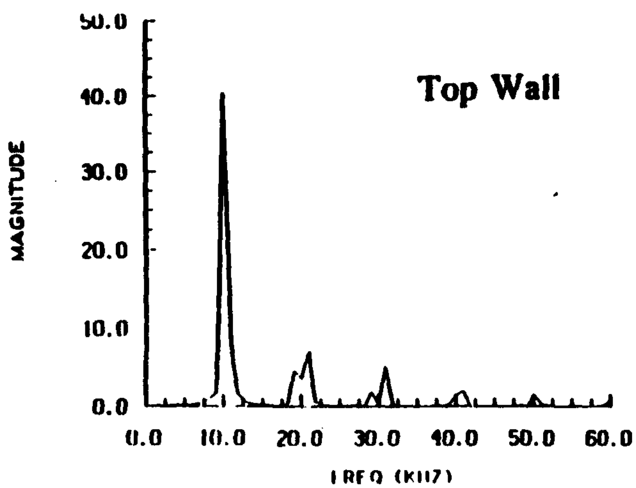


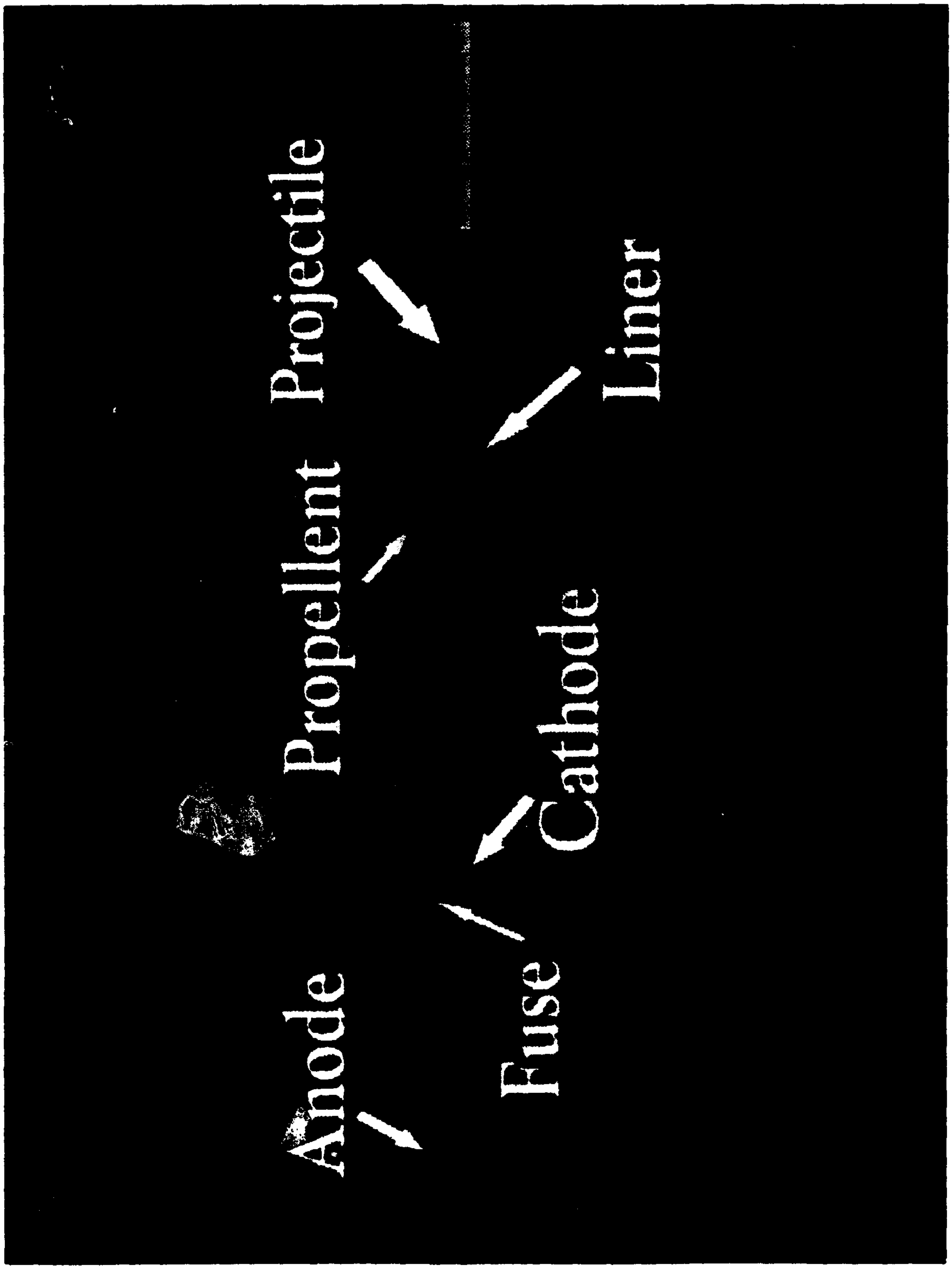


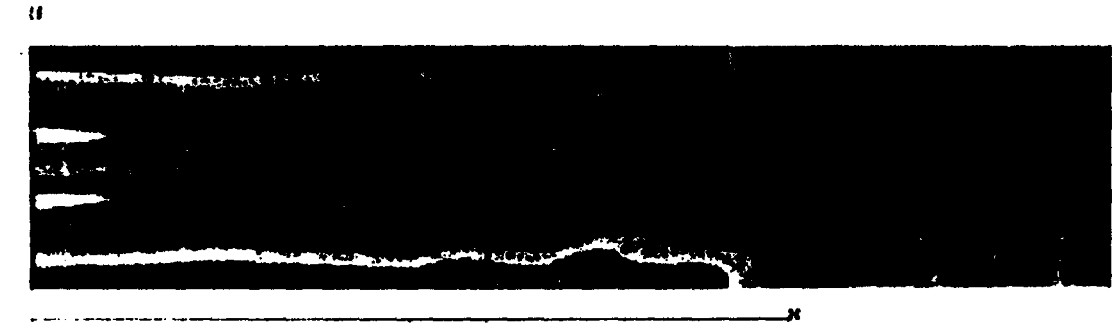
MacCormack Solution

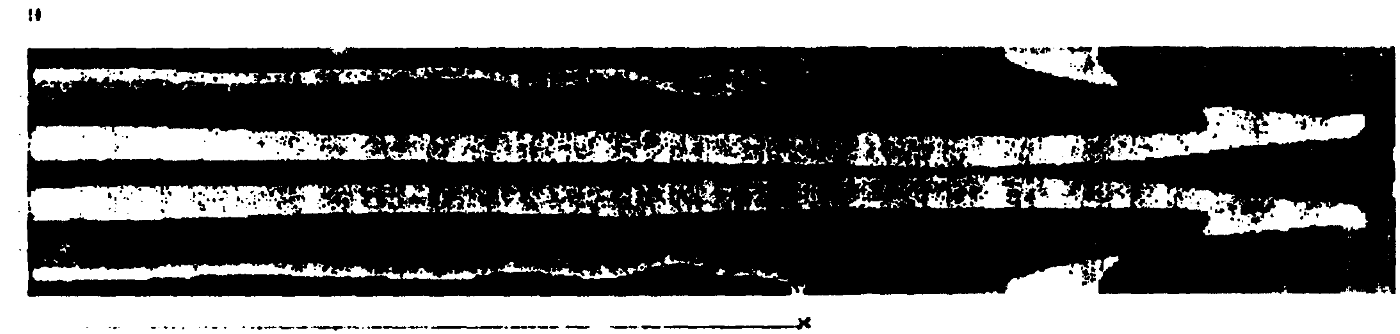
CRAFT (Roe/TVD) Solution

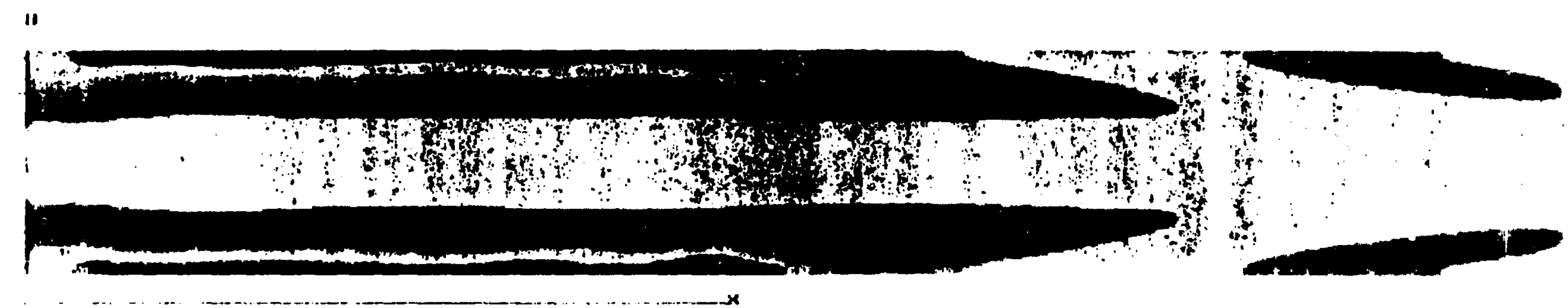


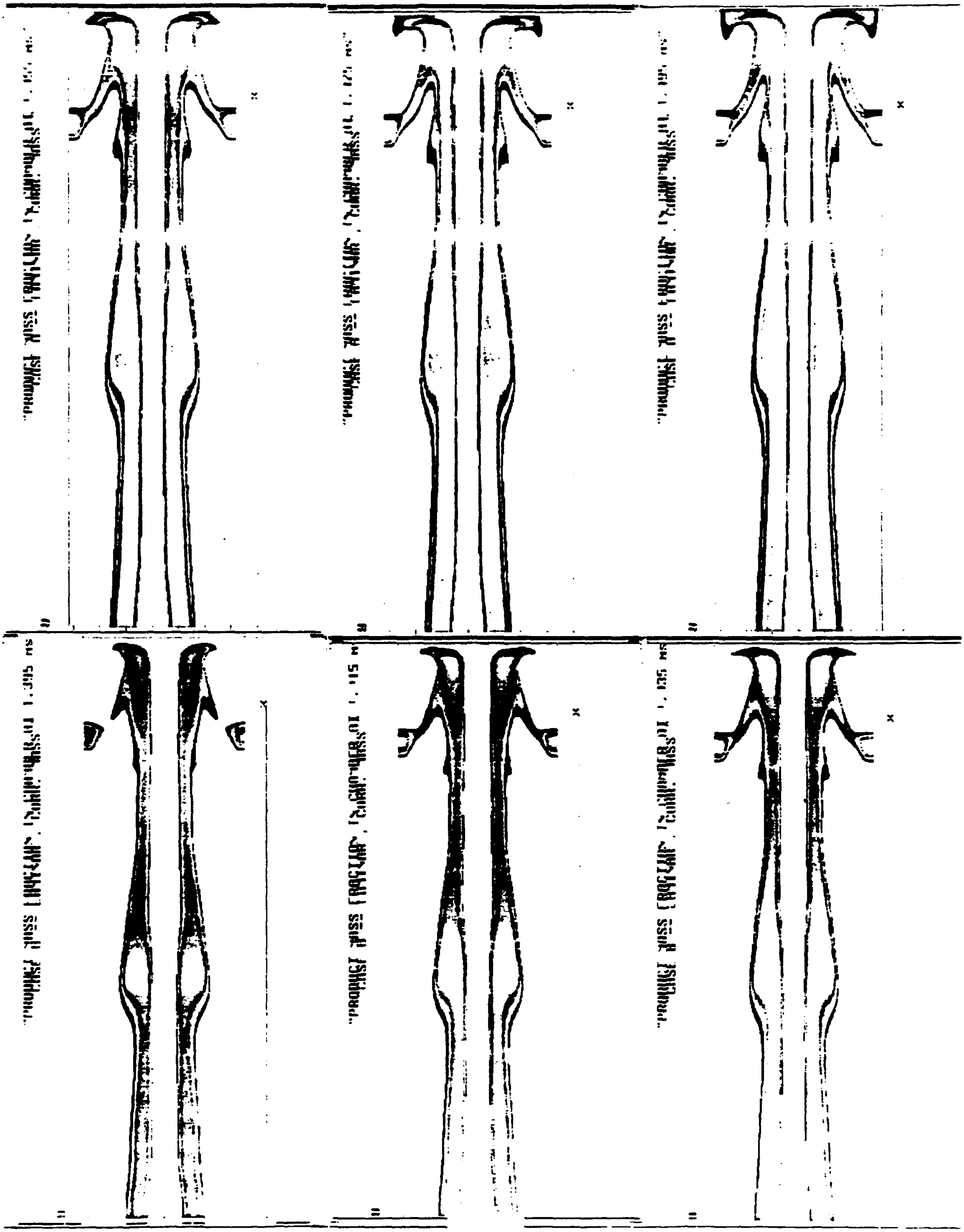



Anode
Propellent
Projectile
Fuse
Cathode
Liner



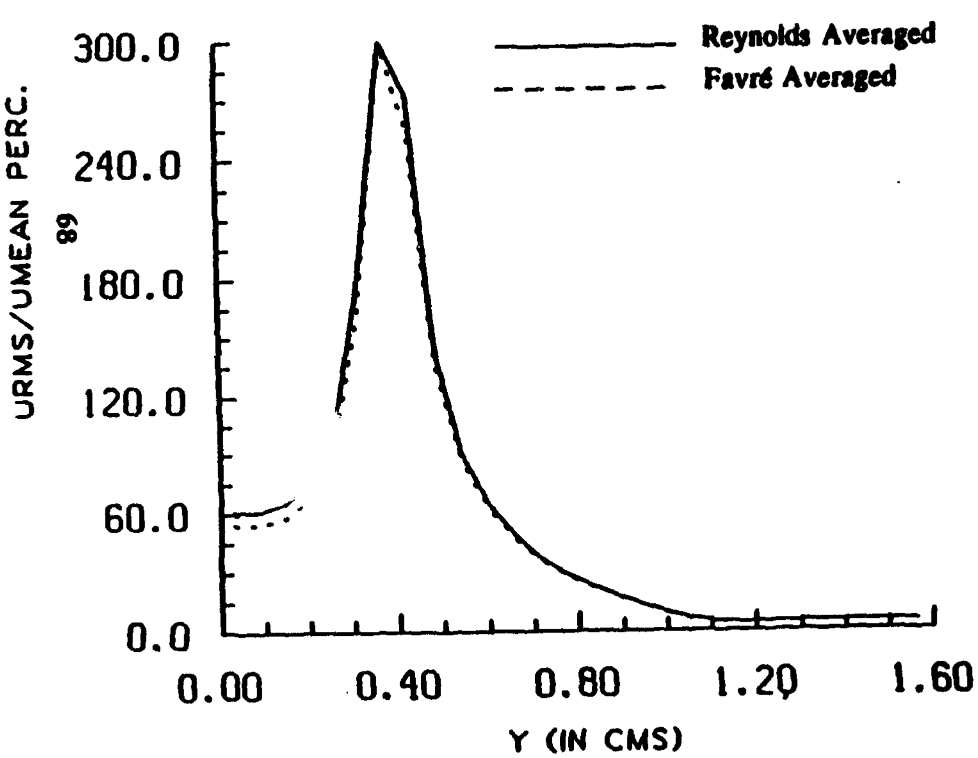




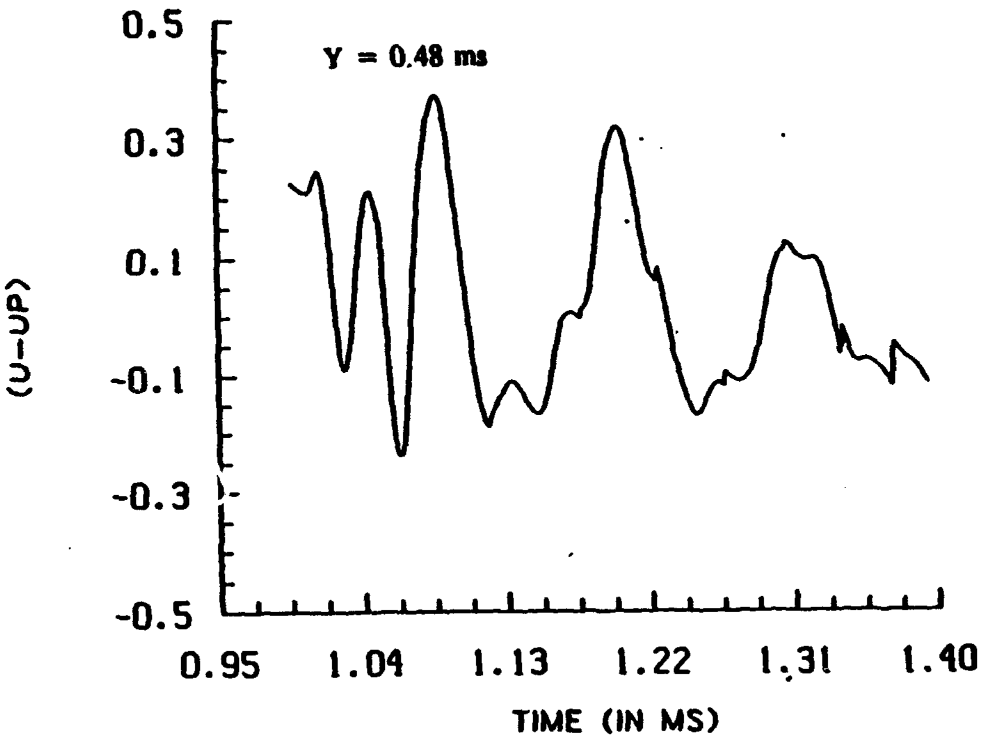


TURBULENCE CHARACTERISTICS IN ULLAGE TUBE 17.5 cms FROM PROJECTILE BASE

(A) Radial Variation of U_{rms}



(B) Instantaneous Axial Velocity at y=0.48 cms



LES vs RNS OVERVIEW / INCOMPRESSIBLE

1. DECOMPOSITION

- LES $u = \bar{u} + u'$ — $\bar{u}$ – *resolveable*; u' – *nonresoveable*

- RNS $u = \bar{u} + u'$ — $\bar{u}$ – *mean*; u' – *fluctuating*

2. AVERAGING

- LES → SPATIAL FILTER TO ELIMINATE HIGH FREQUENCY COMPONENTS

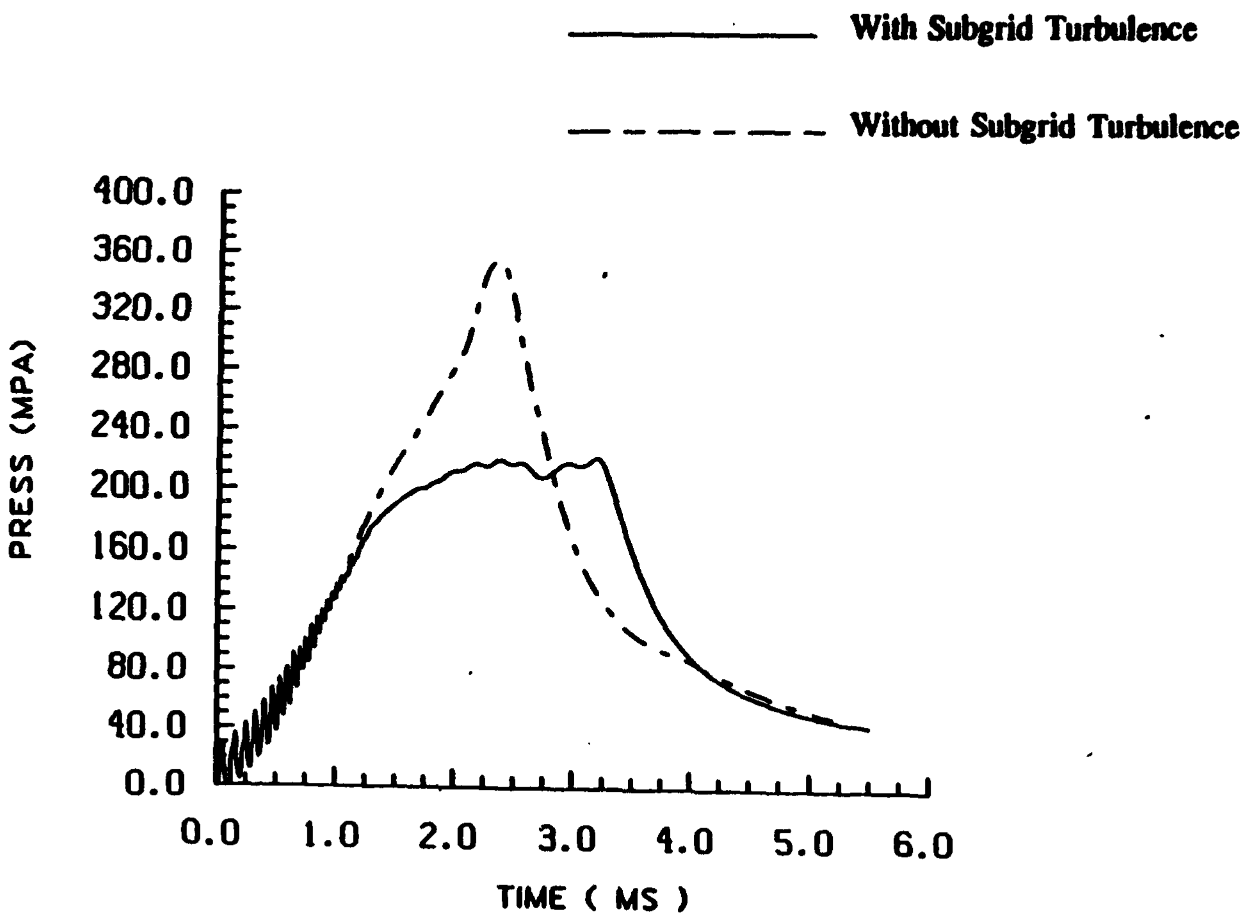
- RNS → TIME-AVERAGING, INTERVAL MUST BE LARGER THAN CONVECTIVE MOTION OF LARGE SCALE STRUCTURE; NOT APPLICABLE FOR SHORT-DURATION FLOWS

3. TERMS FROM AVERAGING

- LES $\overline{u_i' u_j'} + \left(\overline{\bar{u}_i \bar{u}_j} - \bar{u}_i \bar{u}_j\right) + \left(\overline{\bar{u}_i u_j'} - \overline{u_i' \bar{u}_j}\right)$ → INVARIANT ?

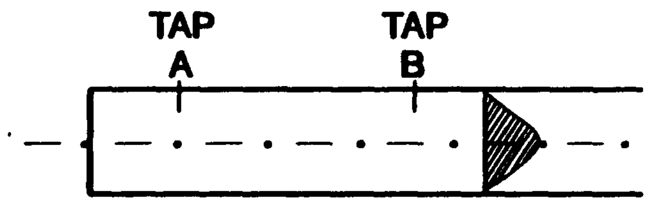
- RNS $\overline{u_i' u_j'}$ → NOT INVARIANT, COEFFICIENTS ARE PROBLEM-DEPENDENT

COMPARISON OF PRESSURE HISTORY WITH AND WITHOUT SUBGRID TURBULENCE

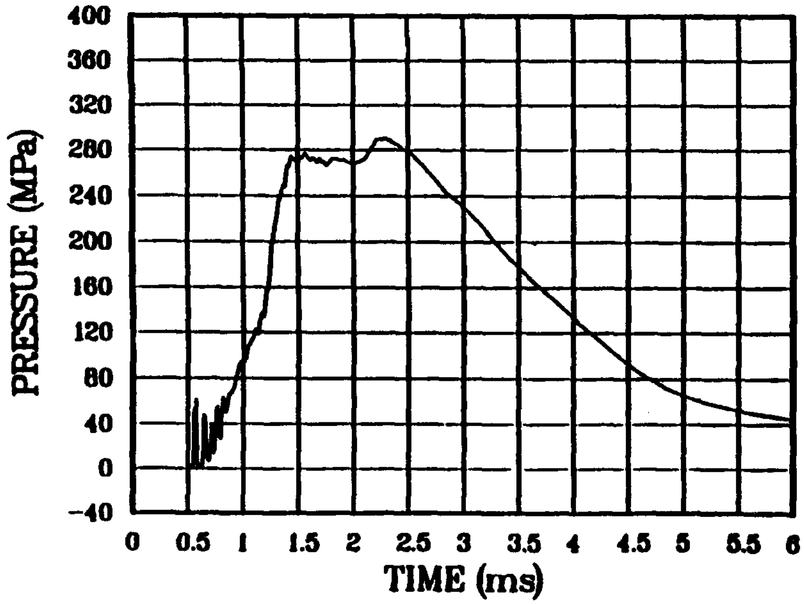


PRESSURE HISTORY AT TAP A

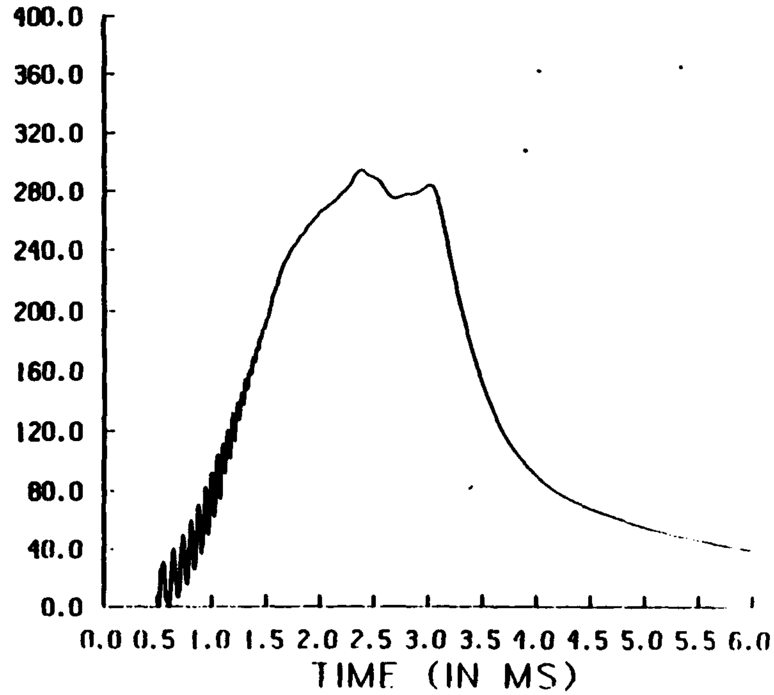
EXPERIMENTAL DATA vs NUMERICAL COMPUTATION FOR FMC SHOT 17

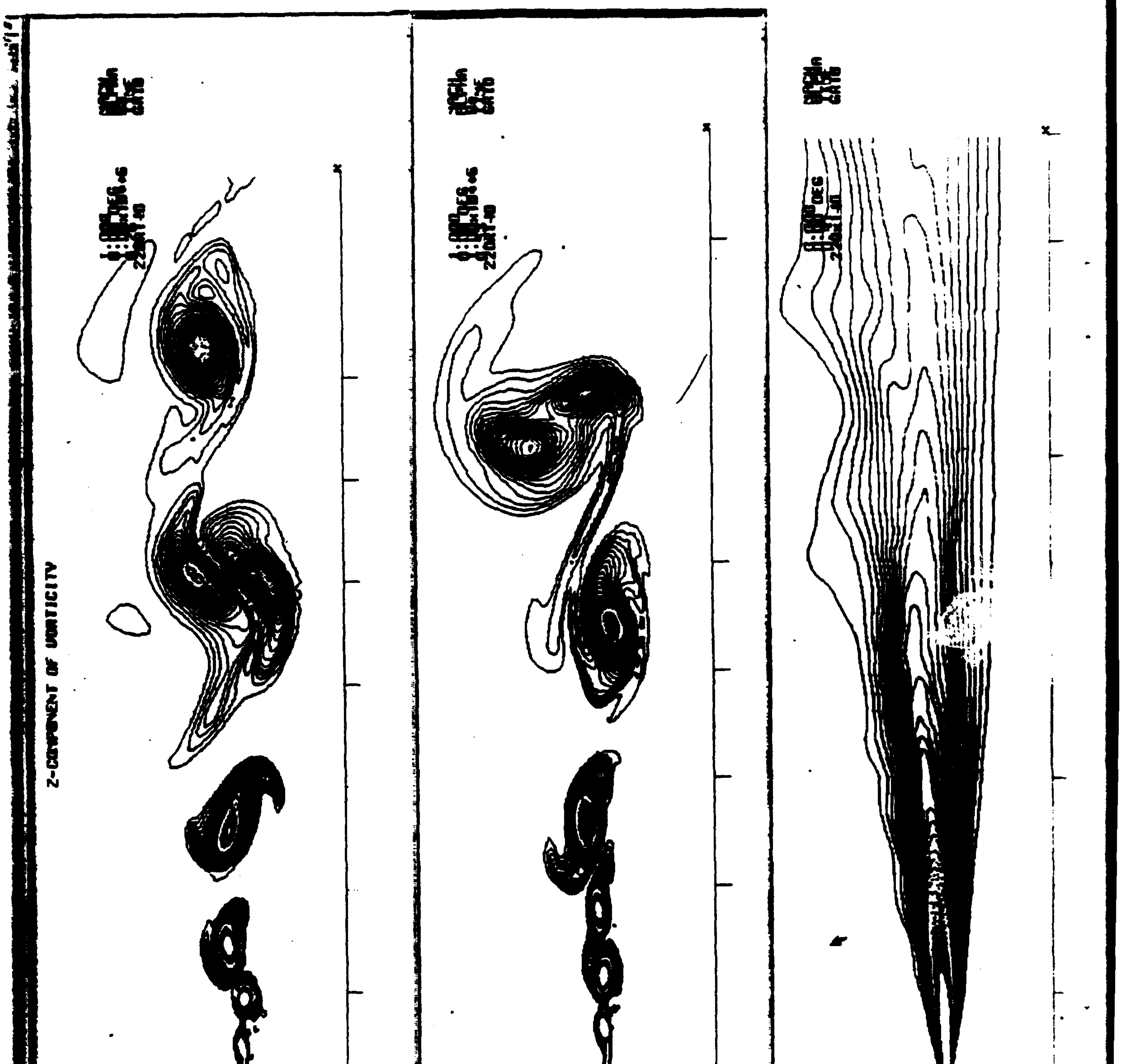


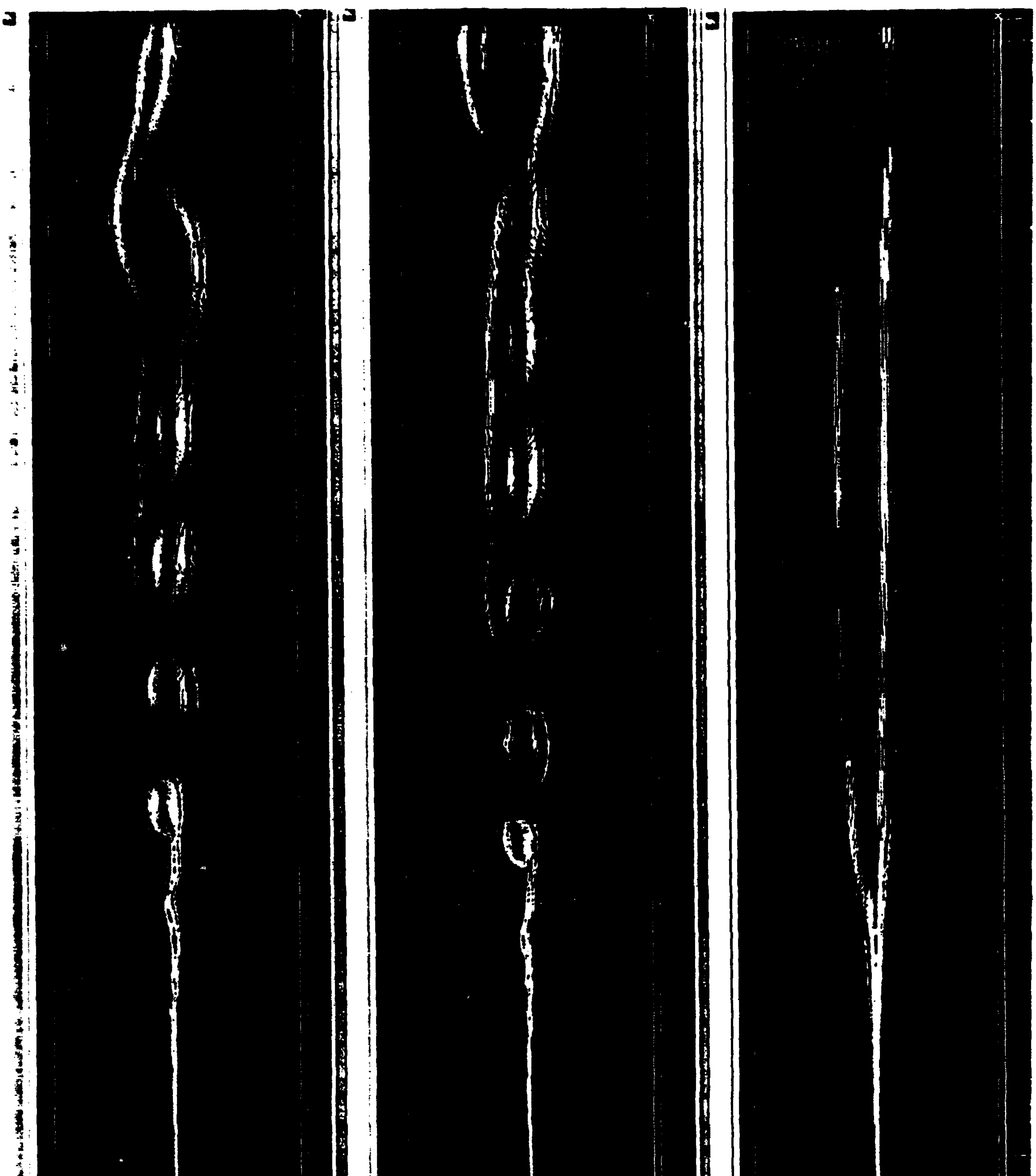
EXPERIMENTAL DATA

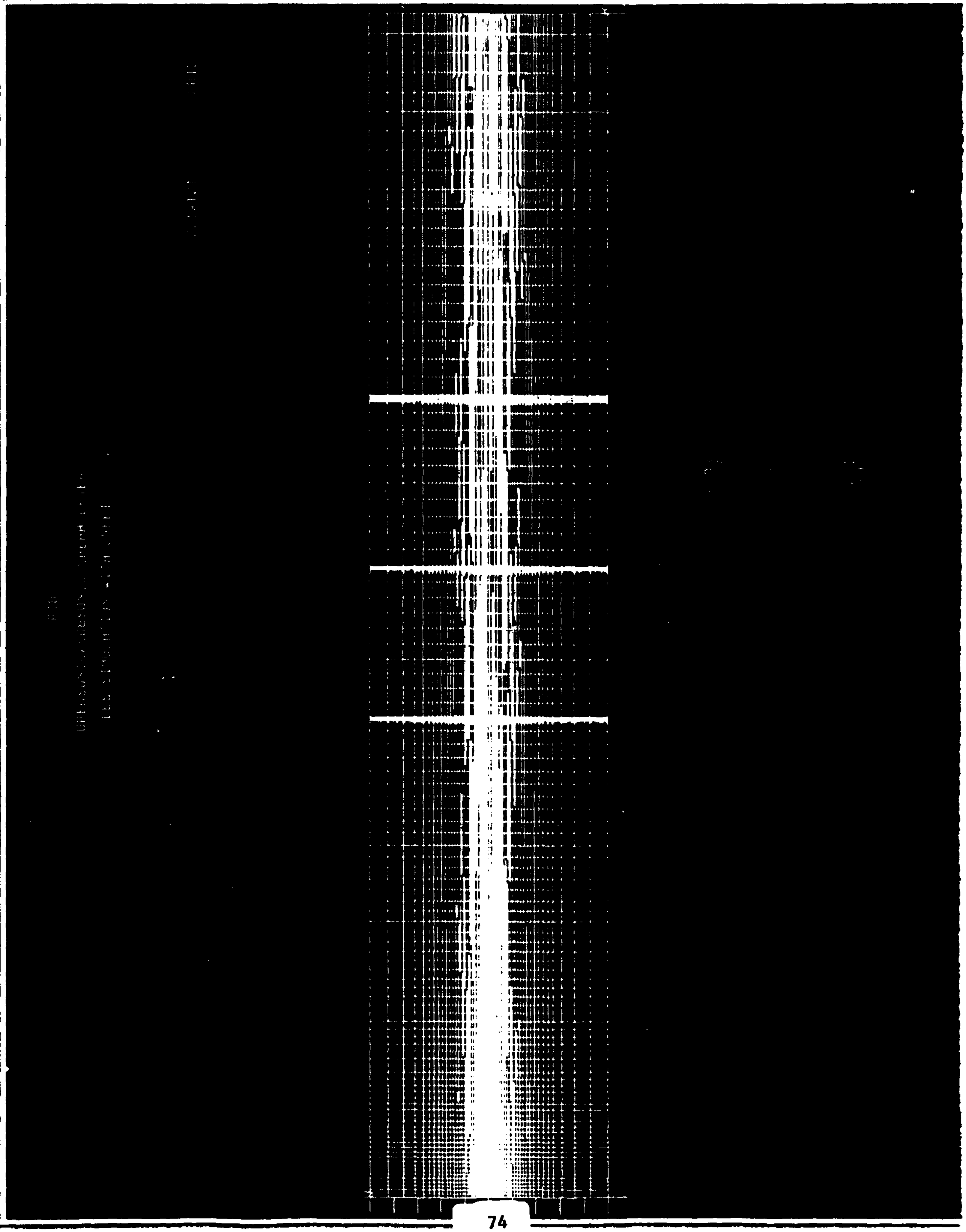


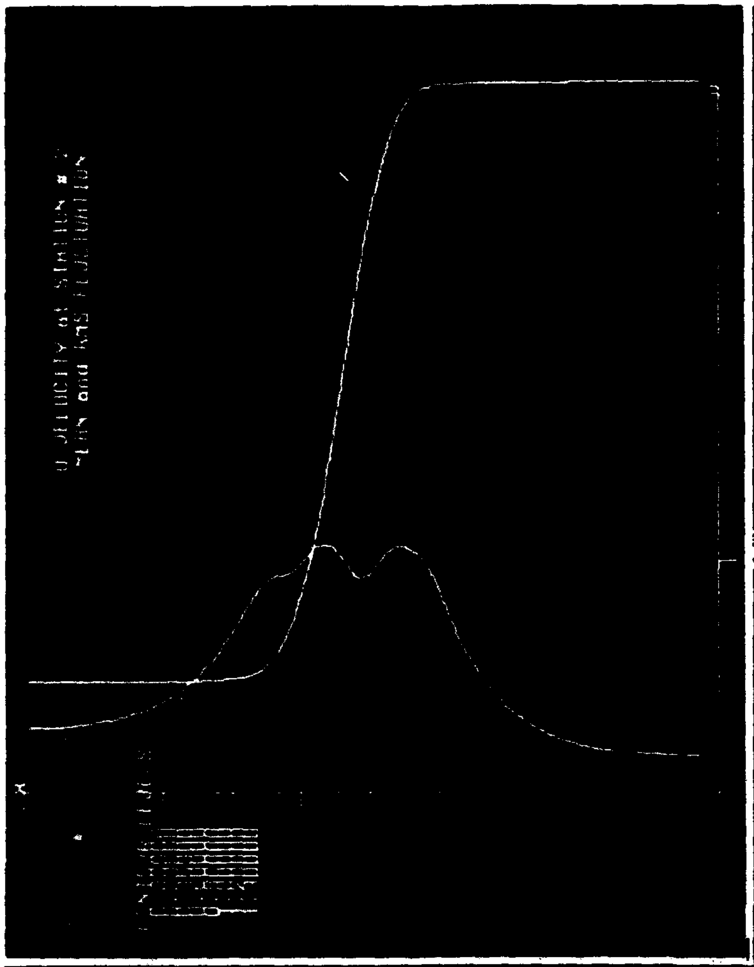
NUMERICAL COMPUTATION

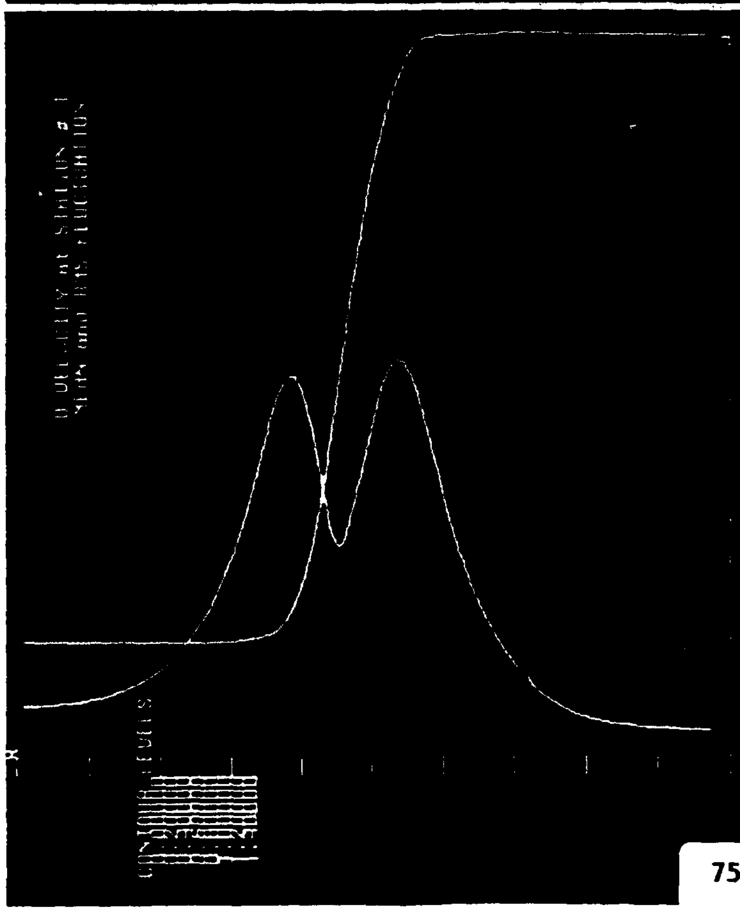


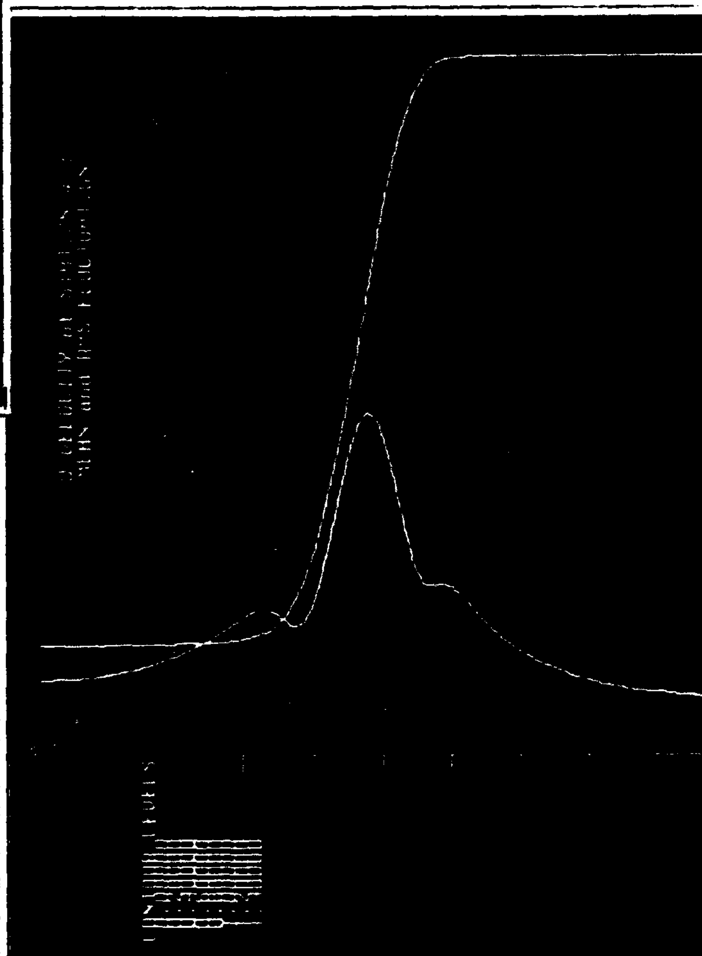

Z-COMPONENT OF VORTICITY
CONTOUR LEVELS
CONTOUR LEVELS
CONTOUR LEVELS

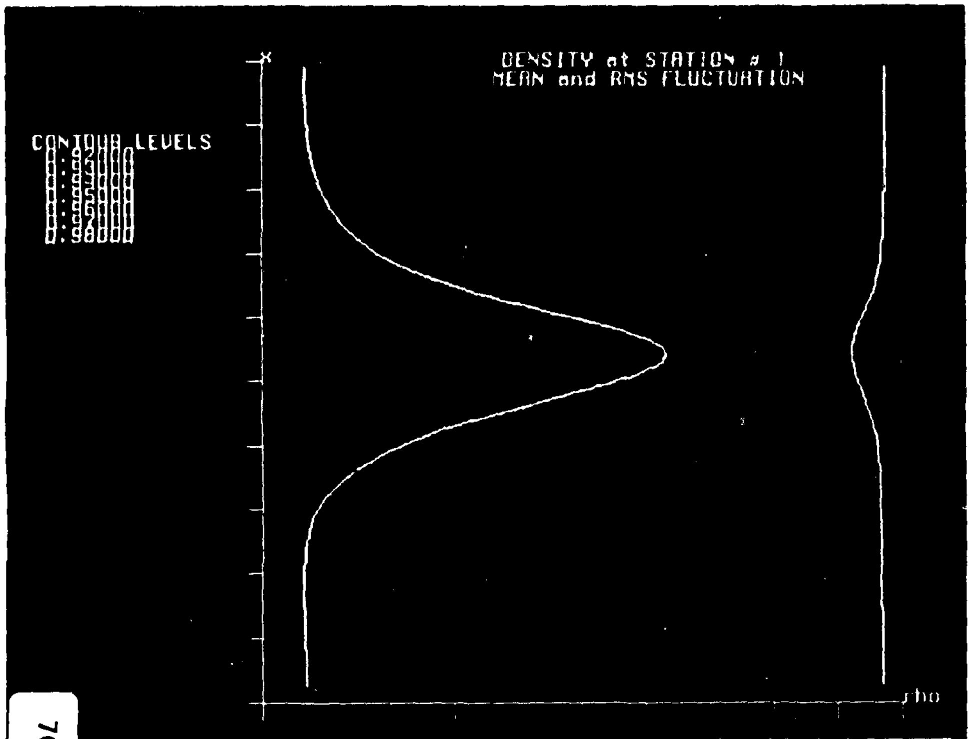


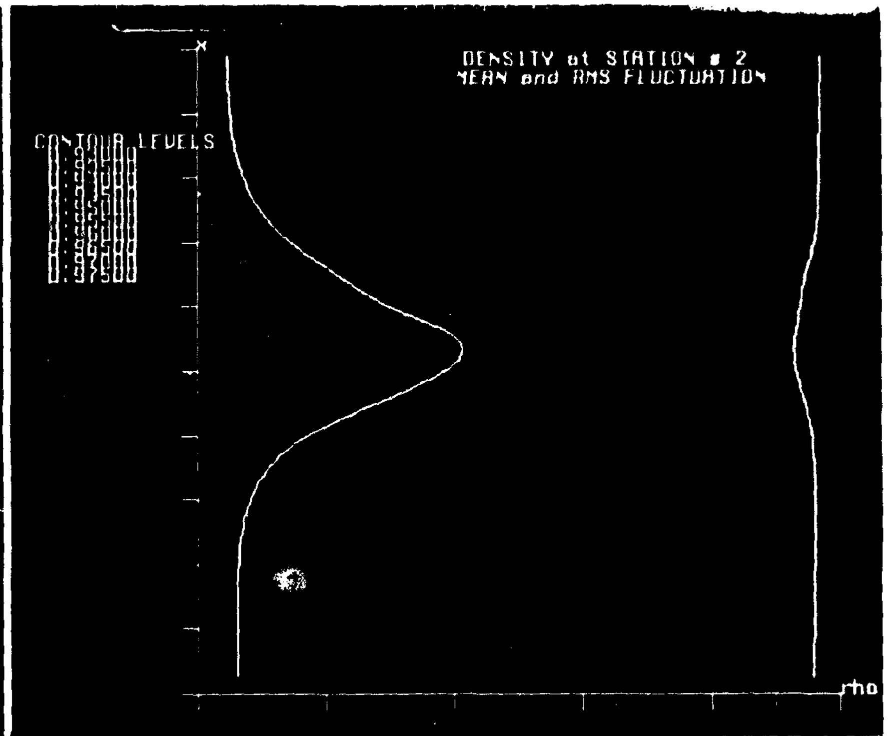


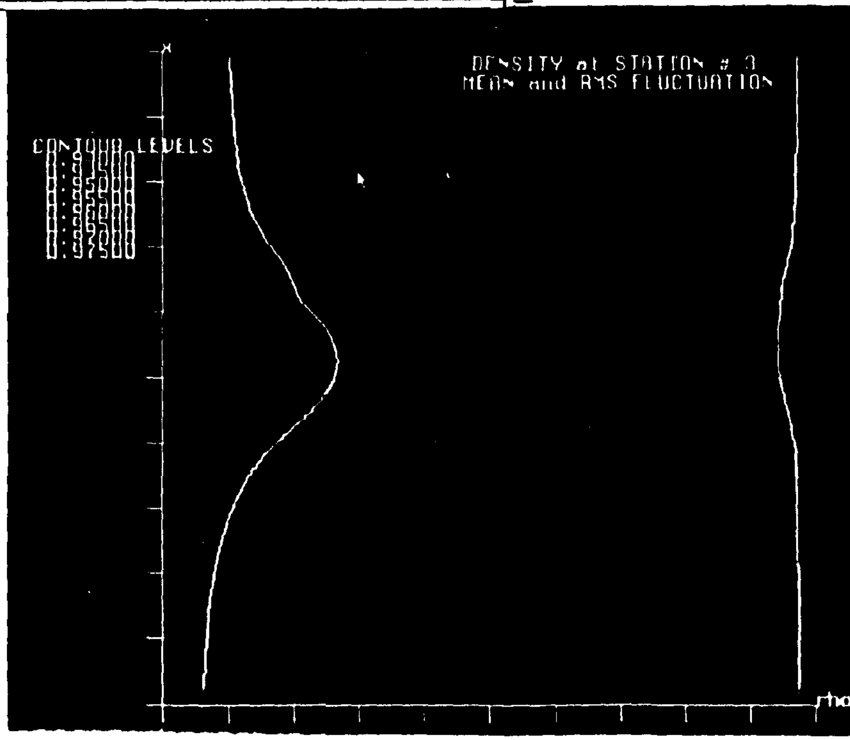




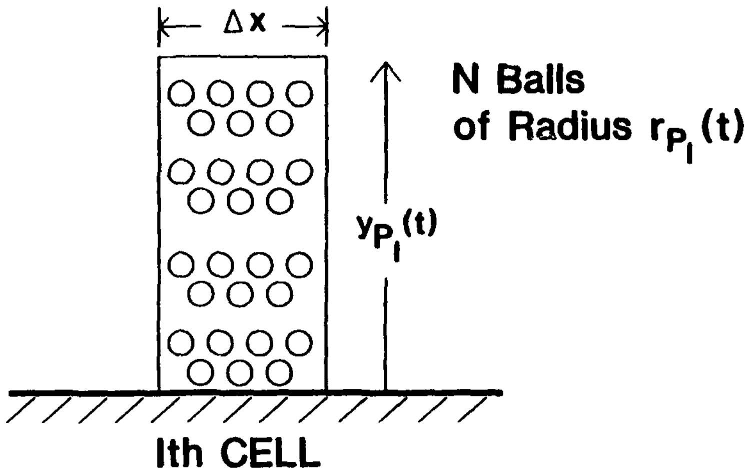



DENSITY at STATION # 1
MEAN and RMS FLUCTUATION
CONTOUR LEVELS
0.92000
0.98000
x
rho


DENSITY at STATION # 2
MEAN and RMS FLUCTUATION
CONTOUR LEVELS
0.97500
x
rho


DENSITY at STATION # 3
MEAN and RMS FLUCTUATION
CONTOUR LEVELS
0.97500
x
rho

PRELIMINARY SOLID PROPELLANT BURNING MODEL



- FIXED-BED ASSUMPTION
- ALL BALLS IN EACH CELL BURN AT SAME RATE
- $r_p(t)$ TRACKED IN EACH CELL
- PRESSURE DEPENDENT BURN RATE — EXTERNAL SURFACE PRESSURE UTILIZED WHICH VARIES AXIALLY

MASS OF PROPELLANT IN CELL = $M_P = \frac{4}{3}\pi r_p^3 \times \rho_p \times N$

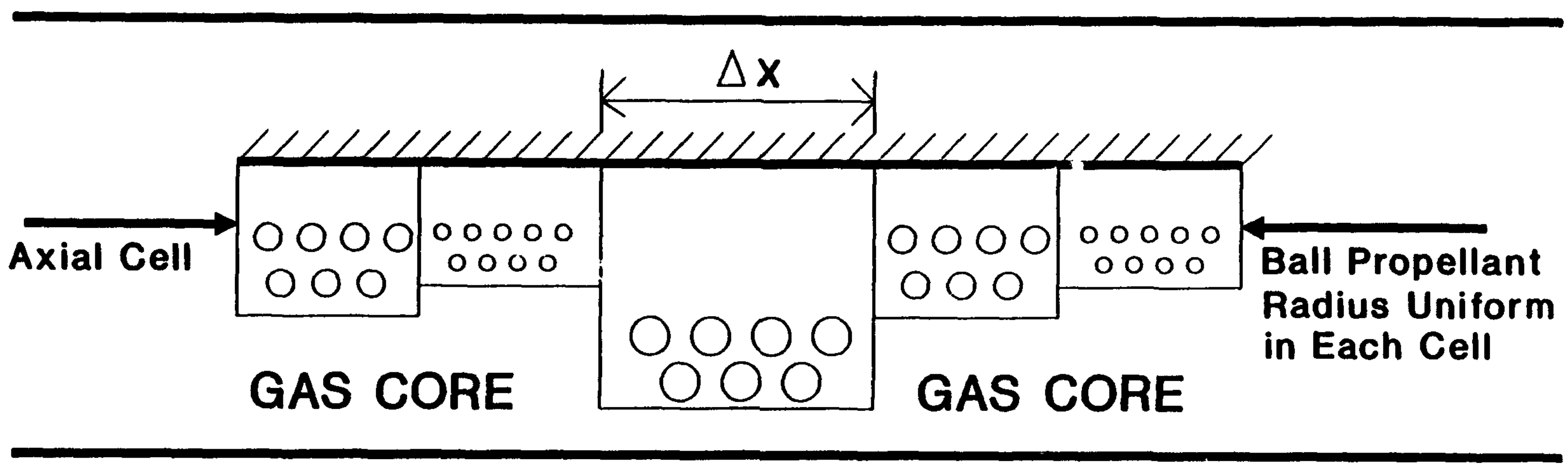
RADIUS CHANGE: $r_p \rightarrow r_p - (\dot{r})\,\Delta t$ {$\dot{r}$ function of pressure}

MASS CHANGE: $\dot{m} = (4\,\pi\, r_p^2)\,\dot{r}\,\rho_p \times N$

REGRESSION VELOCITY: $V_S = \frac{\dot{m}}{\rho L}$ {ρL is loading density}

COMBUSTION PRODUCT FLUX: $\rho_g\, V_g = \rho_L\, V_S$

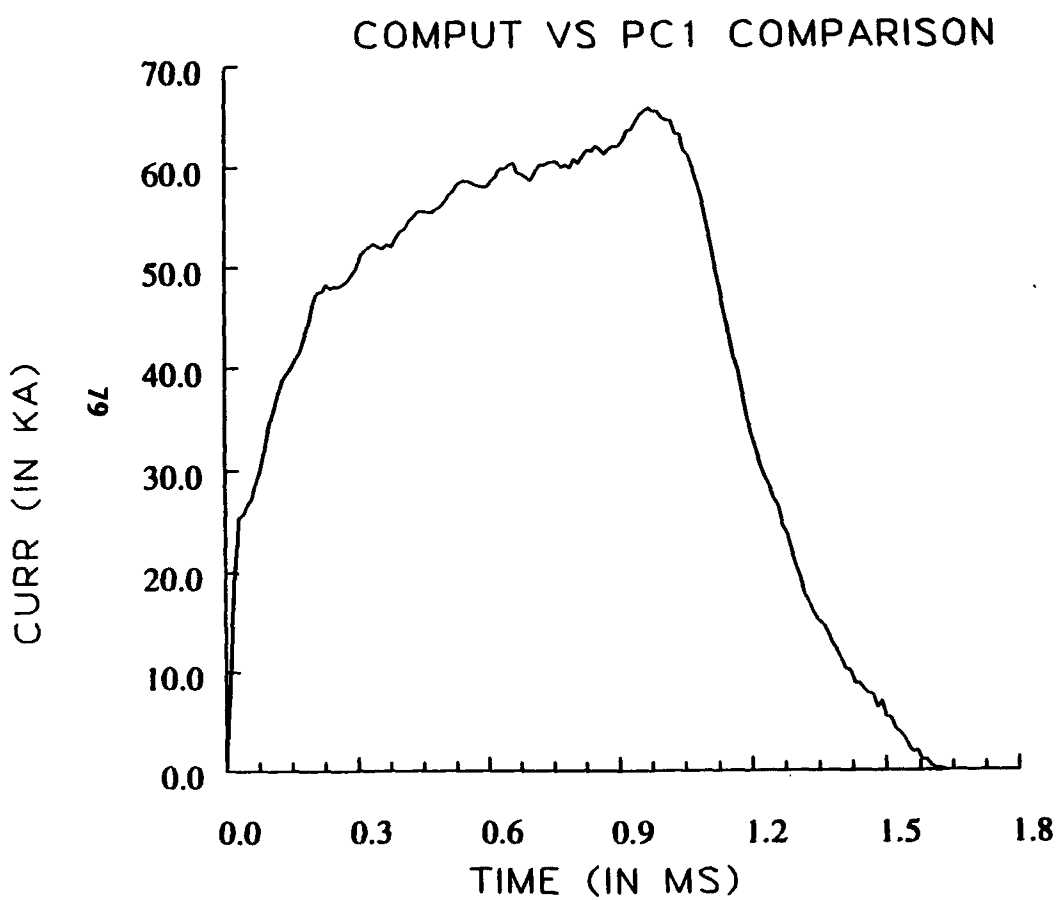
COUPLING OF SOLID PROPELLANT BURN MODEL INTO CRAFT



- BURNING RATE FUNCTION OF LOCAL SURFACE PRESSURE
- GASEOUS PRODUCTS MASS AND ENERGY FLUXES FROM SOLID PROPELLANT SERVE AS BOUNDARY CONDITIONS
- DYNAMIC MOTION OF RECESSING SOLID PROPELLANT ACCOUNTED FOR

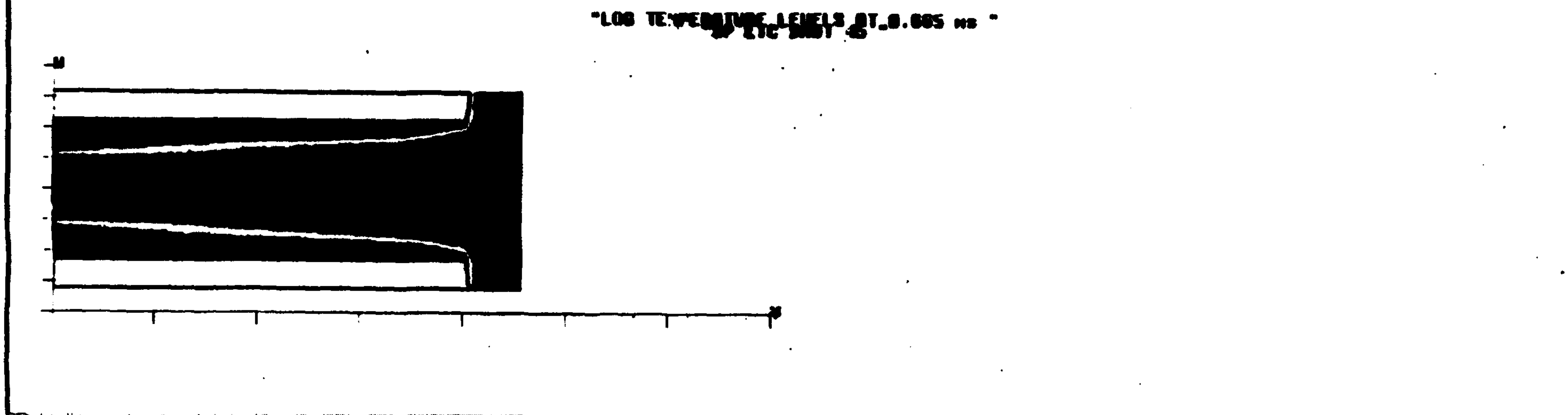
GDLS SHOT 45 INPUT DATA

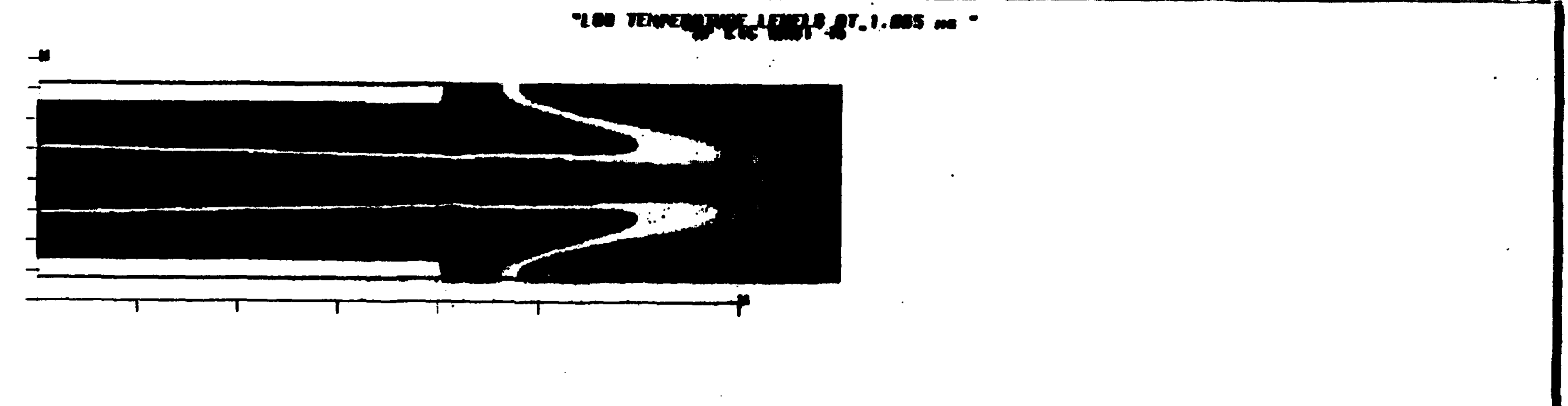
CURRENT HISTORY

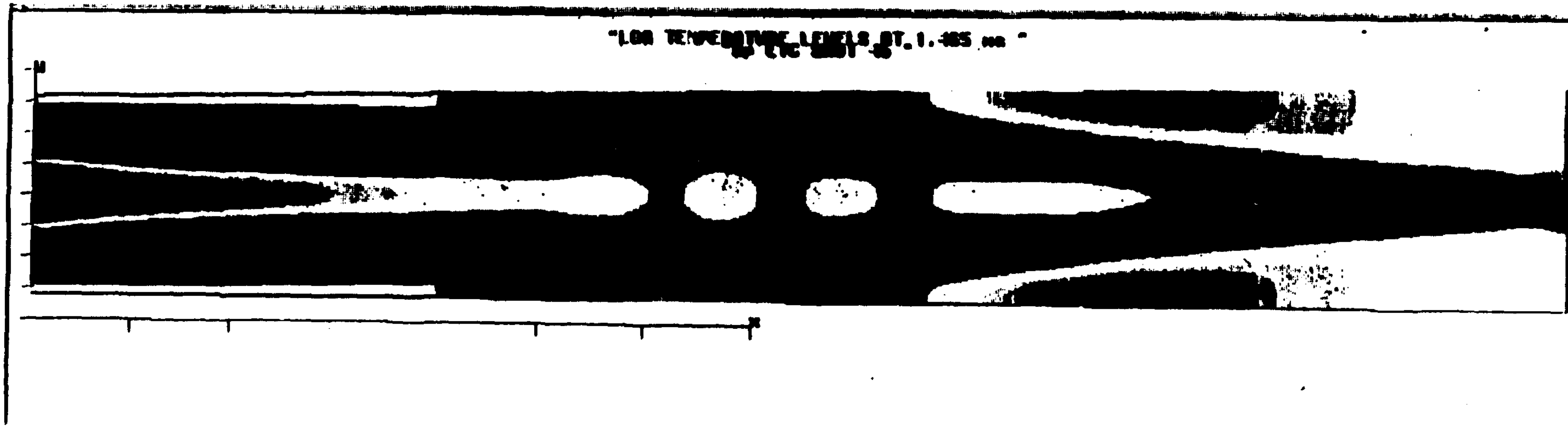


15 LAYER THERMOCHEMISTRY

% of Radius	Flame Temperature (K)


"LOG TEMPERATURE LEVELS AT 0.005 ns"

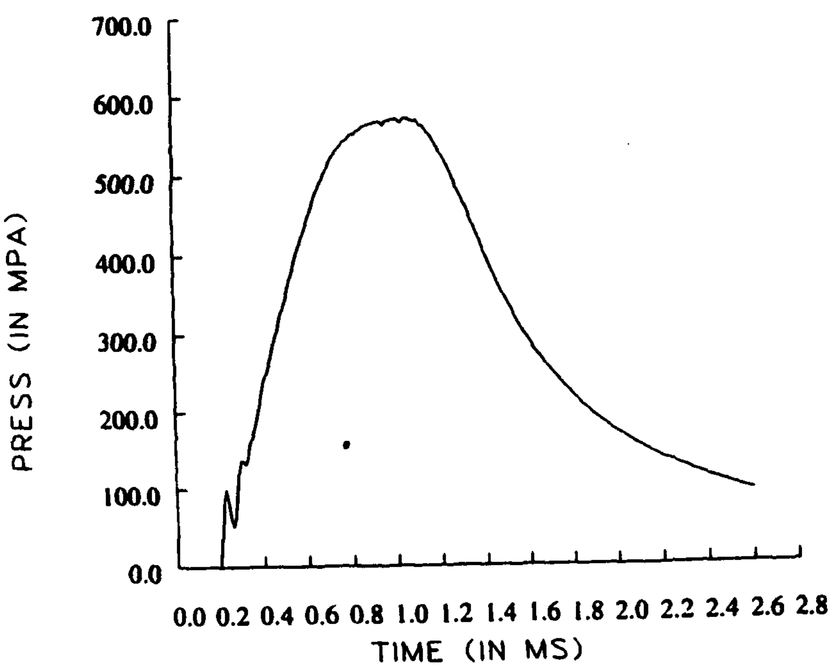

"LOG TEMPERATURE LEVELS AT 1.005 ns"


"LOG TEMPERATURE LEVELS AT

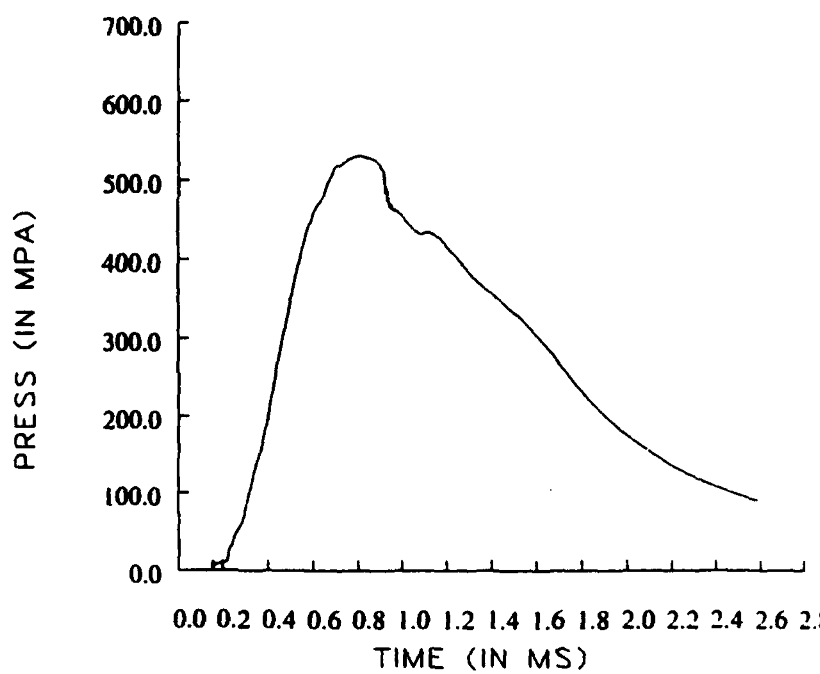
GDLS SHOT 45

PRESSURE HISTORY COMPARISON AT PORT 1

EXPERIMENTAL PRESSURE



COMPUTED PRESSURE



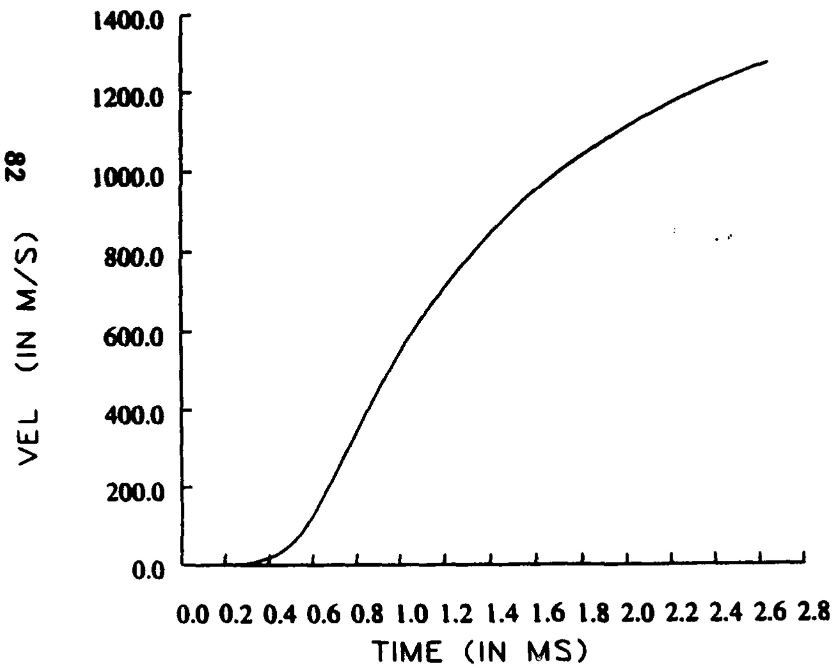
GDLS SHOT 45

PROJECTILE DYNAMICS vs TIME

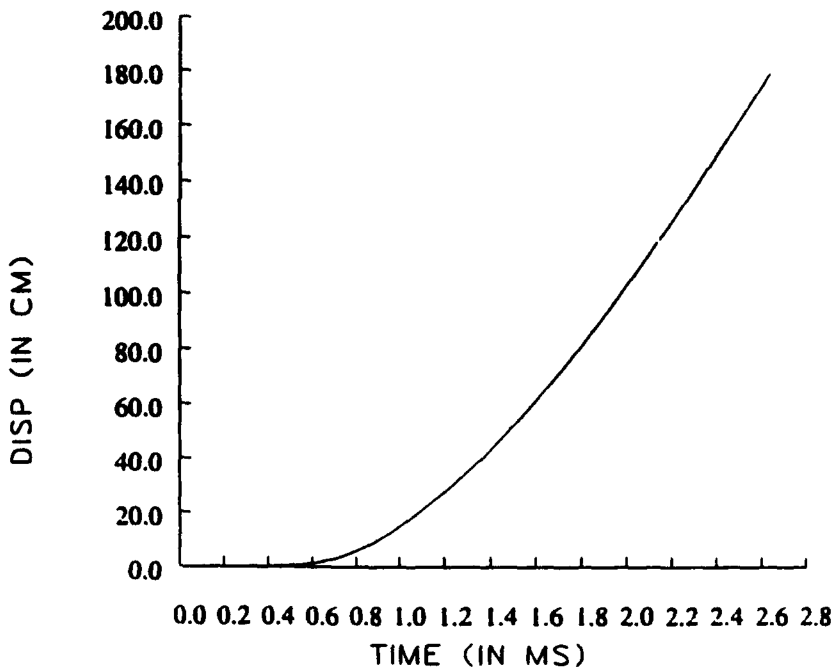
EXPERIMENTAL EXIT VELOCITY AT 130.5 cm = 1170.0 m/s

NUMERICAL EXIT VELOCITY AT 130.5 cm = 1183.75 m/s

VELOCITY

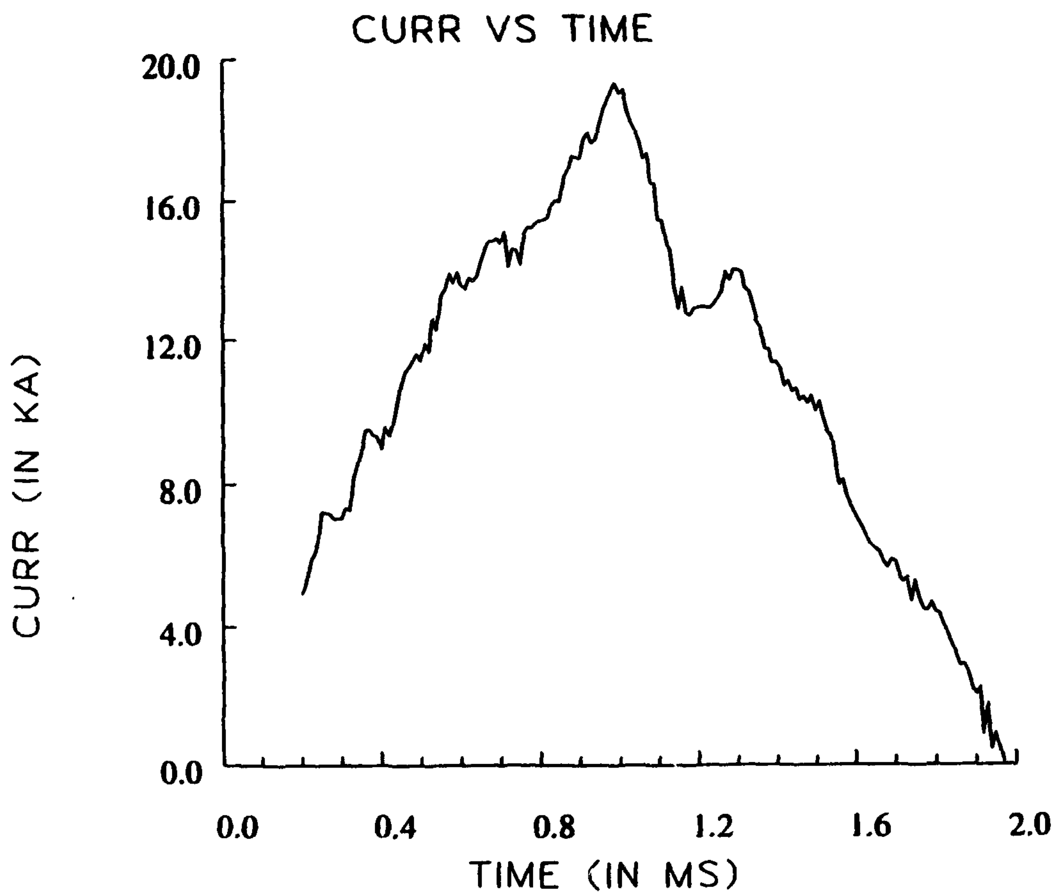


DISPLACEMENT



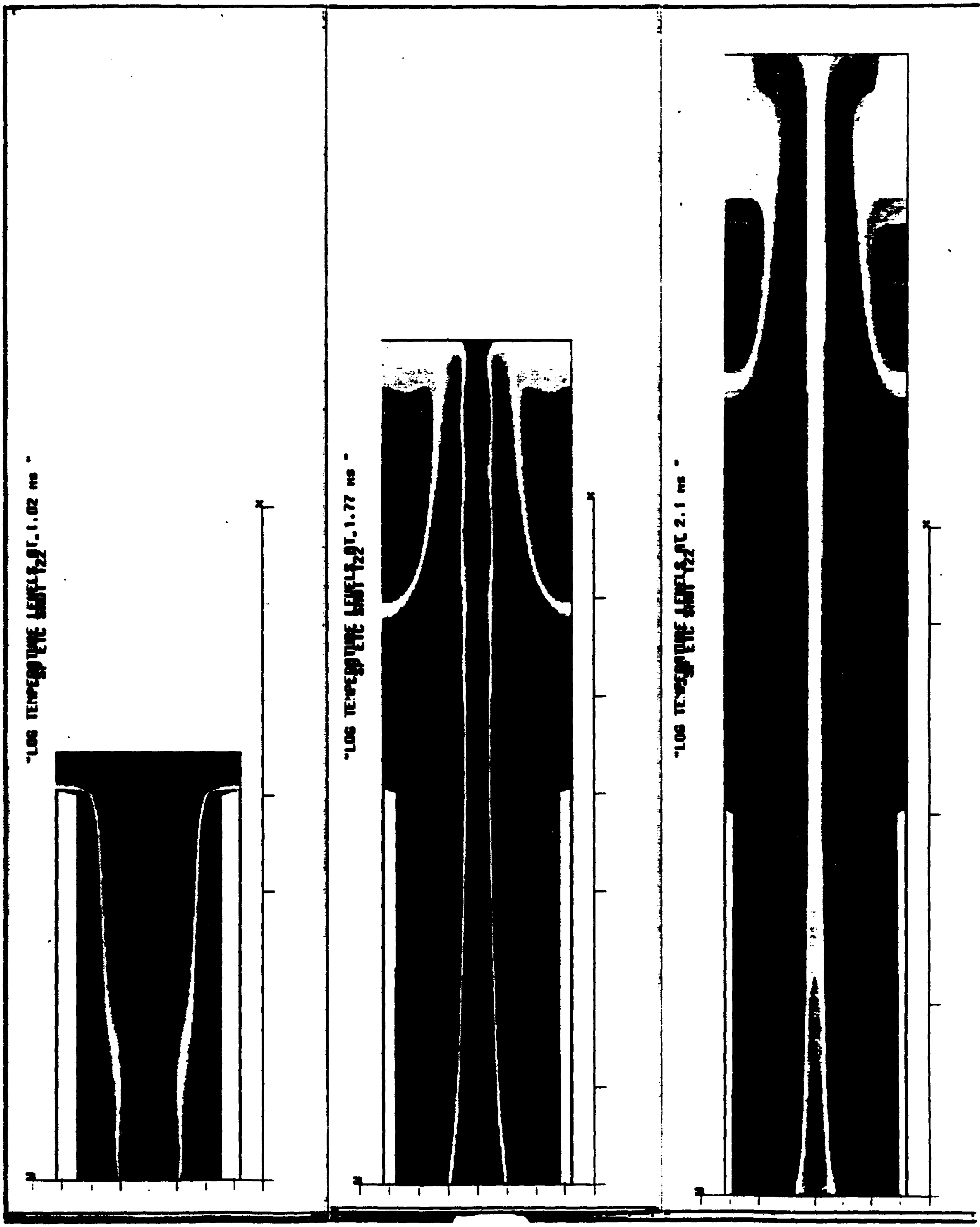
GDLS SHOT 122 INPUT DATA

CURRENT HISTORY



7 LAYER THERMOCHEMISTRY

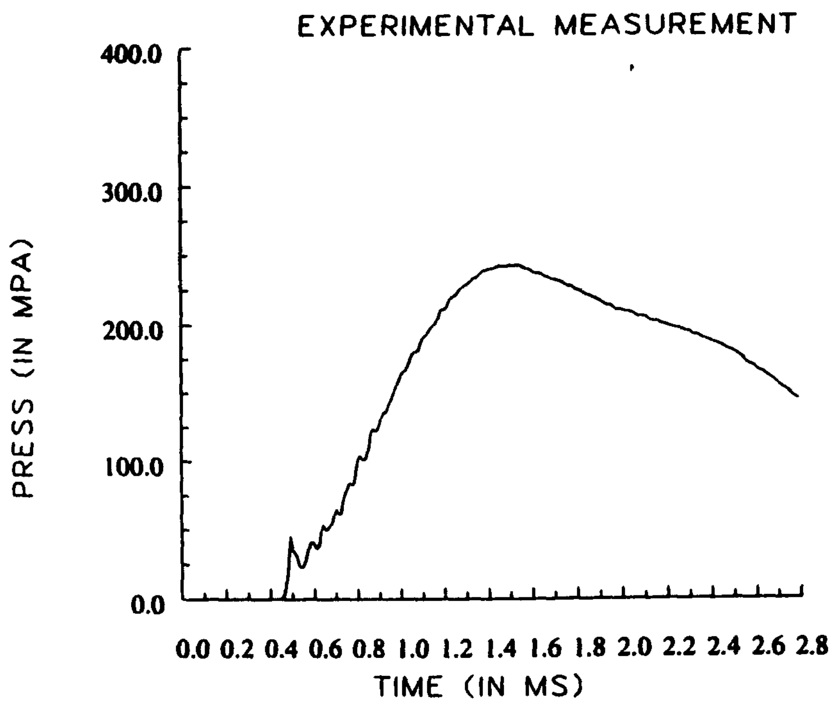
% of Radius	Flame Temperature (K)


"LOG TEMPERATURE LEVELS AT 1.02 ns"
SHOT 122
"LOG TEMPERATURE LEVELS AT 1.77 ns"
SHOT 122
"LOG TEMPERATURE LEVELS AT 2.1 ns"
SHOT 122

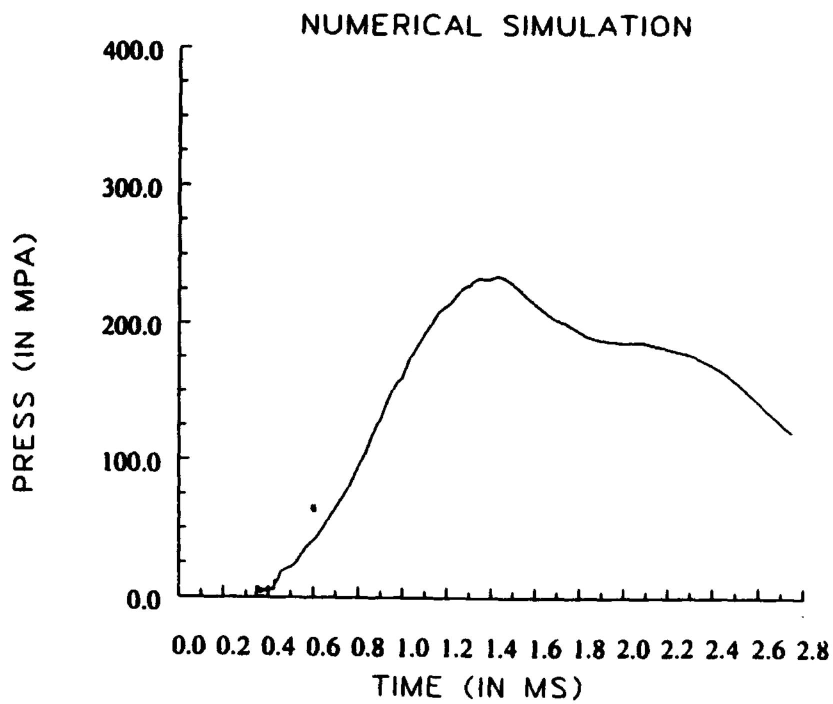
GDLS SHOT 122

PRESSURE HISTORY COMPARISON AT PORT 1

EXPERIMENTAL PRESSURE



COMPUTED PRESSURE



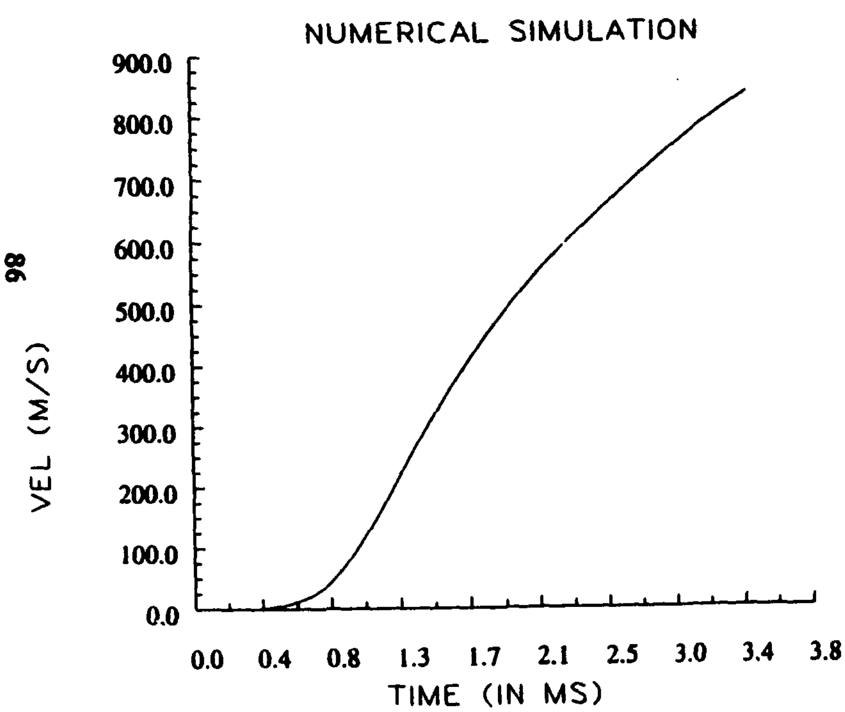
GDLS SHOT 122

PROJECTILE DYNAMICS vs TIME

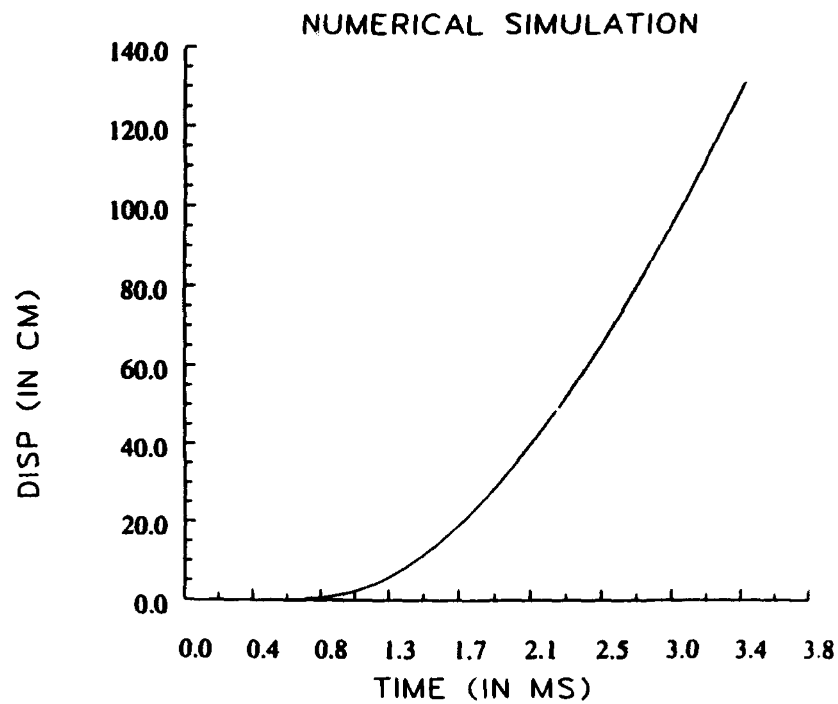
EXPERIMENTAL EXIT VELOCITY AT 130.7 cm = 857 m/s

NUMERICAL EXIT VELOCITY AT 130.7 cm = 837 m/s

VELOCITY



DISPLACEMENT



FUTURE DIRECTION

LP/ETC — PLASMA/WORKING FLUID INTERFACE

- DROPLET FORMATION/CONVECTION/COMBUSTION
- EULERIAN PARTICLE SOLVER OPERATIONAL IN CRAFT
- STRONG NONEQUILIBRIUM COUPLING
- VOLUMETRIC CONTRIBUTIONS

SP/ETC — FLUIDIZED BED/PARTICLE EROSION

- PARTICLE CONVECTION/COMBUSTION
- LAGRANGIAN PARTICLE SOLVER OPERATIONAL IN CRAFT

INTENTIONALLY LEFT BLANK.

Transient, Two-Dimensional Numerical Model of Plasma Behavior in an ETC Capillary

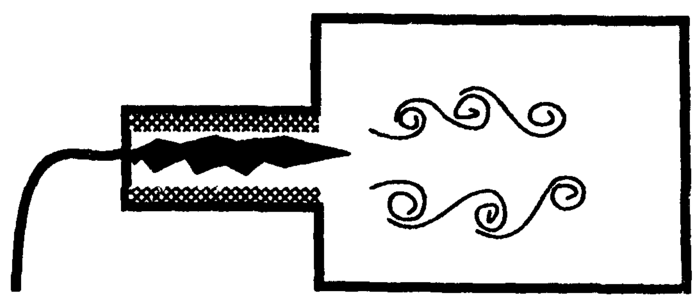
S. N. Kempka, M. W. Glass, D. A. Benson, D. W. Kuntz, G. F Homicz
Sandia National Laboratories
Fluid and Thermal Sciences Department
Albuquerque, NM

Work sponsored by Army Research Laboratory
ARL contact: Gloria Wren

Sandia National Laboratories

ETC Objectives/Issues

- ETC Propulsion Objective: Initiate and **control** combustion with a plasma
  - use a strong, sustained plasma jet to avoid LP combustion instabilities
  - plasma flow provides significant mixing during combustion process
  - control combustion by electrically controlling plasma discharge
- Issue: Lack of repeatability
  - is plasma behaving as expected?



Overview

Sandia National Laboratories

Engineering Sciences Center

- General Approach: Combined experimental and modelling effort
  - non-combustion capillary discharge (SNL experiments)
- Review of Plasma Phenomena
- Motivation for multi-dimensional, transient model
- Phenomenological models
  - turbulence
  - ablation
  - thermal radiation
  - electrical power dissipation: electric field, electrical conductivity
  - plasma initiation
- Demonstration calculation: simulation of SNL experiment ET038

Modelling Focus: Plasma Nonuniformities

Sandia National Laboratories

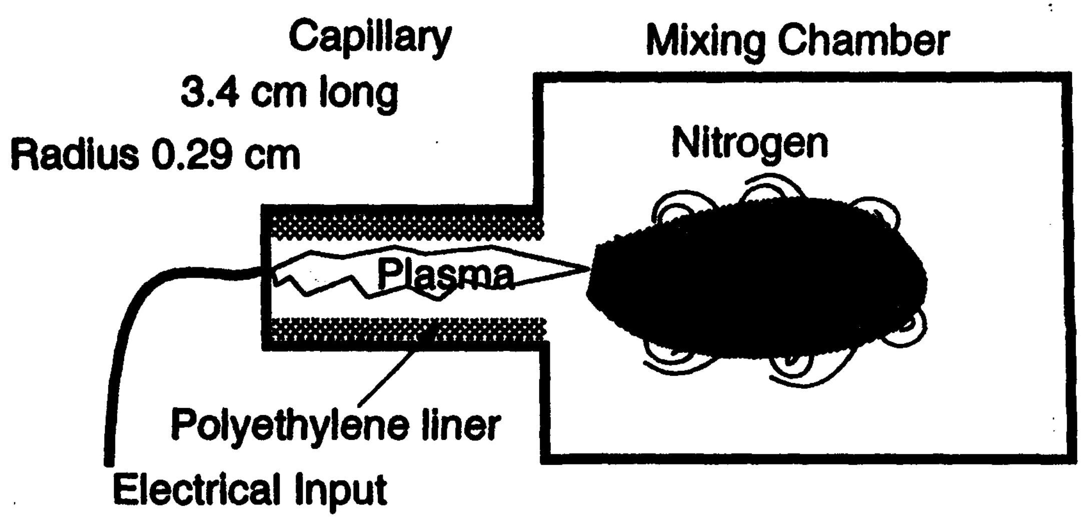
Engineering Sciences Center

- Modeling Objective: Do plasmas behave as expected? (~ isothermal?)
  - Non-uniformity not unlikely in a positive feedback system:
    ohmic deposition increases with increasing temperature
  - Evidence of plasma non-uniformities:
    throughput limit, repeatability problems, 1D model
- Importance of plasma behavior on ETC Performance:
  - Power dissipation: controls plasma flow rate
  - Scaling: relationship of small-scale data to large-scale performance

SNL Capillary Discharge Experiments

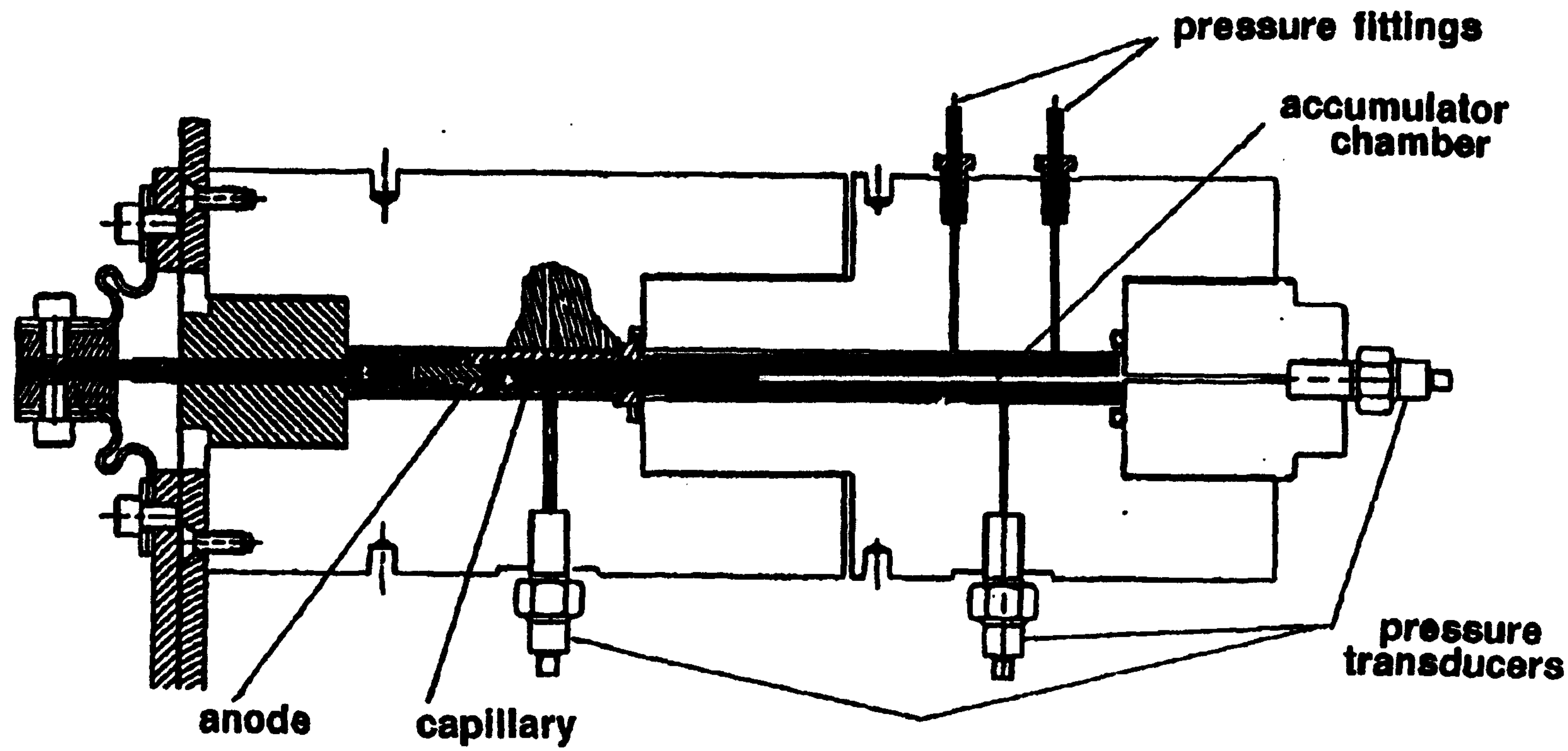
Sandia National Laboratories

Engineering Sciences Center



- pulsed power system charged to 4.0 kV, 3.2 kJ stored energy
- system pre-pressurized to 1000 psi, nitrogen - no propellant
- ablating polyethylene capillary liner

Experimental Setup

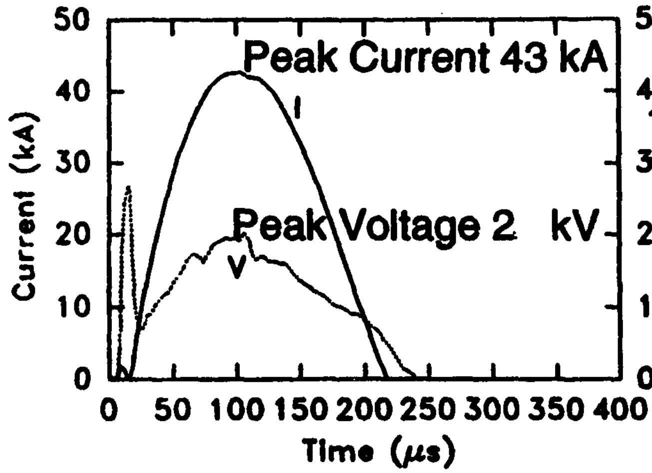


Capillary Discharge Data

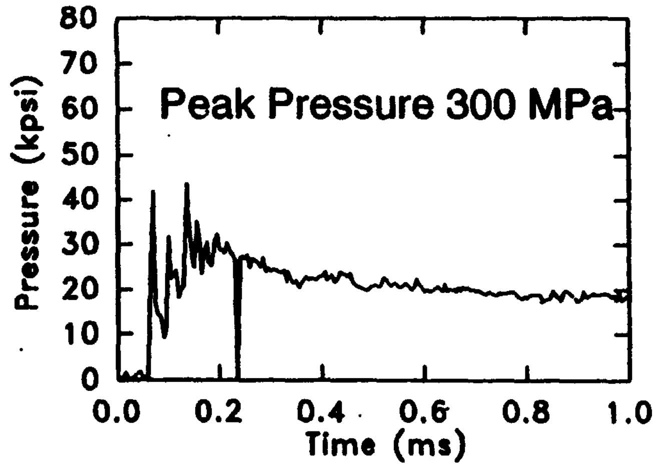
Engineering Sciences Center

Sandia National Laboratories

Capillary Current and Voltage vs Time



Capillary Pressure vs Time

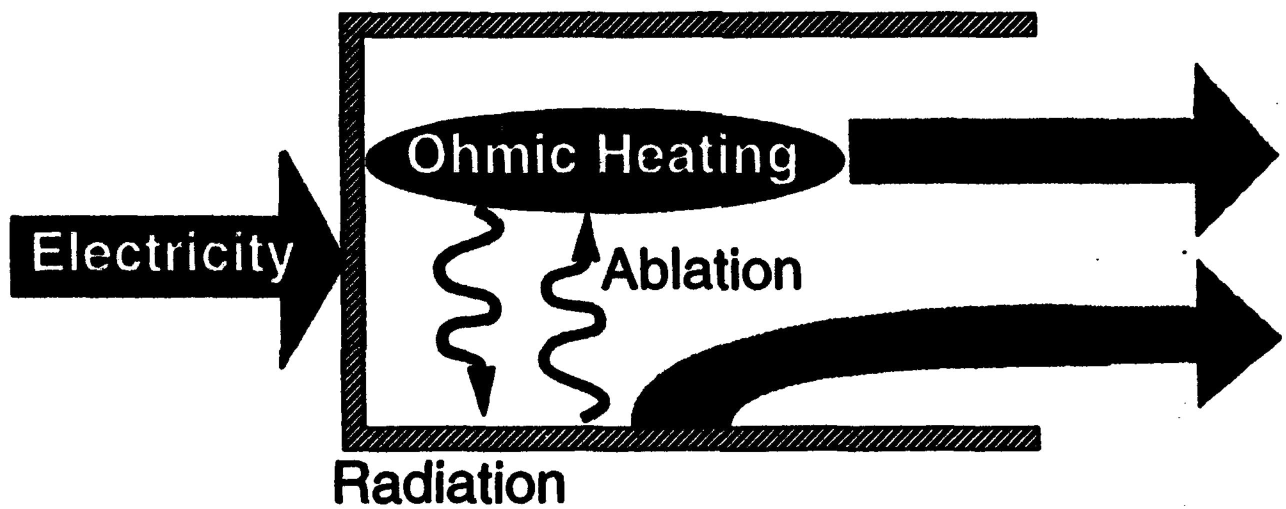


- Duration: ~ 200 µs, peak current occurs at 100 µs
- Mass of ablated polyethylene: 122 mg

Energy Transformation in an ETC Capillary

Sandia National Laboratories

Engineering Sciences Center



- Electrical energy in = convective flow out

Motivation for 2D Transient Model

Sandia National Laboratories

Engineering Sciences Center

- Why 2D?
  - plasma flow from capillary into mixing chamber is 2D
    - 2D Hydrodynamic coupling between capillary and mixing chamber
  - electric field and electric current could be 2D

- Why transient?
  - assess assumption of steady-state: does it exist?
  - ablation rates are transient: only time-averaged rate data available

- Reduce reliance on experimental data in simulations
  - 1D models require Pressure, Electric Field, Current specifications
  - developing 2D model to require only voltage data

Model Description

- Gas species, including dissociation and ionization
  - $C, C^+, C^{++}, H, H^+, N_2, N, N^+$
  - Saha equations for ionization
  - Lighthill dissociation model for nitrogen
- Conservation equations: compressible mass, momentum, energy
- *Ohmic heating due to transient applied voltage difference*
  - 2D Electric field based on transient voltage data
  - plasma electrical conductivity: ion-electron, neutral-electron terms
- Radiative transport: Method of Discrete Ordinates
  - Zel'dovich and Raizer model for gas absorptance
- Ablation of polyethylene
- Ideal Gas Equation of State

Governing Equations

- Mass Conservation for species i=C, H, N $\frac{\partial \rho_i}{\partial t} + \nabla \cdot (\rho_i \vec{u}) = 0$

- Conservation of Momentum $\frac{\partial}{\partial t}(\rho u_j) + \nabla \cdot (\rho u_j \vec{u}) = -\nabla P$

- Conservation of Energy

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot \left(\rho \vec{u} \left(E + \frac{P}{\rho}\right)\right) = \xi^2 \sigma + \nabla \cdot q_r$$

Ohmic Heating
(Electric Field)^2*Electrical Conductivity

Thermal
Radiation

Temperature Evaluation

Sandia National Laboratories

Engineering Sciences Center

- Find temperature from energy values
  - Energy = thermal energy (ions, neutrals) + kinetic
  - All species, ions in a cell have the same temperature

$$\rho E = \rho|\vec{u}|^2/2 +$$

$$\sum_j \frac{3}{2} n_j kT (1 - (1 - \chi_{diss,j})\, \Theta_{diss,j}) + n_j \chi_j^+ (\frac{3}{2}kT + I_j^+)$$

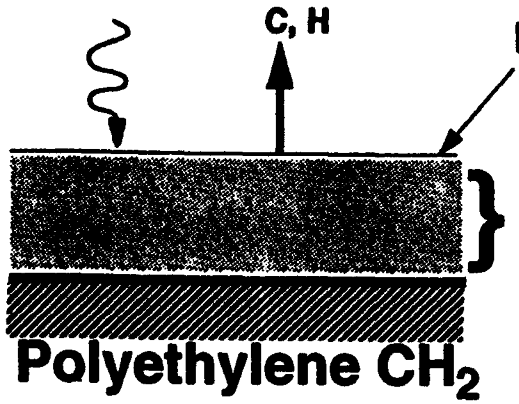
$$n_j \chi_j^{++} (3kT + I_j^+ + I_j^{++}) \quad , n_j \; -$$

n_j number density, χ_j^+ - ionization fraction, I_j^+ - ionization energy

Ablation

Sandia National Laboratories

Engineering Sciences Center



- Glass phase transformations
- Spalling, particles
- Intermediate species
- Non-constant heats of vaporization and dissociation
- Non-thermodynamic equilibrium
- Spectral radiative transport
- kinetic energy of ablated material significant

- Idealization of ablation

  equilibrium energy balance: incident radiation = ablative enthalpy flux

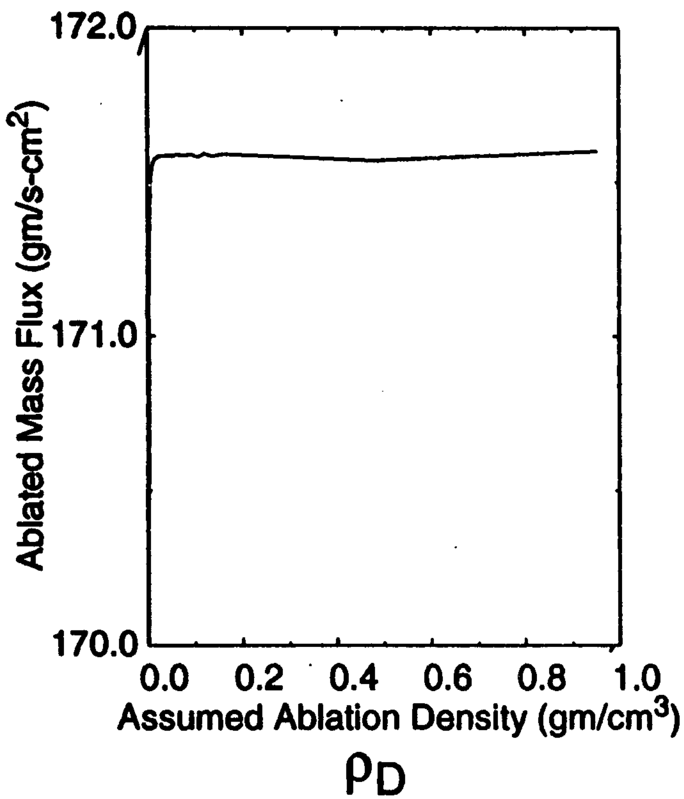
$$q''_{radiation} = \rho_D u \{ \frac{5}{2} R T_D + \frac{u^2}{2} + \gamma \}$$

- Assume dissociation temperature T_D, density ρ_D, latent heat γ
- Solve cubic equation for u, given radiative flux

Ablation Model Features

Engineering Sciences Center

Sandia National Laboratories



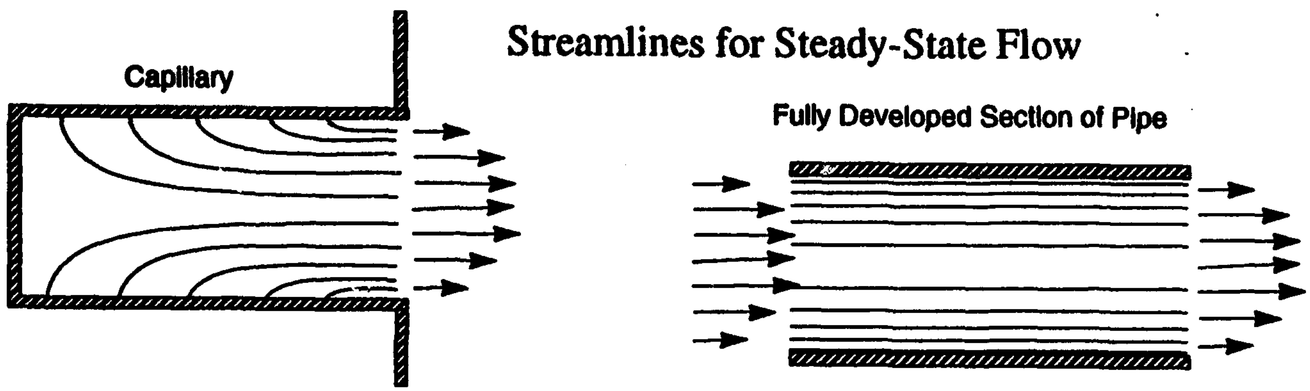
- Assume 4 eV blackbody heat flux
- Find that ablation mass flux is relatively insensitive to assumed polyethylene density
- Calculated ablation rate for ET038: 340 gm/s
- ET038 Ablation rate data (time-averaged) rate: 610 gm/s

Turbulence in ETC Capillaries

Sandia National Laboratories

Engineering Sciences Center

- Need to assess importance of turbulence



- Compare capillaries to pipe flows
  - no flow at back wall, no development length - turbulence questionable
  - different boundary conditions (capillary wall blowing drives flow)
  - volumetric heat source
  - radiation

Turbulence in ETC Capillaries, Cont'd

Sandia National Laboratories

Engineering Sciences Center

- Compare conductivities: fluid, turbulent, radiative

$$\rho C_p \frac{DT}{Dt} = \nabla \cdot [\,(k_{fluid} + k_{turbulence} + k_{radiation})\,\nabla T]$$

typically, $k_{fluid} \ll k_{turbulence}$

- Compare $k_{radiation}$ and $k_{turbulence}$

  - at 5 eV, 10^{22} cm^{-3} (1D model: significant radial variations)

Turbulence in ETC Capillaries, Cont'd

- Turbulent conductivity (wall-generated turbulence)
  - $k_{turbulence} \approx \mu_{turbulence} C_p \quad , \quad \mu_{turbulence} \approx O(10^2)\, \mu_{fluid}$
  - Spitzer formula for plasma viscosity

  $k_{turbulence} \approx 9 \cdot 10^3$ W/cm-eV

- Radiative conductivity: Zel'dovich and Raizer

  $k_{radiation} \approx 3 \cdot 10^6$ W/cm-eV

- **Radiation dominates wall-generated turbulence for this example**
  - radiation and turbulence are equivalent at 2 eV, where radial variations (due to radiation) are negligible

Turbulence in ETC Capillaries, Cont'd

Turbulent conductivity (wall-generated turbulence)

Sandia National Laboratories

Engineering Sciences Center

- Turbulent conductivity (free-shear layer turbulence)

$$k_{turbulence} \approx 9 \cdot 10^{5} \quad \text{W/cm-eV}$$

- Radiative conductivity: Zel'dovich and Raizer

$$k_{radiation} \approx 3 \cdot 10^{6} \quad \text{W/cm-eV}$$

- **Radiation & free shear layer turbulent transport rates are similar**
  - origin of free-shear layer turbulence: baroclinic vorticity generation
  - turbulence models inappropriate for transitional flow
- Approach: use no turbulence model, examine solution fields for waves

Electric Field Model

Sandia National Laboratories

Engineering Sciences Center

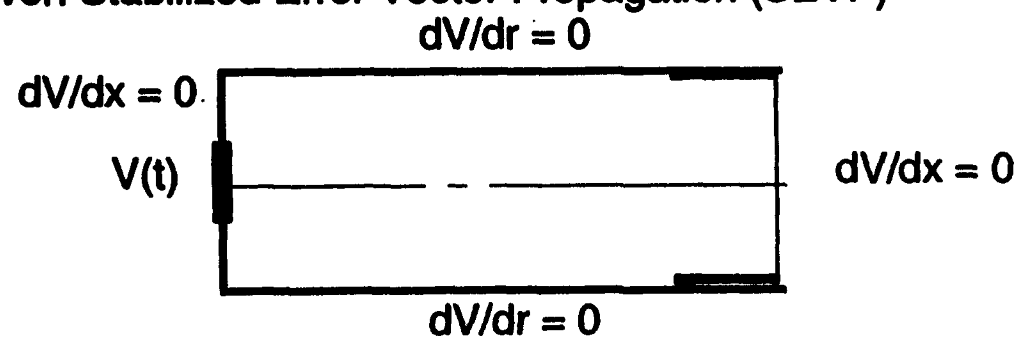
- Assume quasi-steady state

  - Zero divergence of current

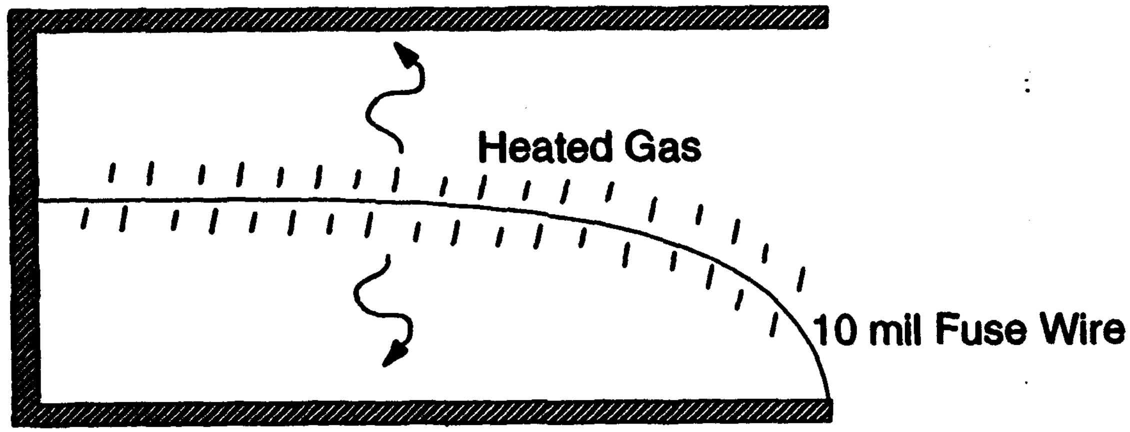
$$\nabla \bullet (\sigma(T) \nabla V(t)) = 0$$

  - time t
  - temperature T
  - electrical conductivity σ
  - ohmic heating: $\sigma (\nabla V \cdot \nabla V)$

- Solver: Stabilized Error Vector Propagation (SEVP)



Plasma Initiation



- Initially, all current carried by fuse wire
- At late times, ionized gas carries all the current
- How does this transition occur?

Uniform Power Deposition Calculation

Sandia National Laboratories

Engineering Sciences Center

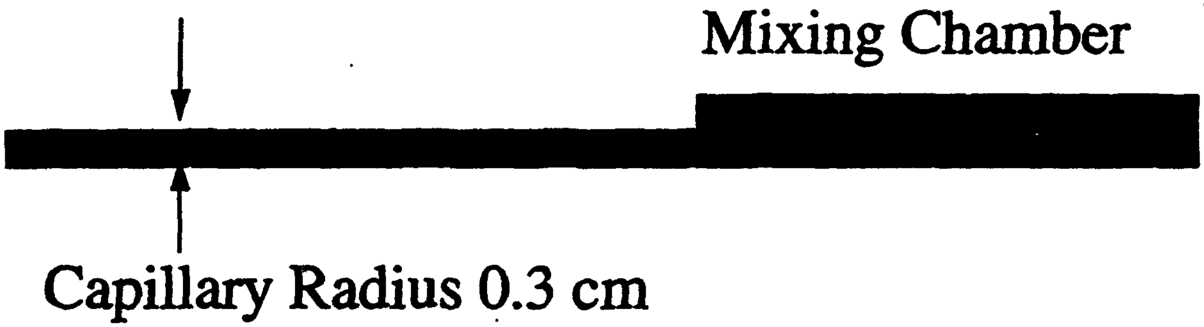
$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\rho \vec{u} (E + \frac{P}{\rho})) = \xi^2 \sigma + \nabla \cdot q_r$$

Thermal Radiation

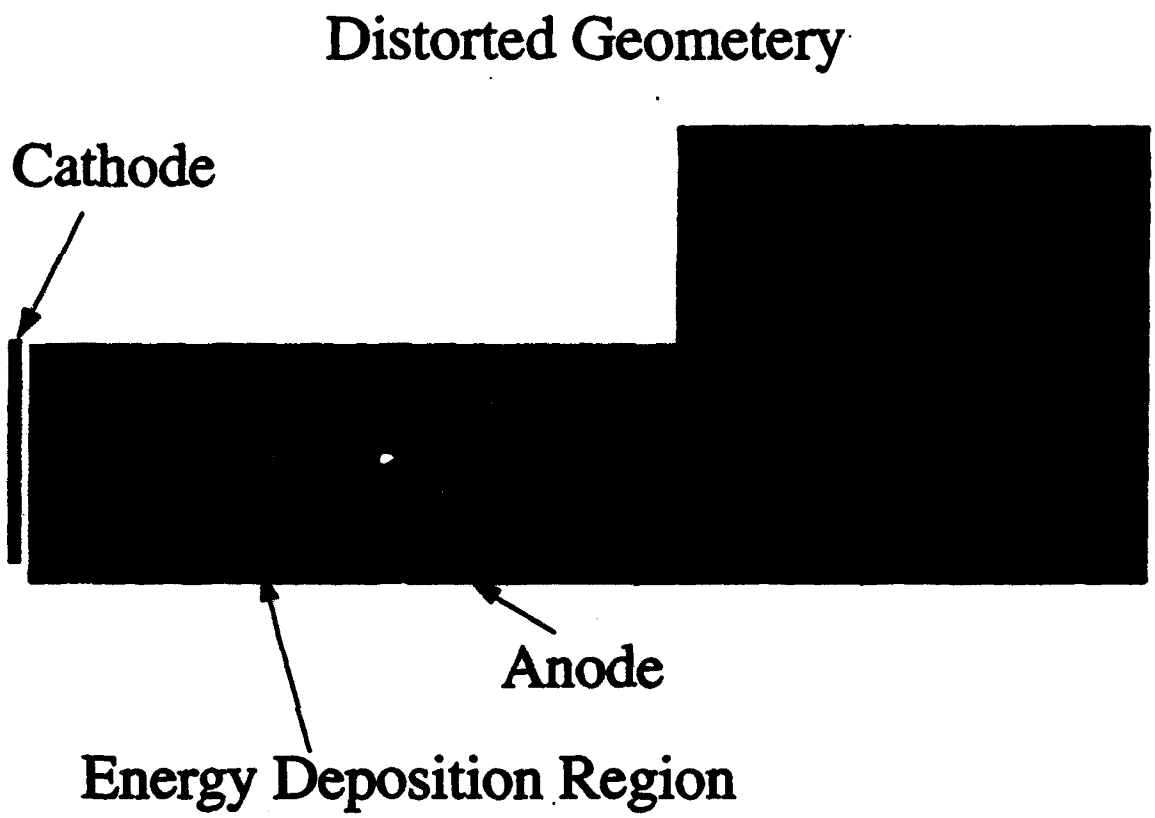
Ohmic Heating
(Electric Field)^2*Electrical Conductivity
Replace with (Power data)/(Capillary Volume)

- Calculate ohmic heating given voltage data
  - but don't use it, just compare with power data
  - if ohmic heating agrees with power data:
    - Current will agree with data: power = voltage * current
    - Resistance will agree with data: power = voltage^2 /R

Axisymmetric Model of Capillary and Mixing Chamber

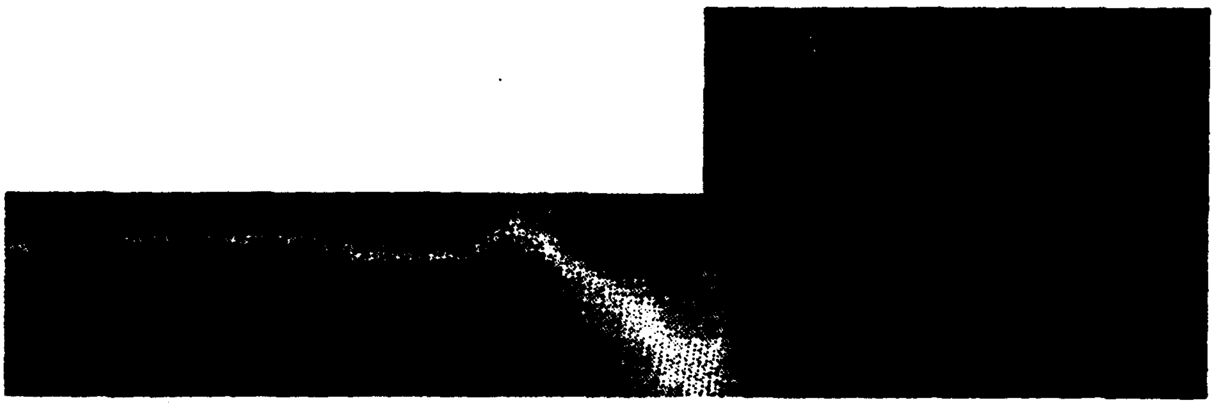


Overall Length 11.4 cm


Distorted Geometery
Cathode
Anode
Energy Deposition Region

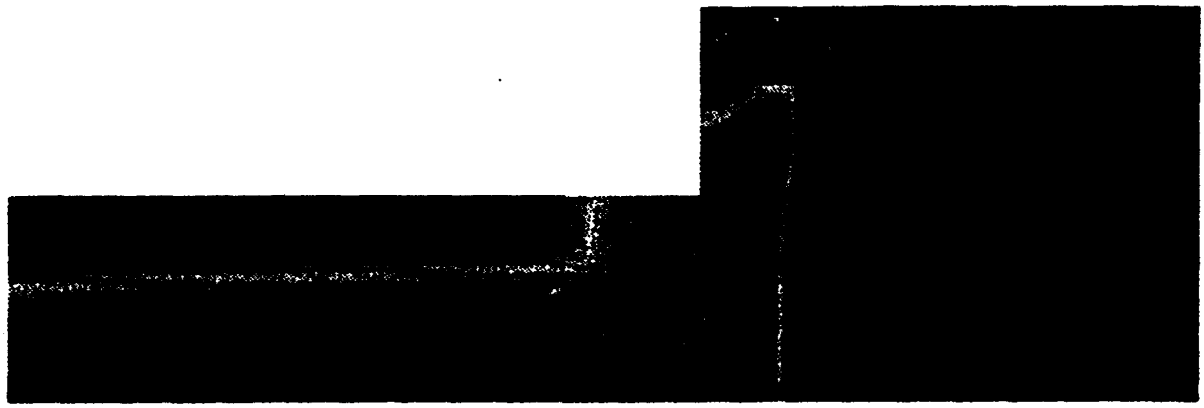
100 μs

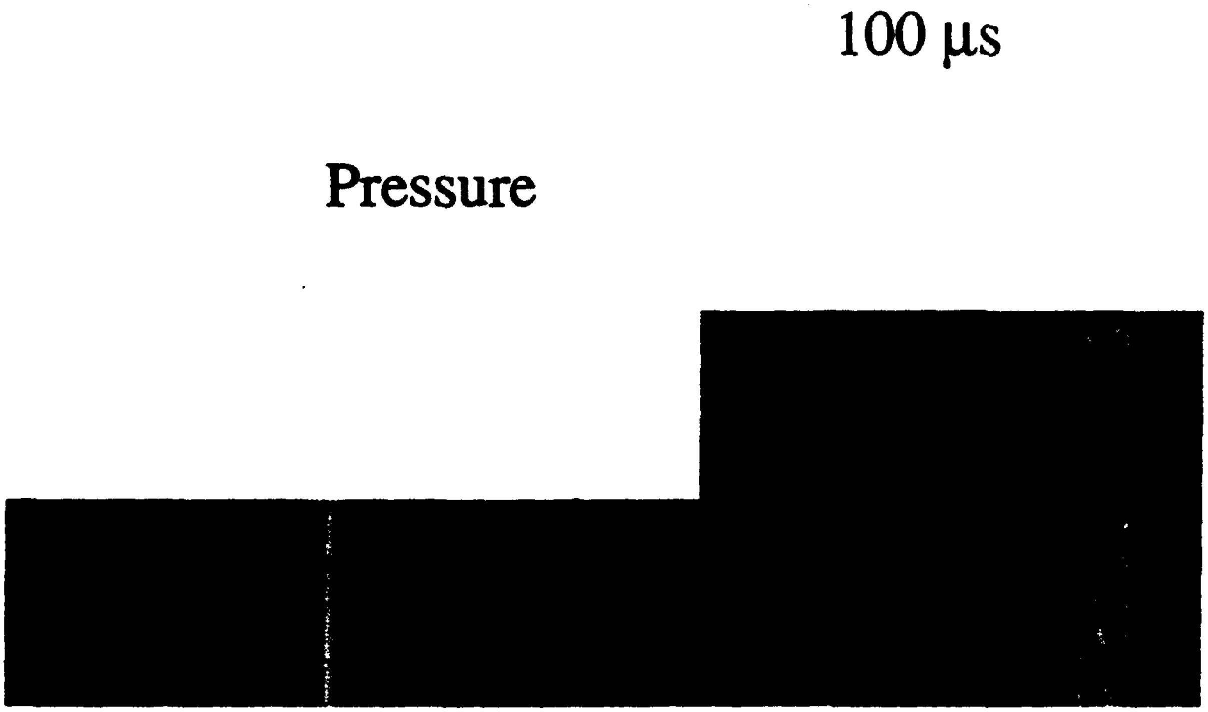
Temperature (4.2 eV)



200 µs

Temperature (3.3 eV)



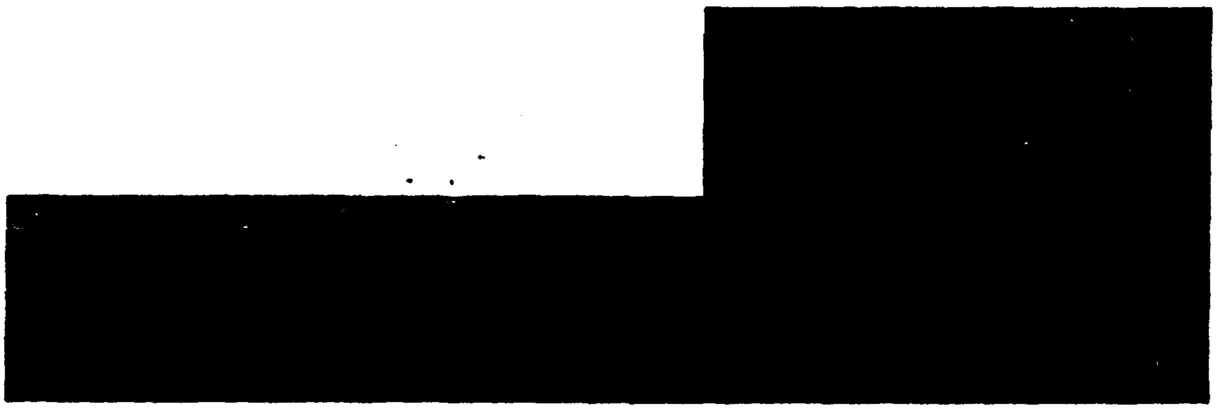

100 μs
Pressure

200 μs

Pressure

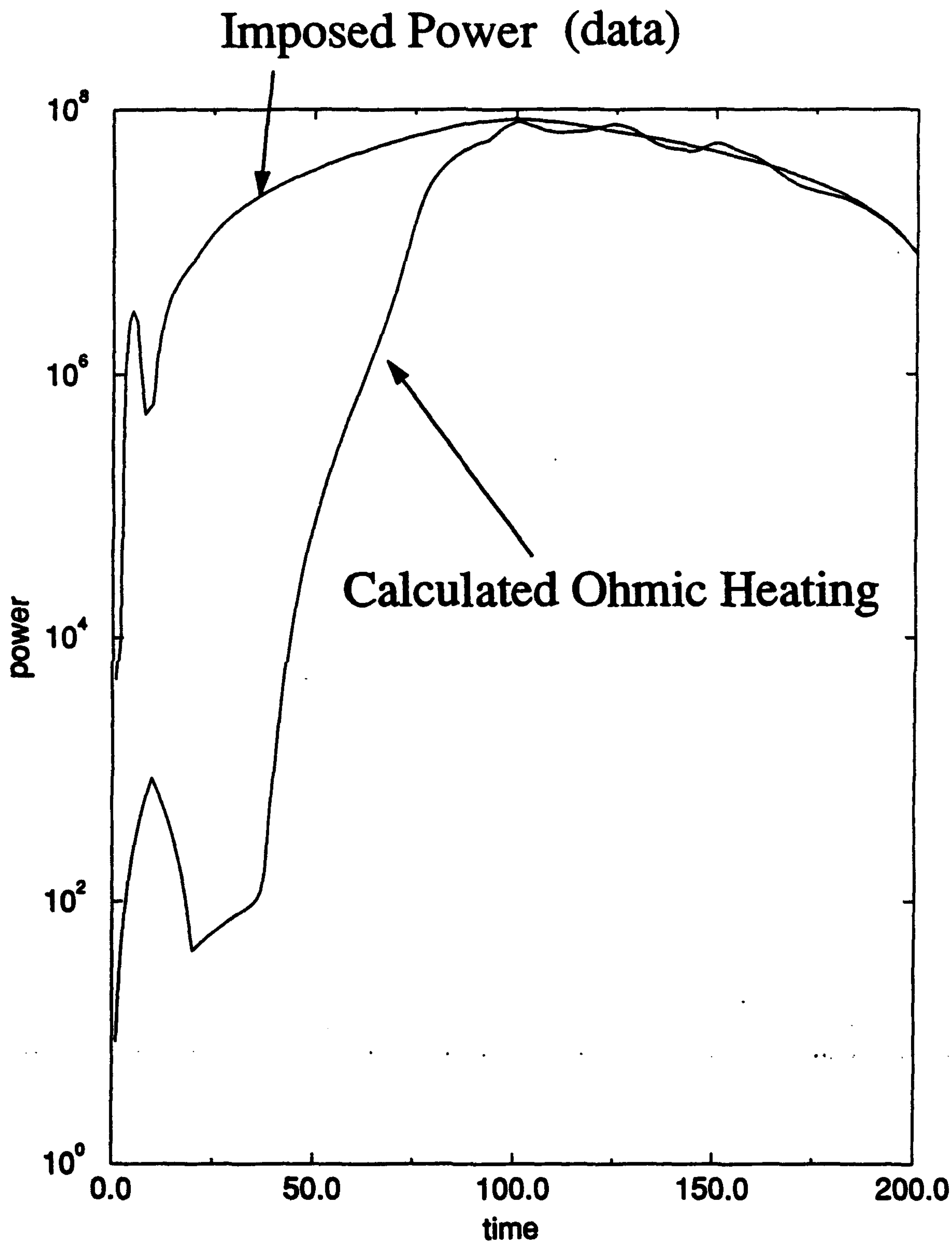
100 μs

Polyethylene Density (10^{-3})



200 μs

Polyethylene Density (10^{-2})


Imposed Power (data)
Calculated Ohmic Heating
power
time
10^8
10^6
10^4
10^2
10^0
0.0
50.0
100.0
150.0
200.0

Plasma Initiation, cont'd

Centerline of Cartridge

- Radiative flux on polyethylene very small even if wire is initially hot
  - Ablated polyethylene is not an early participant
- Aluminum vaporizes, provides new electrical path
- Lee-More Model for aluminum electrical conductivity - progress

Summary

Sandia National Laboratories

Engineering Sciences Center

- Two-dimensional, transient model formulation
  - ohmic heating (voltage data, electrical conductivity -> voltage field)
  - discrete ordinate thermal radiation
  - ablation model
  - ionization, dissociation
- Uniform Power Deposition calculation (no fuse wire)
  - Transient pressure larger than data
  - Ohmic heating small at early times, good at later times
    - electrical conductivity too low at early-time
- Work in progress: include fuse wire vaporization
  - provides high electrical conductivity at early times
  - convected out of cartridge by late times

Electric Armaments

FMC

In-Bore Doppler Radar Measurements Of Projectile Kinematics

Workshop on ETC Modeling
Army Research Laboratory
Aberdeen, Maryland
May 12 - 13, 1993

Patrick Janke, Senior Engineer
Jahn Dyvik, Staff Engineer
Advanced Armaments
FMC Naval Systems Division
Minneapolis, Minnesota
U.S.A.

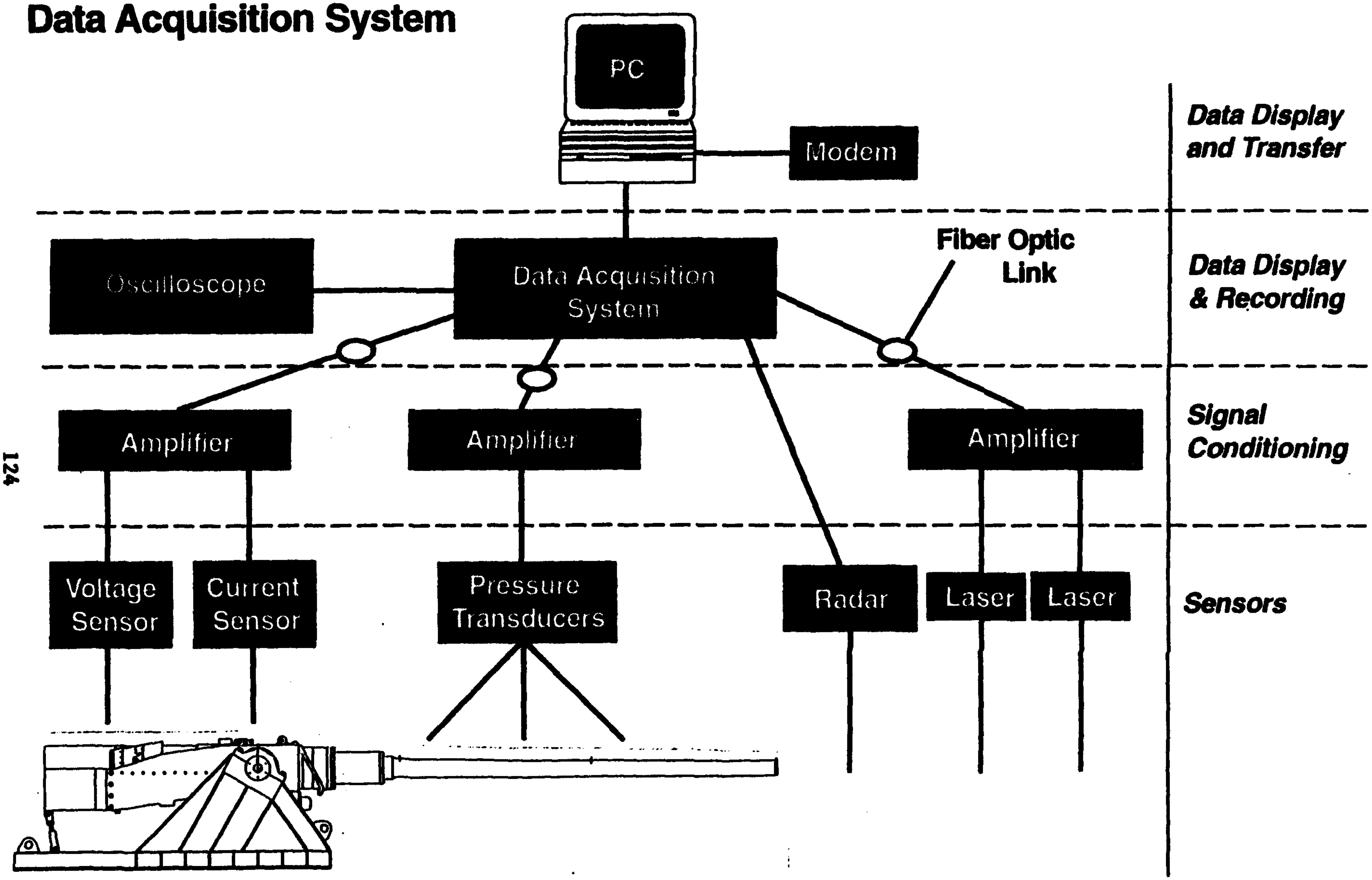
Janke/ARL Pres/5/12/93/1

OUTLINE

- Automated Data Acquisition, Transfer and Reduction
- In-Bore Radar Measurements of Projectile Kinematics
- Development of an Inverse Ballistic Model
- Conclusions

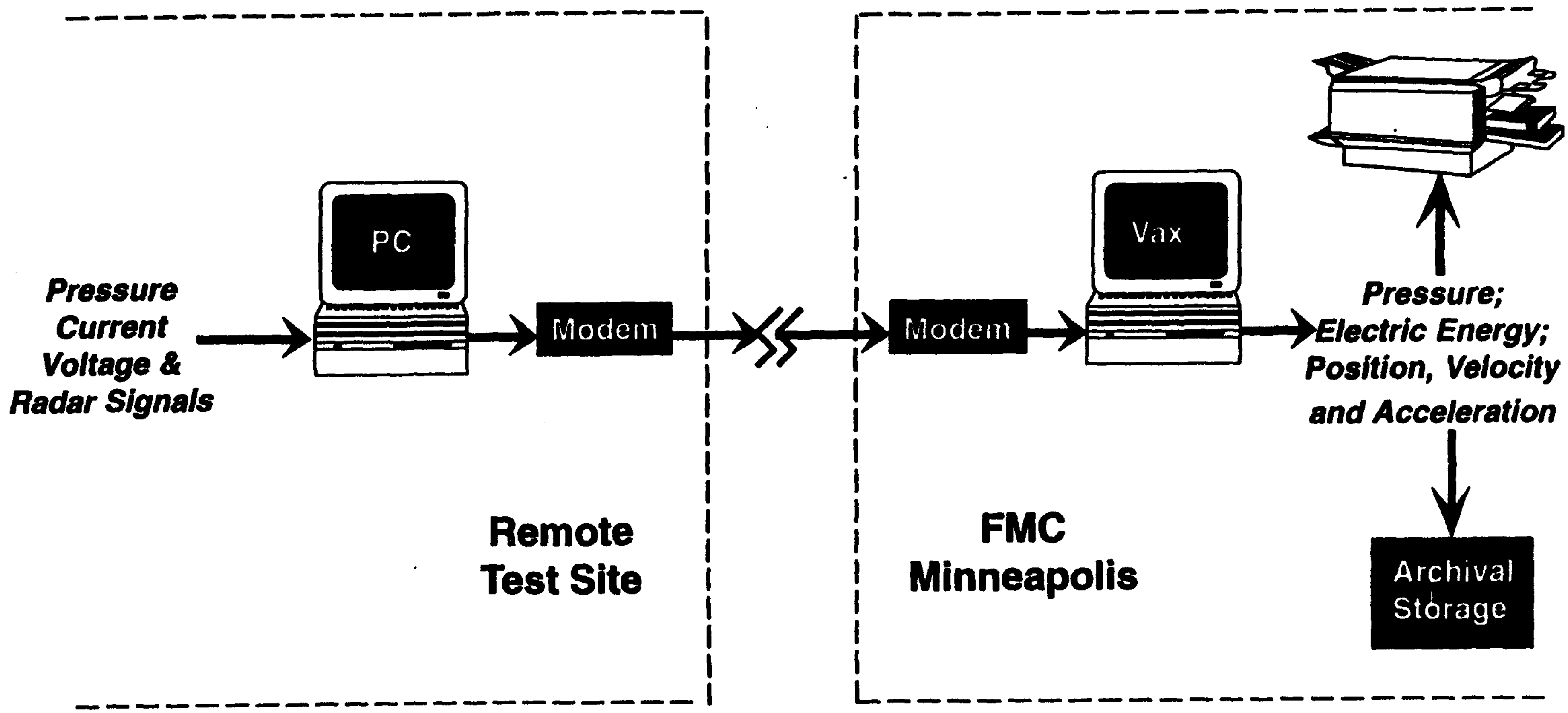
Automated Data Acquisition, Transfer, and Reduction

Data Acquisition System



Janke/ARL Pres/5/12/93/4

Automated Data Transfer & Reduction



Janke/ARL Pres/5/12/93/5

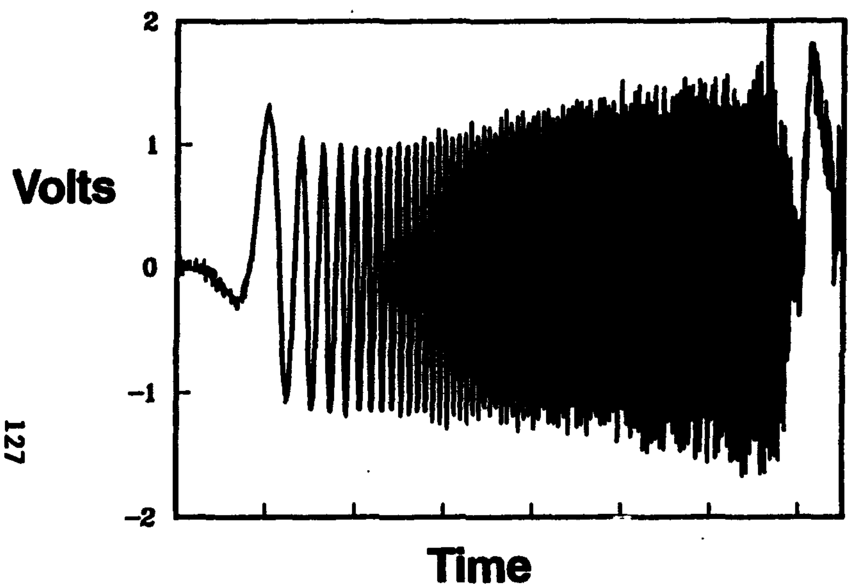
In-Bore Radar Measurements of Projectile Kinematics

Electric Armaments

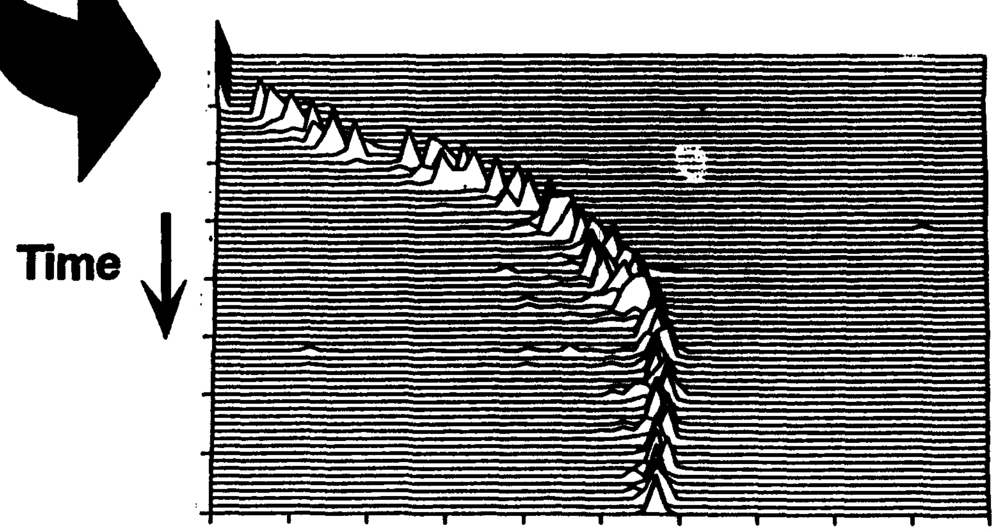
FMC

Analysis of In-Bore Doppler Radar Data

Doppler Signal



Power Waterfall

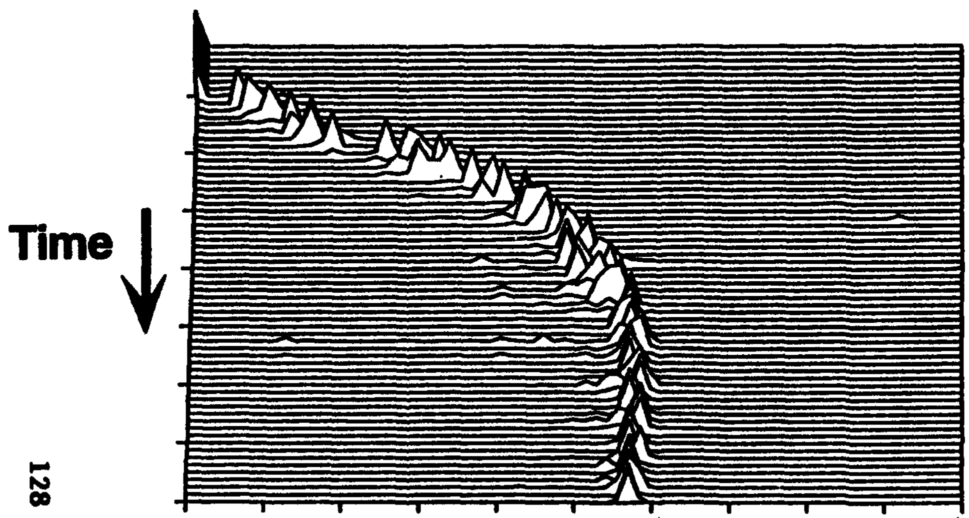


- *Separate into overlapping intervals*
- *FFT each interval*
- *High pass filter at muzzle exit*

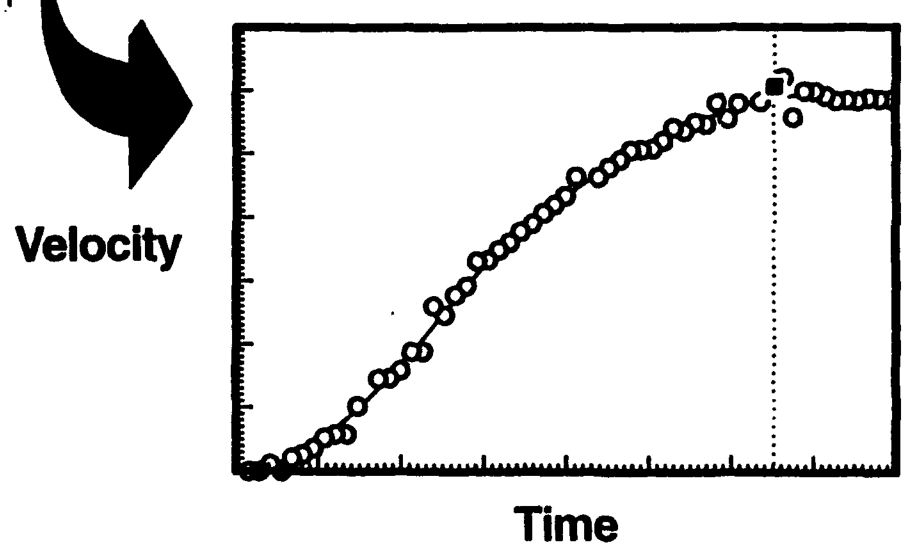
Janke/ARL Pres/5/12/93/7

Analysis of In-Bore Doppler Radar Data

Power Waterfall



Projectile Velocity



- *Locate peak of power spectrum*
- *Remove data points with low SNR*
- *Convert Doppler frequency to projectile velocity*

Janke/ARL Pres/5/12/93/8

Projectile Velocity

Free Flight:

$$V(t) = \frac{c}{1 + 2\left(\frac{f_o}{f_D(t)}\right)} \cong \frac{c\, f_D(t)}{2 f_o}; \quad \text{since} \left(\frac{V(t)}{c} << 1\right)$$

In-Bore:

$$V(t) = \left(\frac{c\, f_D(t)}{2 f_o}\right) \frac{1}{\sqrt{1 - \left(\frac{f_c}{f_D(t)}\right)^2}}; \quad f_c = \frac{0.293c}{D/2}$$

$V(t)$ = Projectile Velocity

$f_D(t)$ = Doppler Frequency

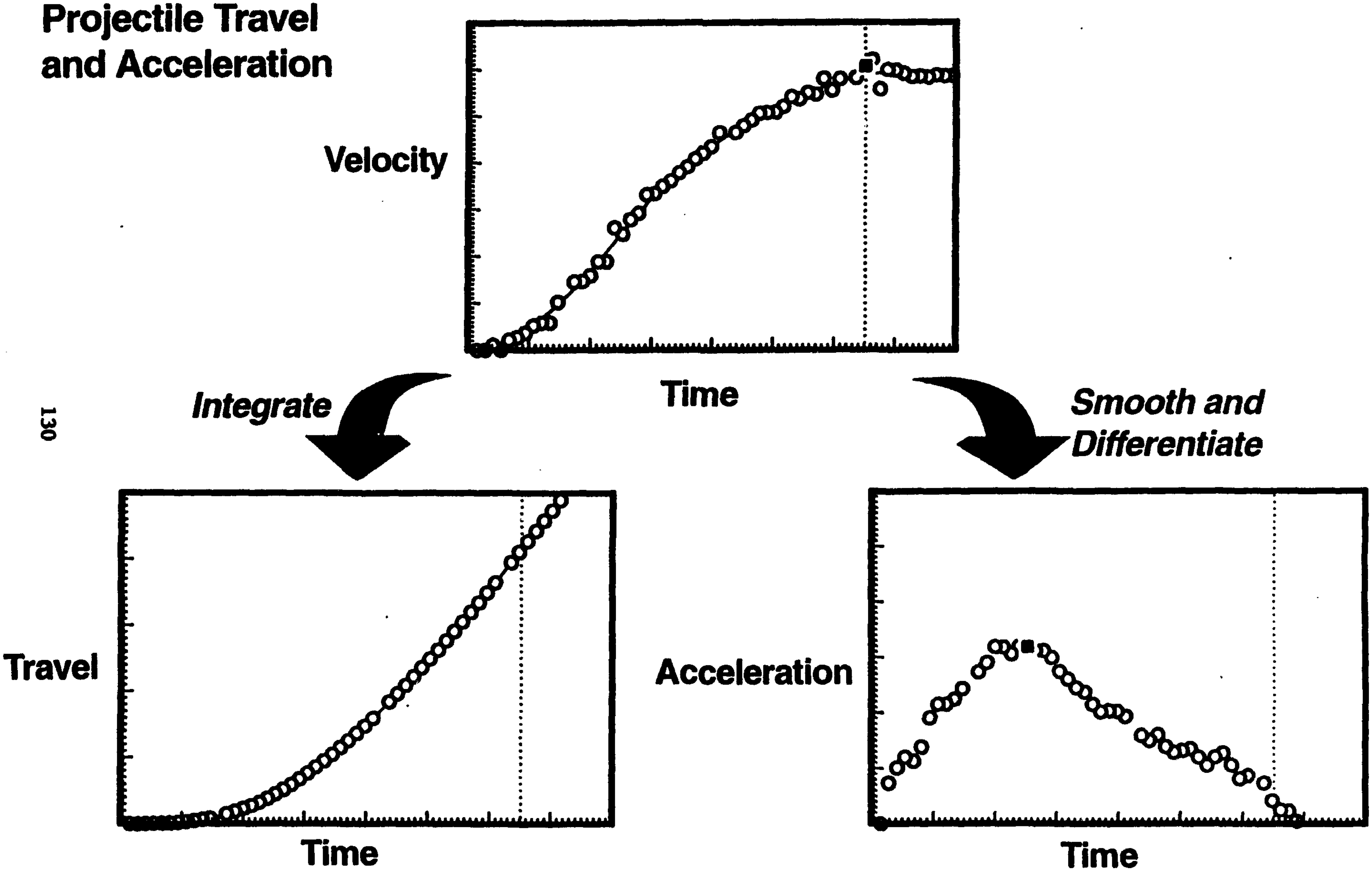
f_o = Transmit Frequency

f_c = Cutoff Frequency

c = Speed of Light

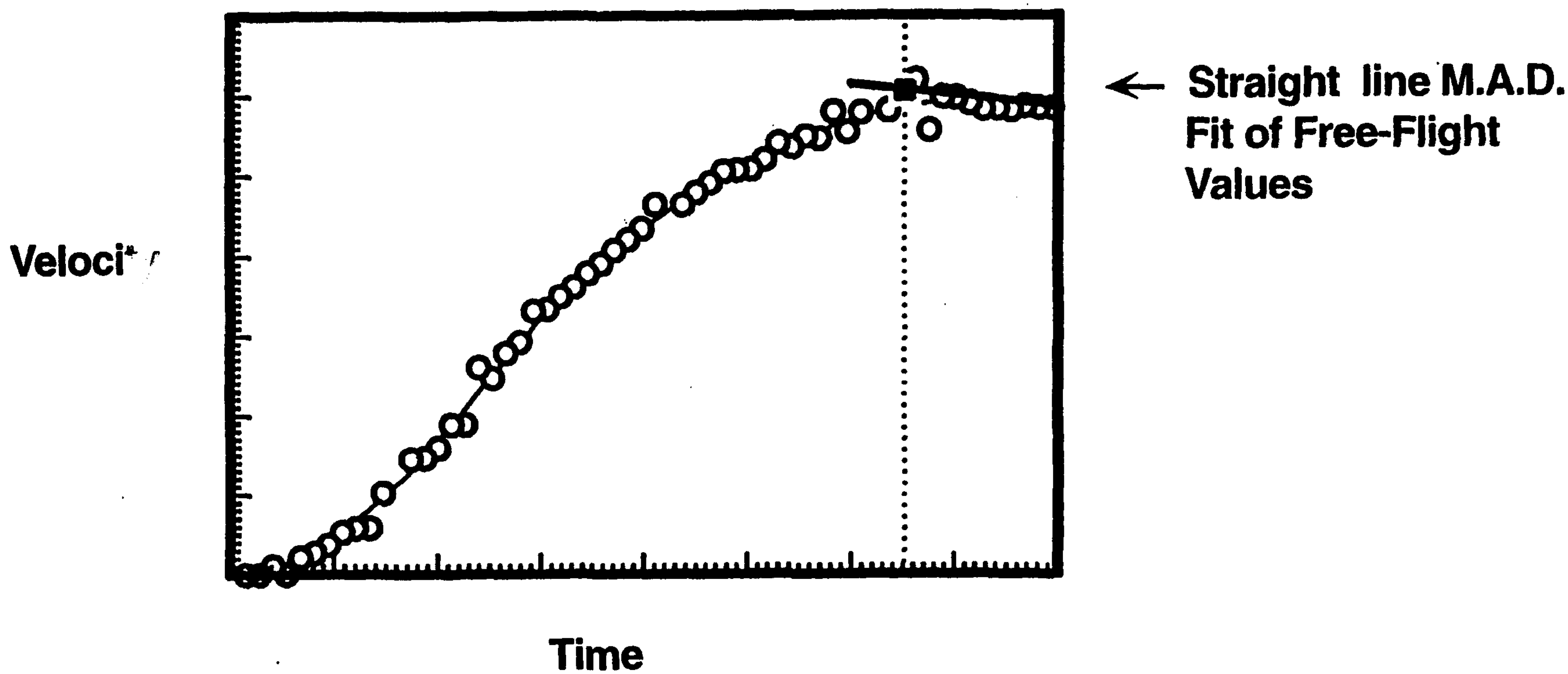
D = Bore Diameter

Projectile Travel and Acceleration



Electric Armaments

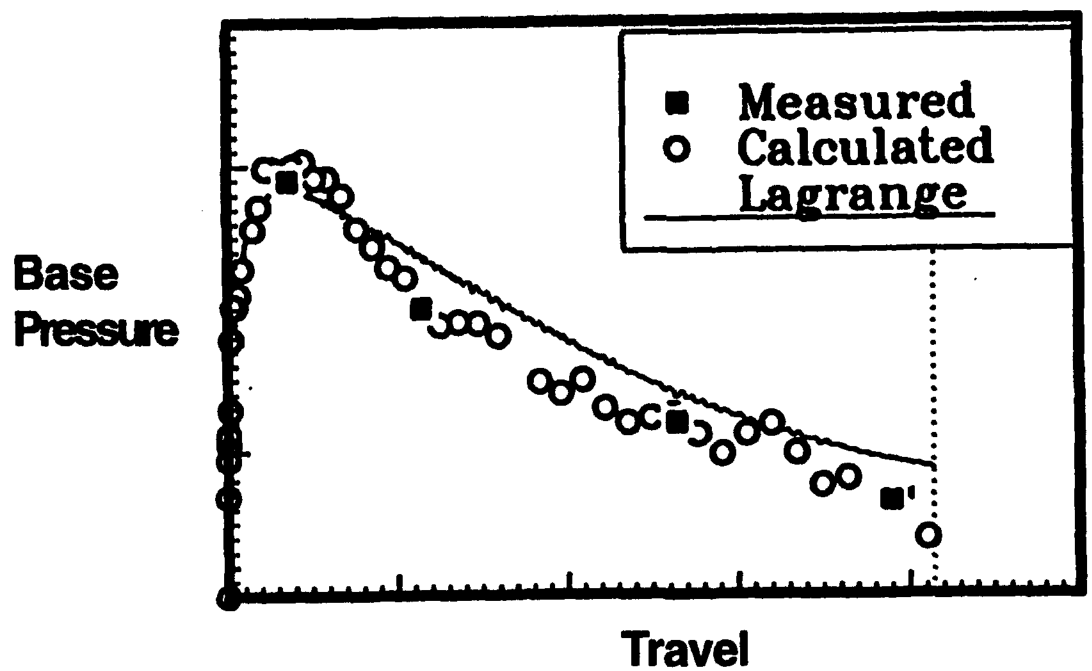
Muzzle Velocity



Janke/ARL Pres/5/12/93/11

Projectile Base Pressure

$$P_{base}(t) = \frac{m\,a(t) + F_{res}(t)}{A_b}$$



Development of an Inverse Ballistic Model

Inverse Model - Formulation

1st Law Energy Balance:

$$Electrical + Chemical = Work + Heat\ \ Loss$$

$$E_{elec}(t) + c\,z(t)\left(\frac{I}{T_f(\gamma-1)}\right)\left(T_f - T(t)\right) = \left(\tfrac{1}{2}mV^2(t) + \tfrac{1}{6}cV^2(t)\right) + E_{heat}(t)$$

Noble - Abel Equation of State:

$$\overline{P(t)}\left(V_c + X(t)A_b - \frac{c(1-z(t))}{\rho_s} - b\,c\,z(t)\right) = RT(t)\frac{c\,z(t)}{M}$$

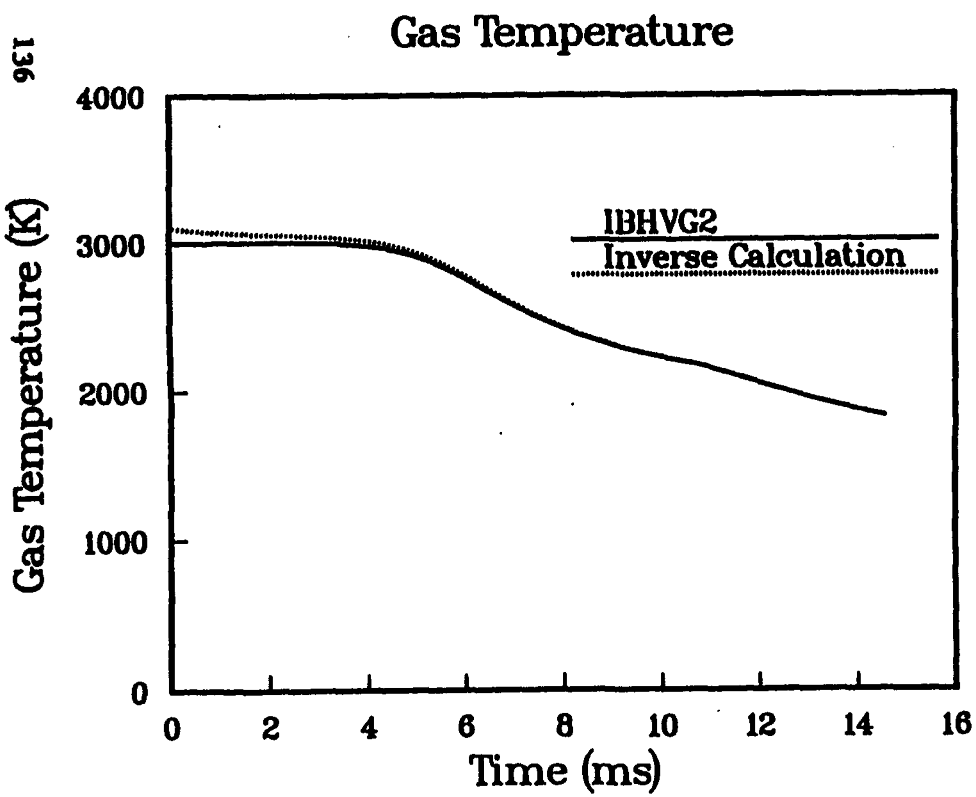
Inverse Model - Formulation

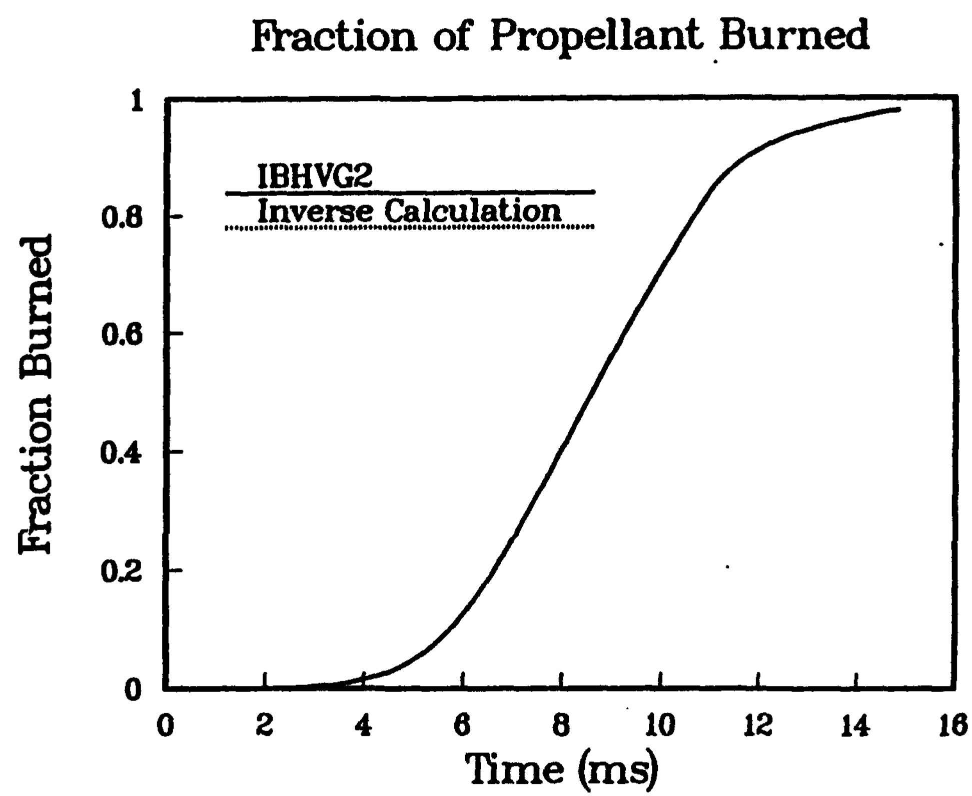
Combine and Solve for Fraction Burned:

$$z(t) = \frac{\frac{V^2(t)}{2}\left(m + c/3\right) + \frac{\overline{P(t)}}{\gamma - 1}\left(V_c + X(t)A_b - c/\rho_s\right) + E_{heat}(t) - E_{elec}(t)}{\frac{c}{\gamma - 1}\left(I + \overline{P(t)}\left(b - 1/\rho_s\right)\right)}$$

$E_{heat}(t)$ **is calculated by modified Nordheim model.**

Verification of Inverse Model





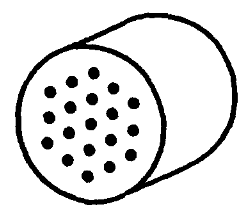
Inverse Model - Solid Propellant Extensions

Mass Burn Rate:

$$\dot{m}(t) = c\frac{dz(t)}{dt}$$

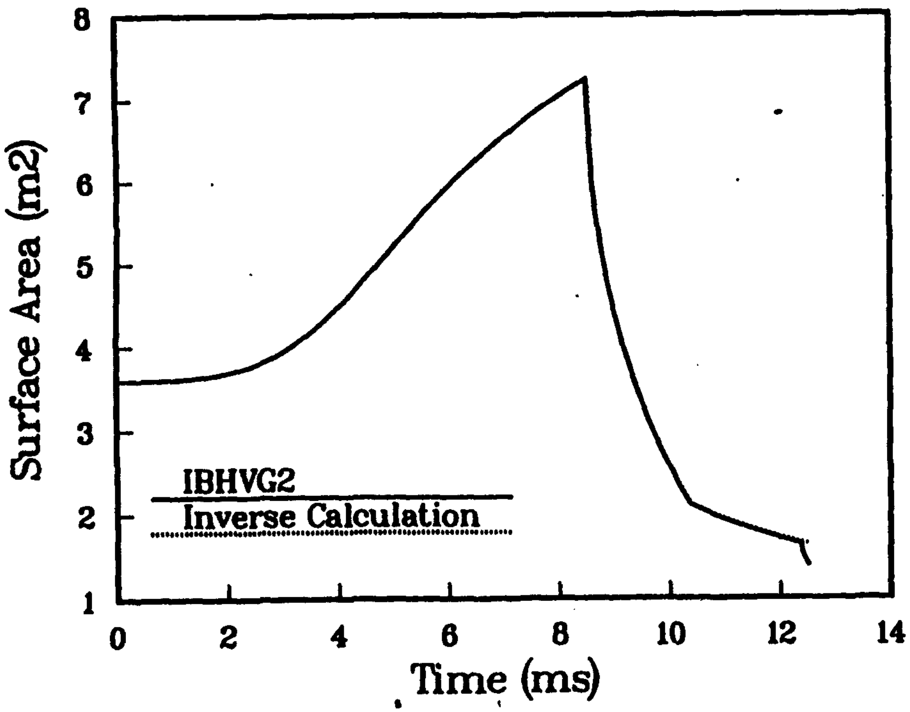
Linear Regression Rate:

$$\dot{r}(t) = \frac{\dot{m}(t)}{\rho_s S(z)}; \quad S(z) = \text{Geometric Form Function}$$

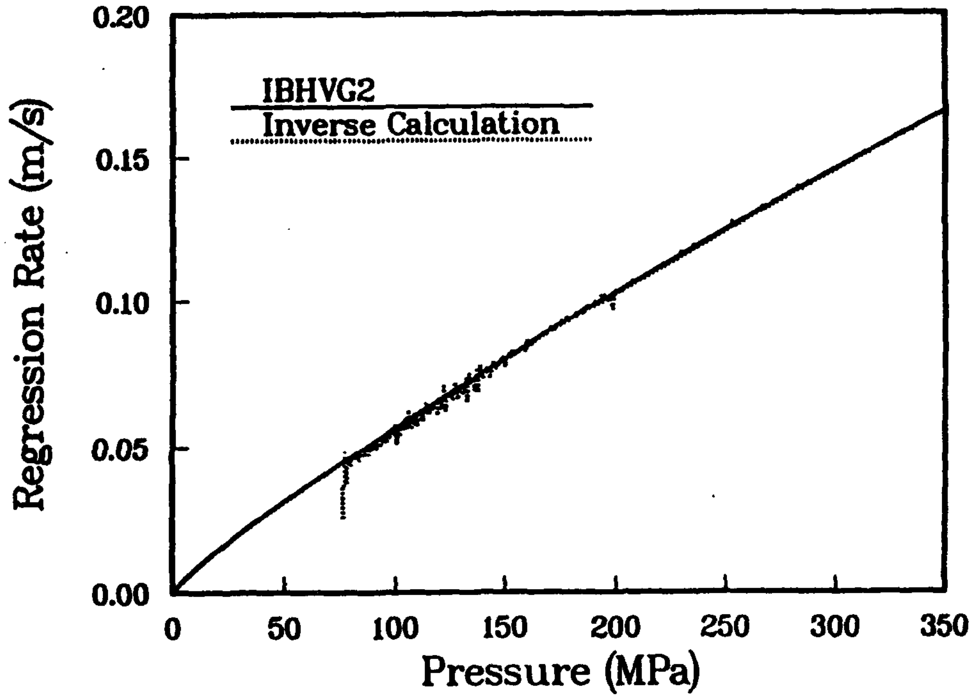


Verification of Inverse Model

Propellant Surface Area



Linear Regression Rate



Conclusions:

- Automated data transfer and reduction system provides fast, convenient access to shot results.
- Projectile travel is accurately measured using in-bore radar.
- In-bore radar provides a reasonable estimate of projectile acceleration and base pressure.
- Inverse analysis matches IBHVG2 results very well; model is ready for application to experimental data.

INTENTIONALLY LEFT BLANK.

Enhanced Propellant Burn Rate
through Plasma Erosion

L.E. Harris, D. Chui, J. Prezelski, P. O'Reilly, D.S. Downs
US Army Research, Development, and Engineering Center
Picatinny Arsenal, NJ
and
W.F. Oberle
US Army Research Laboratory
Aberdeen Proving Ground, MD
and
J.R. Greig
GT-Devices
Alexandria, Va
and
H.A. McElroy and J.G. Buzzett
Olin Ordnance
St. Petersburg, FL

ABSTRACT

In both ETC gun firings and ETC closed bomb experiments to date, it has been observed that the burn rates of solid propellants are not altered by the presence of the ET plasma except through the pressure created by the addition of the electric energy. However, in a recent series of ET gun firings, we have observed that the burn rate of the propellant can be dramatically increased by the erosive effect of the plasma. The propellant was JA-2, and for these ETC gun firings the whole propellant charge was cast as a "single perf" monolithic grain. The central perforation was 0.25 inch diameter and the outside diameter of the grain was 1.10 inch. The propellant was fired in a 30mm (bore diameter) gun in the Army's ET Gun Facility at GT-Devices. The plasma generator was a high pressure capillary discharge and the emerging plasma was carefully injected into the central perforation in the propellant grain. All other surfaces of the propellant grain were inhibited using silicone grease. The charge design is described in detail, and results obtained by simulating these firings using IBHVG2 are discussed. From these simulations, it is concluded that the burn rate achieved in these gun firings was enhanced significantly through the erosive effect of the plasma.

Enhanced Propellant Burn Rate Through Plasma Erosion

L. E. Harris, D. Chiu, J.Prezelski, P.O'Reilly, R. Marchak and D. S. Downs

US Army Research, Development and Engineering Center

Picatinny Arsenal, NJ

W. F. Oberle

US Army Research Laboratory

Aberdeen, MD

J. R. Greig

GT Devices

Alexandria, Va

OUTLINE

- **CBP Model**
- **System Requirements**
  - Tank
  - TMD
- **JA2 Monolith Gun Firings**
  - Experimental configuration
  - IBHVG2 Predictions
  - Pt traces and Residue
  - Inverse analysis

CBP EQUATIONS

$$Z_p = \frac{1}{\gamma}\left(\frac{I\,m}{P_{mean}\,A_b} - \frac{V_c - m\,\eta - V_{sb}}{A_b}\right) \quad (1)$$

$$Z_p = \frac{1}{2}\ddot{Z}_p t^2 \quad (2)$$

$$\dot{Z}_p = \frac{1}{2}\ddot{Z}\,t \quad (3)$$

$$m = \frac{Z_p \gamma A_b + V_c - C/\rho}{\frac{1}{P_{mean}} + \eta - \frac{1}{\rho}} \quad (4)$$

$$m = \frac{\frac{1}{2}\ddot{Z}_p t^2 \gamma A_b + V_c - C/\rho}{\frac{1}{P_{mean}} + \eta - \frac{1}{\rho}} \quad (5)$$

$$\dot{m} = \frac{\ddot{Z}_p t \gamma A_b}{\frac{1}{P_{mean}} + \eta - \frac{1}{\rho}} \quad (6)$$

CBP EQUATIONS

$$\bar{\dot{m}} = \frac{\tilde{\bar{Z}}_p \, \gamma A_b}{\frac{1}{P_{mean}} + \eta - \frac{1}{\rho}} \tag{7}$$

$$m = \frac{1}{2} \bar{\dot{m}} \, t^2 + m_0 \tag{8}$$

$$m_e = \frac{V_c - C/\rho}{\frac{1}{P_{mean}} + \eta - \frac{1}{\rho}} \tag{9}$$

$$Z_p^{bo} = \frac{1}{\gamma} \left(\frac{IC}{P_{mean}^{bo} A_b} - \Lambda \right) \tag{10}$$

$$E_p^{MZ} = E_p^{BO} \left\{ 1 + \frac{1}{\gamma - 1} \left[\frac{\bar{\bar{Z}}_p^{bo}}{Z_p^{bo}} \right] \left[1 - \left(\frac{\bar{\bar{Z}}_p^{bo}}{\bar{\bar{Z}}_p^{mz}} \right)^{\gamma - 1} \right] \right\}. \tag{11}$$

CBP EQUATIONS

$$\dot{m} = \rho S \dot{r} \tag{12}$$

$$\dot{r}_p = \frac{\bar{m}}{2\pi l_c r_p \rho} \tag{13}$$

$$r_p = \left(\frac{\bar{m} t^2}{2\pi l_c \rho} + r_{p0}^2\right)^{\frac{1}{2}} \tag{14}$$

Table III CBP Calculation of Interior Ballistics Time Profiles in a 120mm M256 Tank Gun

t(MS)	Z_p(M)	V_p(M/S)	T_m(K)	f(1)	$\dot{M}$(KG/S)
0.00	0.000	0	3,424	0.004	0
0.10	0.002	42	3,244	0.002	268
0.20	0.008	85	3,037	0.007	536
0.30	0.019	127	2,933	0.016	804
0.40	0.034	169	2,881	0.028	1,072
0.50	0.053	211	2,854	0.043	1,341
1.00	0.211	423	2,812	0.173	2,681
1.50	0.476	634	2,804	0.388	4,022
2.00	0.846	846	2,801	0.690	5,362
2.40	1.218	1,015	2,800	0.994	6,435
2.41	1.225	1,018	2,800	1.000	6,453

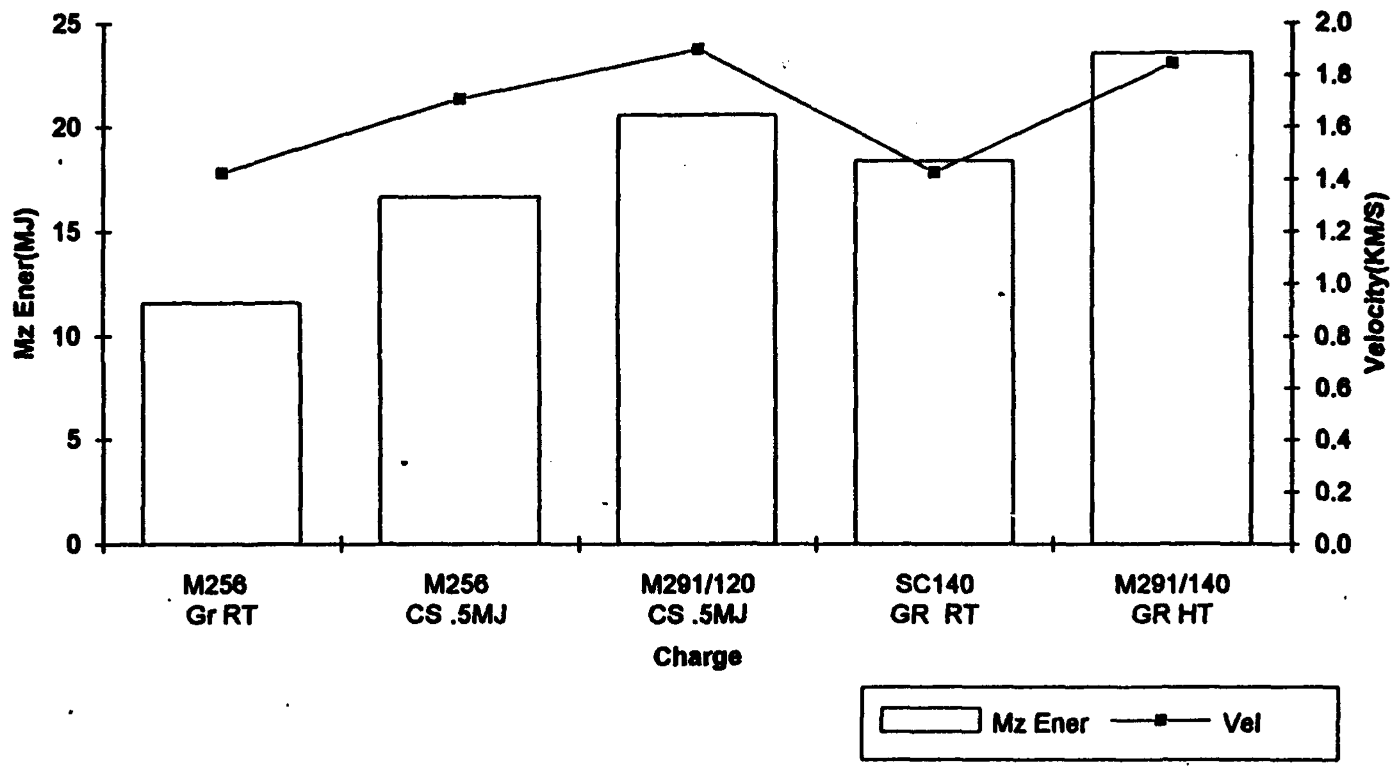


Figure 4. Projectile muzzle velocity versus velocity for 120- and 140-mm tank guns

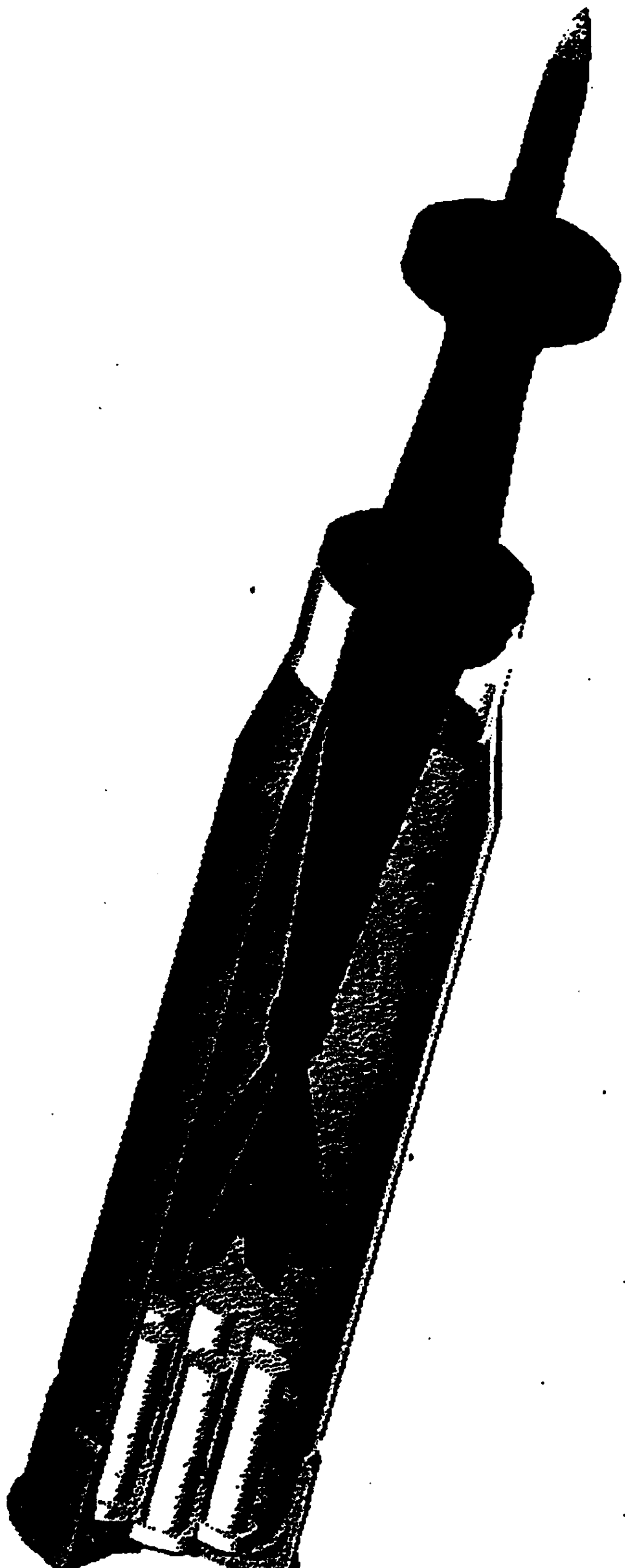


Figure 6. 120-mm M291 ETC tank gun cartridge

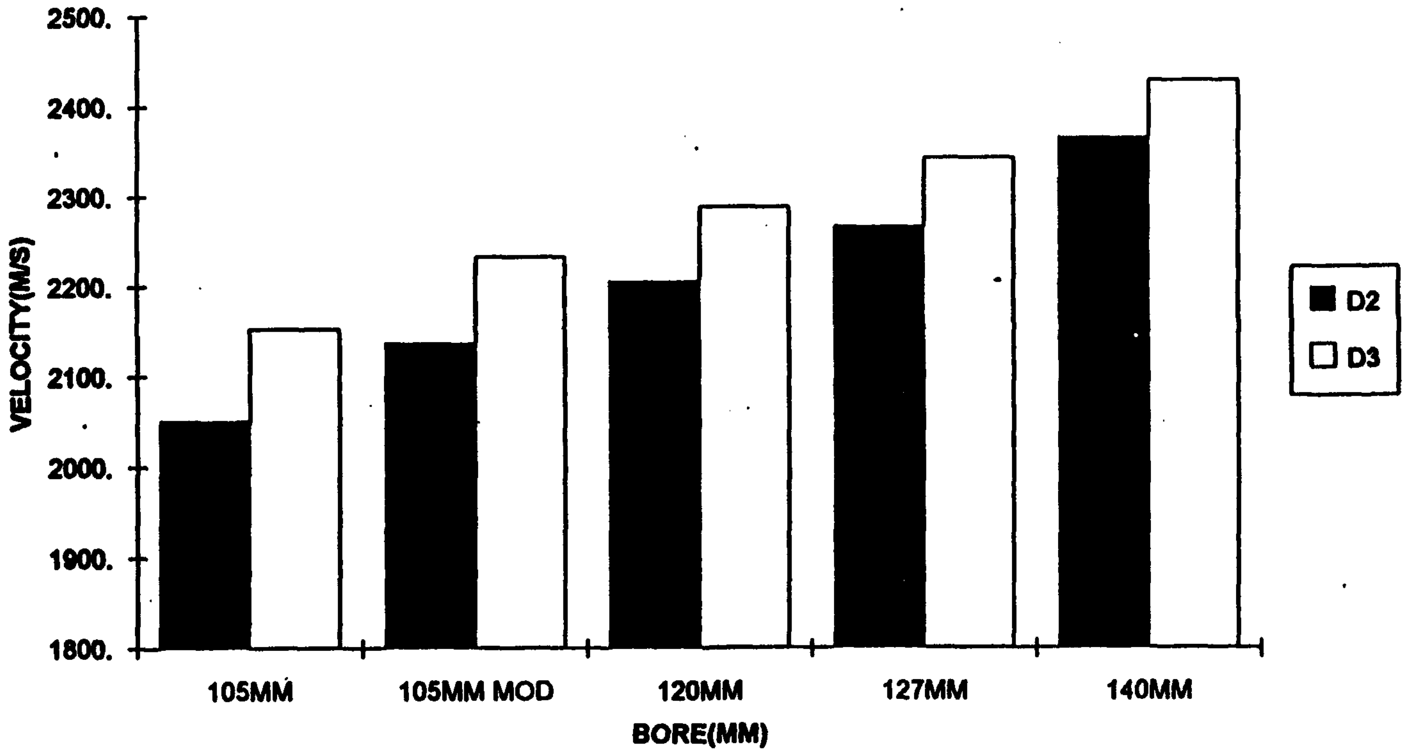


Figure 8. Muzzle velocity in various air defense guns

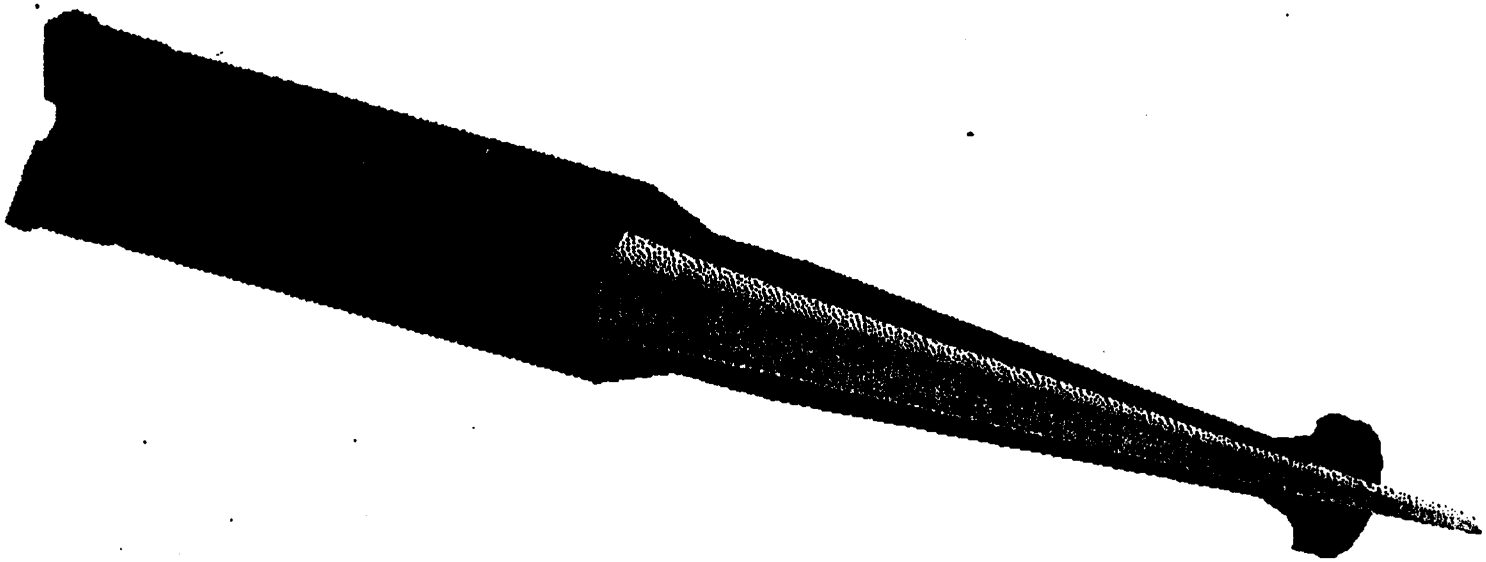


Figure 9. 105-mm ETC air defense cartridge

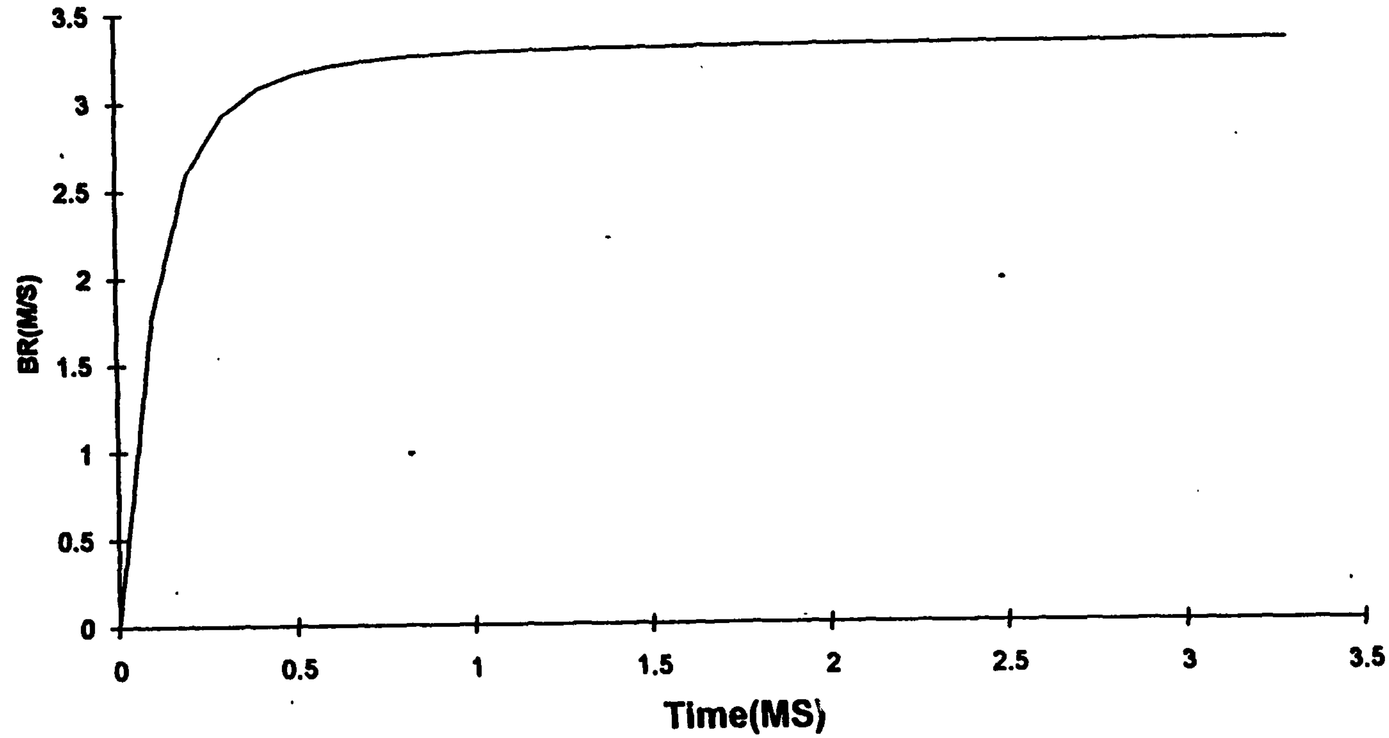


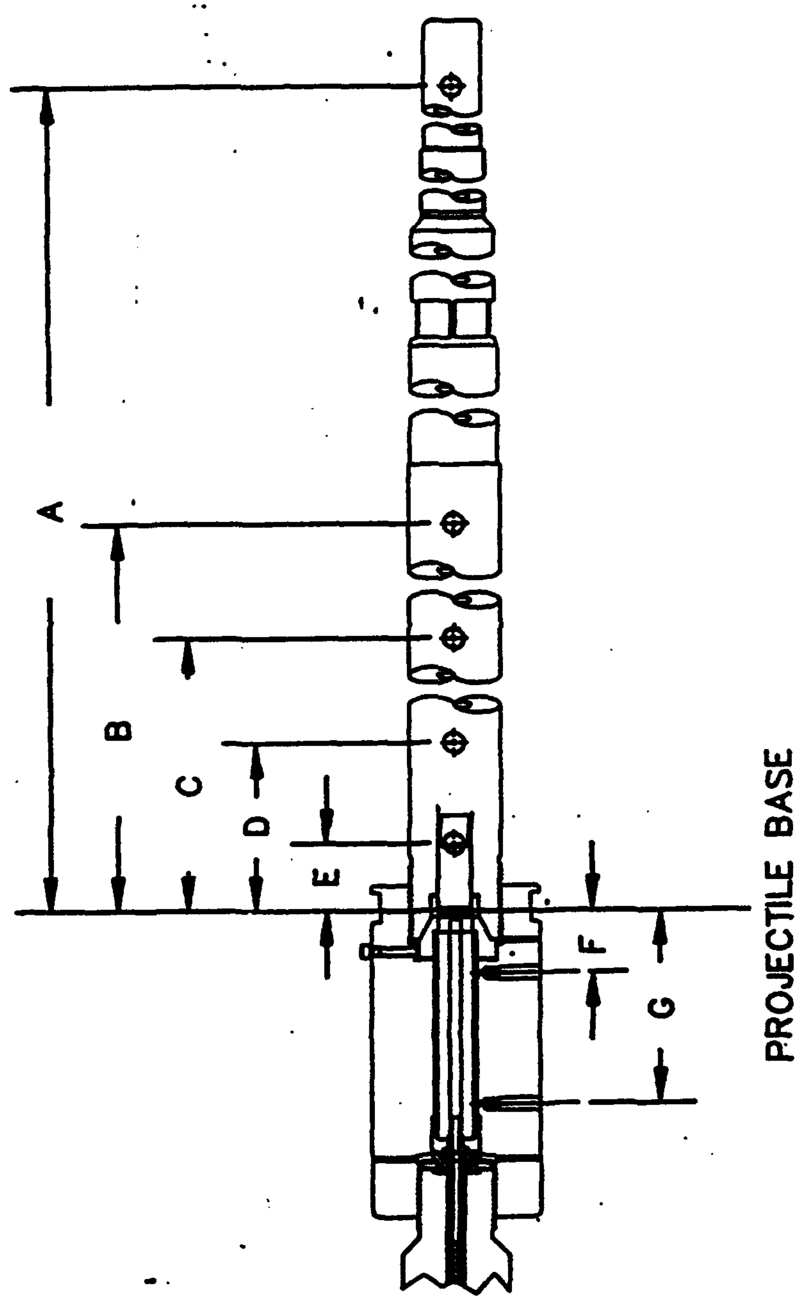
Figure 10. Propellant burning rate versus time for 120-mm M291 ETC cartridge

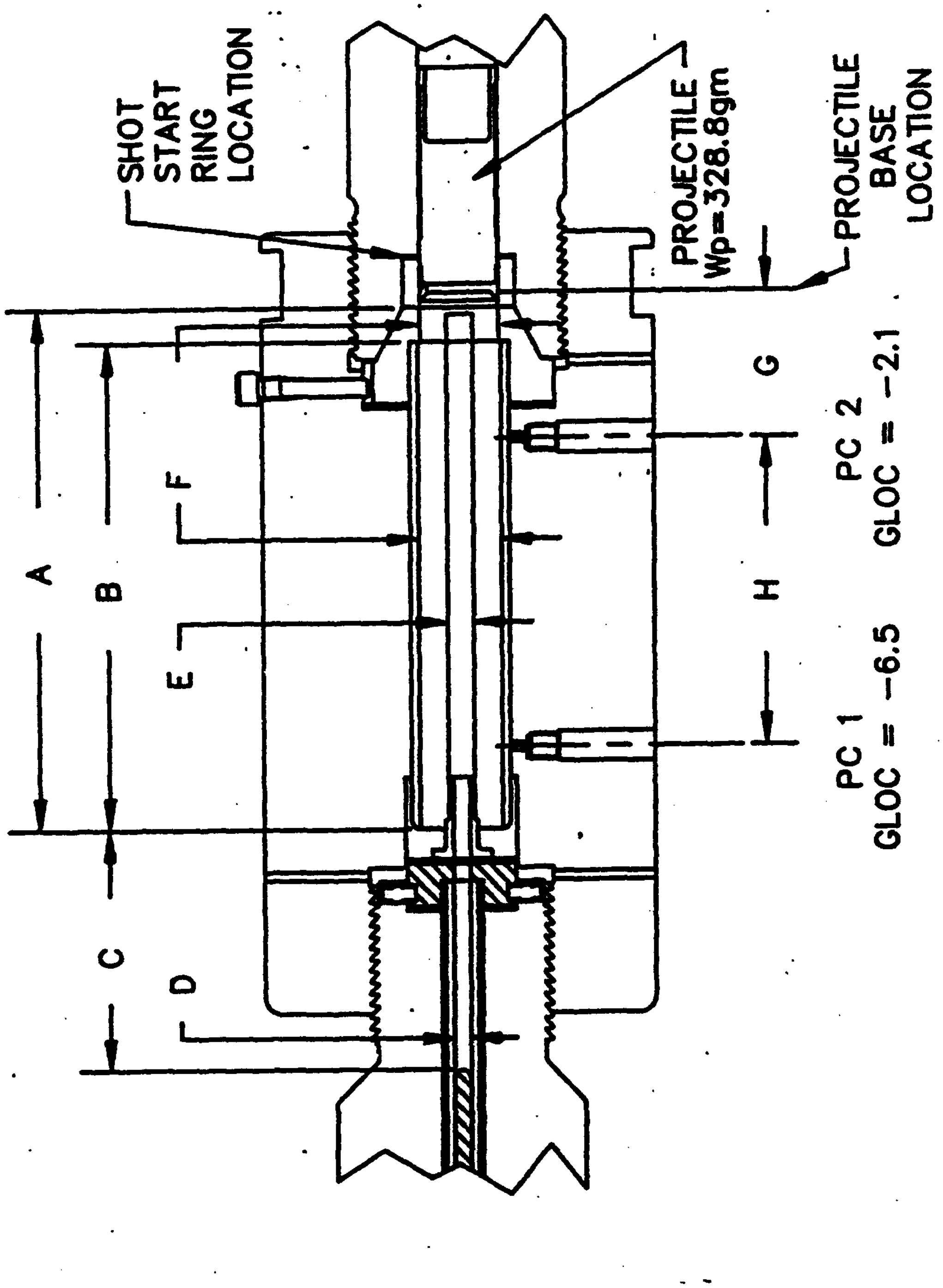
Summary

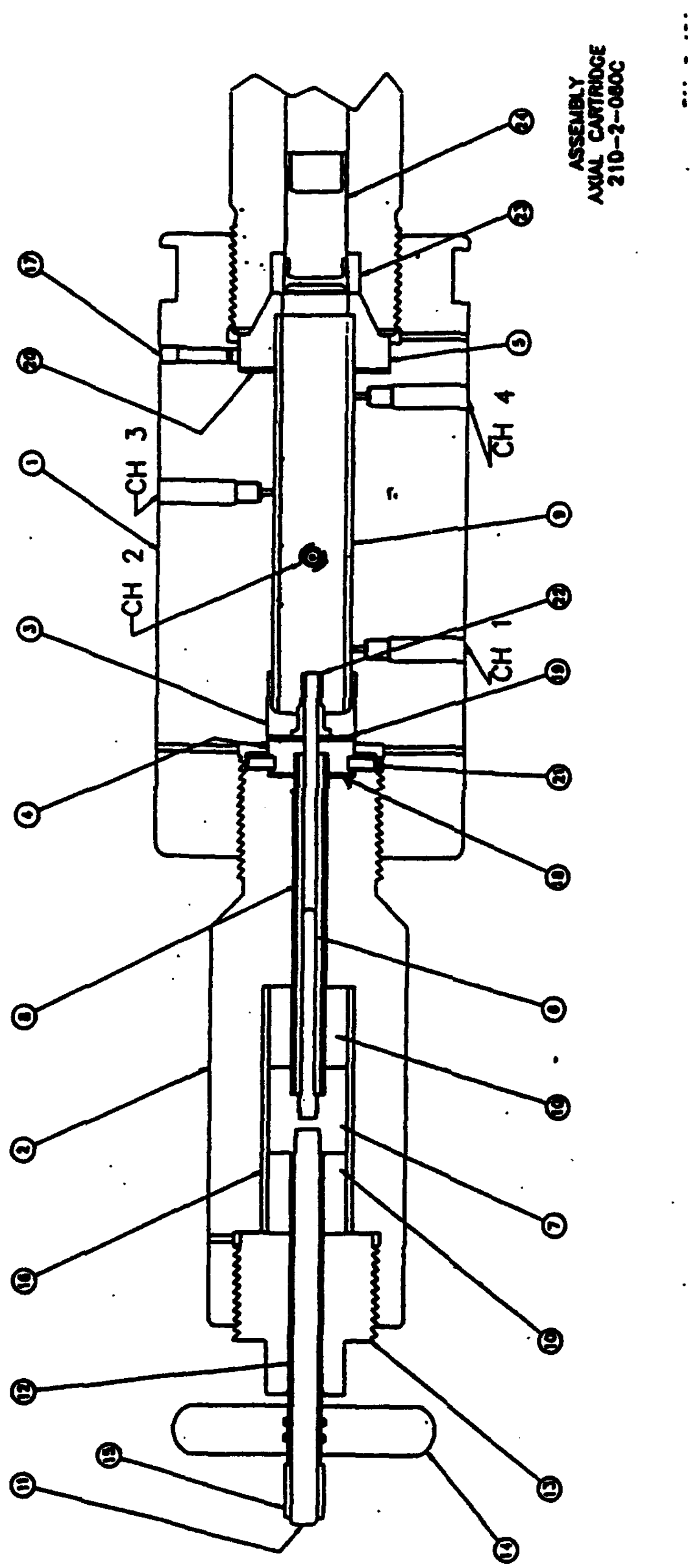
–In the CBP model a 120mm M291 ETC gun using a cartridge with JA2 at a LD equal to its density with 0.5 MJ/KG EE attains a muzzle velocity of 1900 M/S that is slightly higher than a conventional 140mm M291 Tank Gun using granular JA2 at a LD of 1.

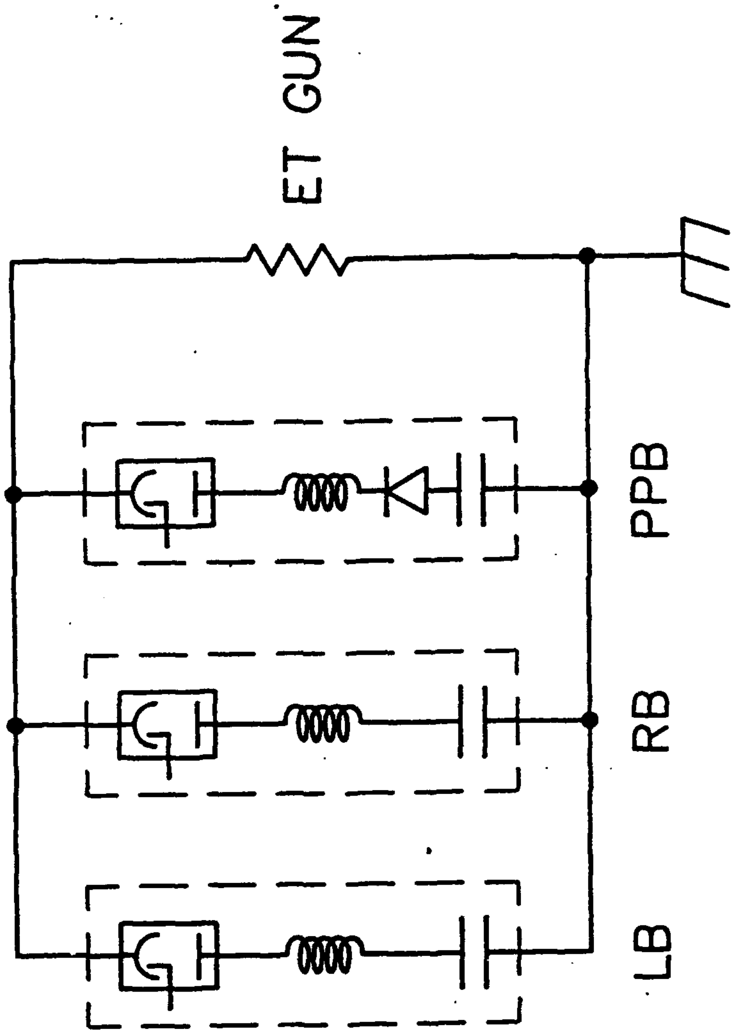
–CBP calculations indicate that a similar design for a 105mm ETC Air Defense gun will achieve velocities greater than 2 KM/s for both the D2 and D3 smart projectiles.

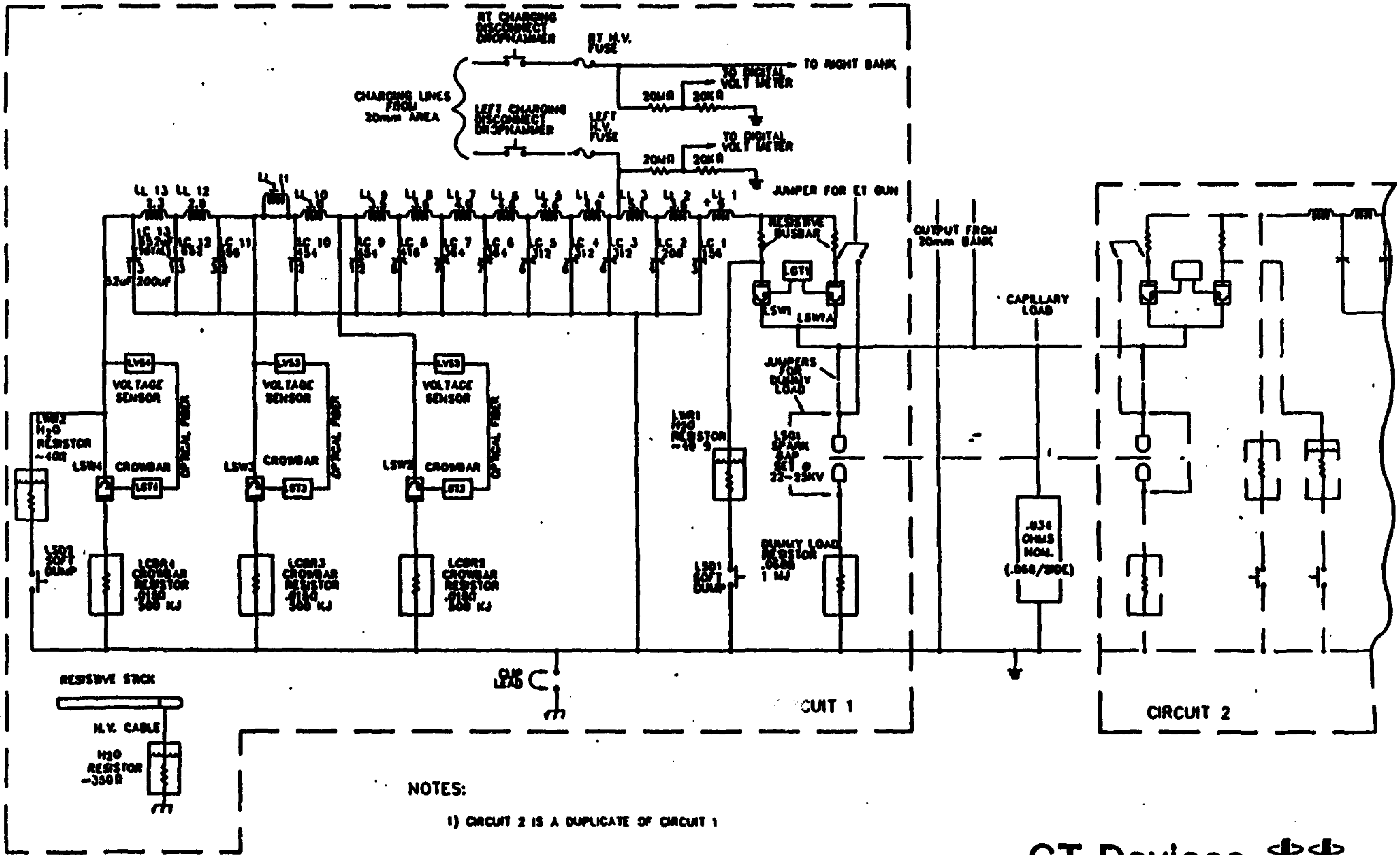
–If the mass generation rate required to meet the above performance is not achievement, plasma influenced grain de–consolidation at the correct rate would be required to meet performance.


A
B
C
D
E
F
G
PROJECTILE BASE


SHOT START RING LOCATION
PROJECTILE Wp=328.8gm
PROJECTILE BASE LOCATION
A
B
C
D
E
F
G
H
PC 1 GLOC = −6.5
PC 2 GLOC = −2.1


ASSEMBLY
AXIAL CARTRIDGE
210-2-080C
CH 1
CH 2
CH 3
CH 4


ET GUN
PPB
RB
LB



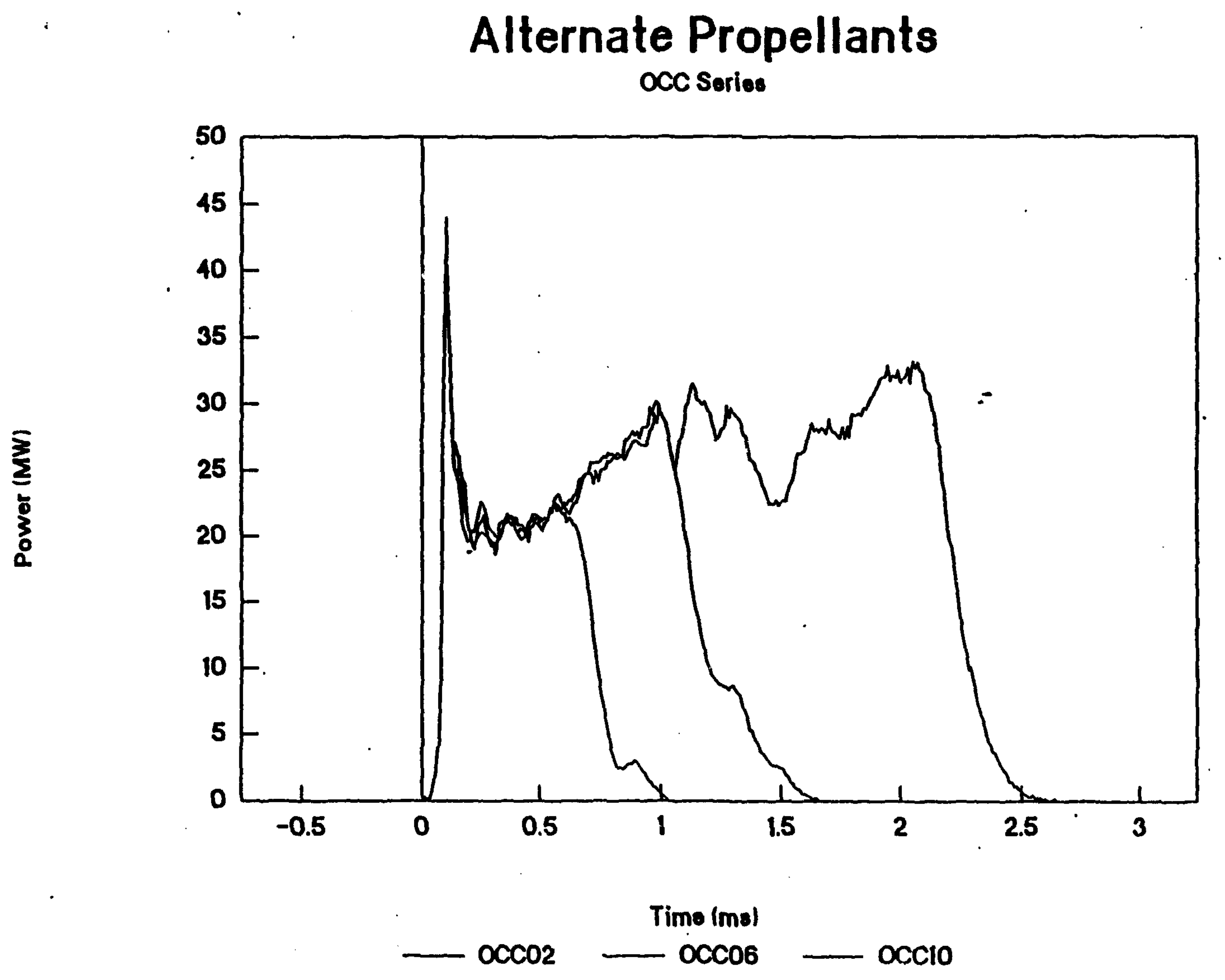
NOTES:

1) CIRCUIT 2 IS A DUPLICATE OF CIRCUIT 1

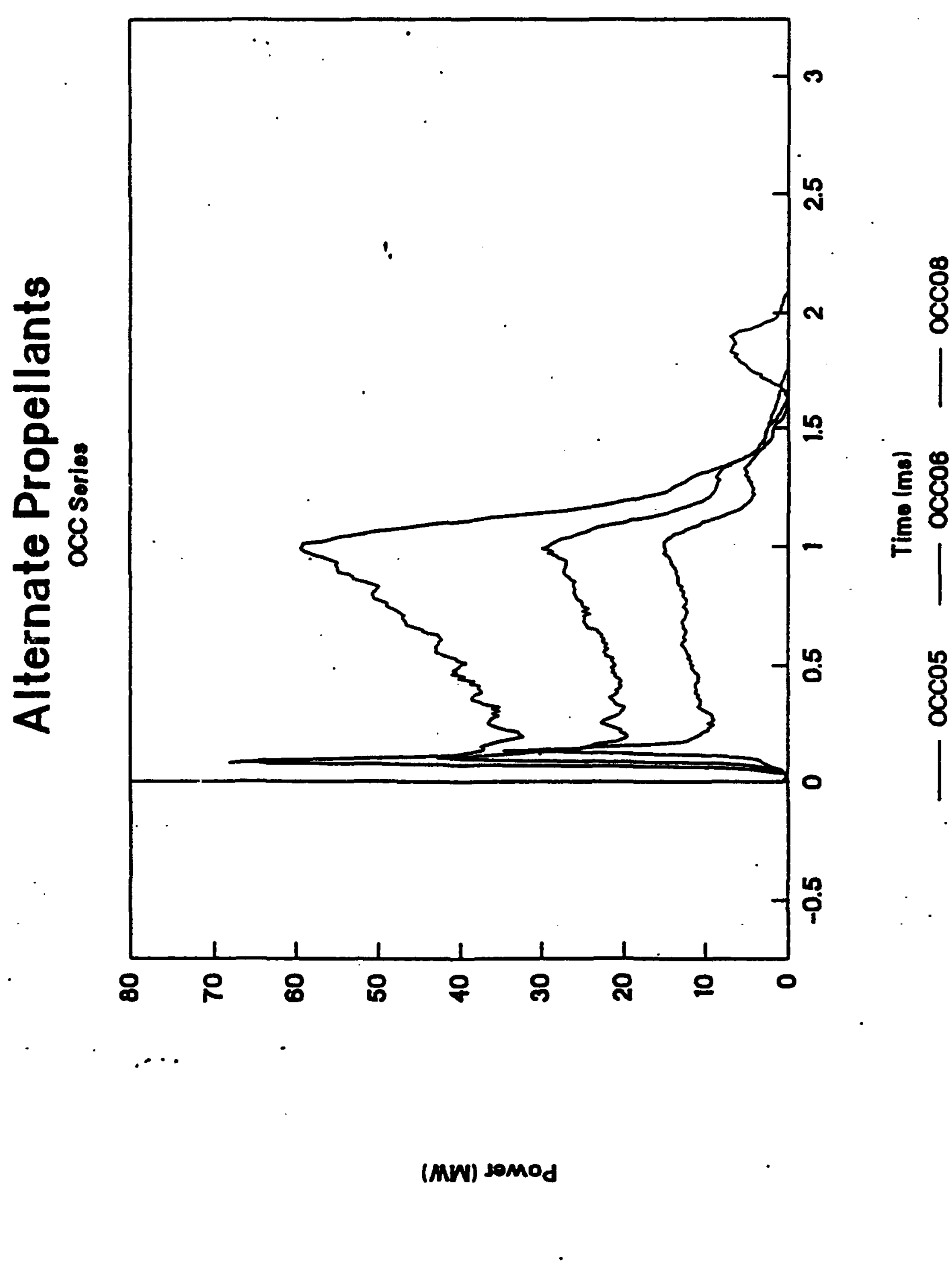
GT-Devices

SCHEMATIC DIAGRAM
30mm PFN

21A-6-193



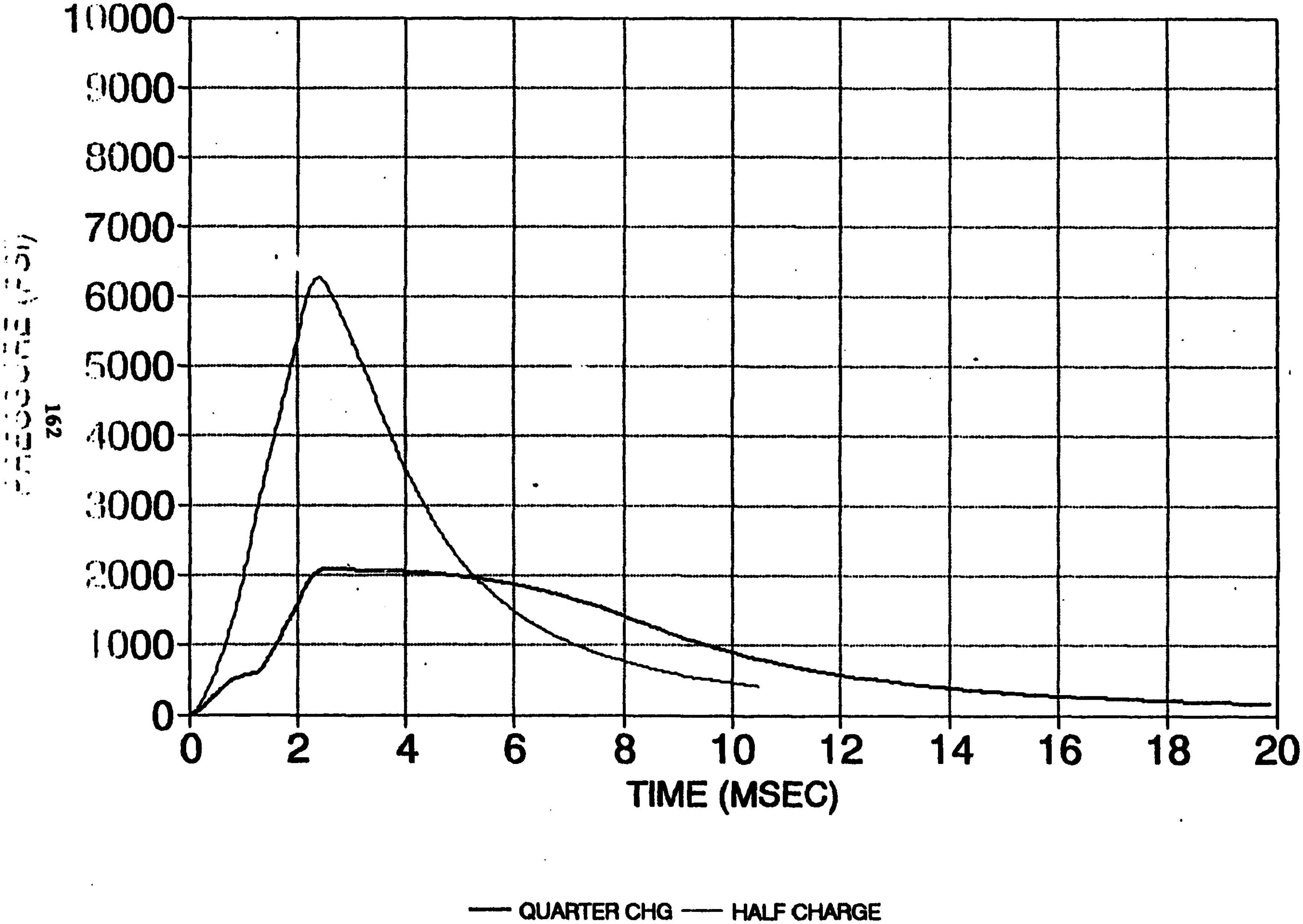
Alternate Propellants
OCC Series
Power (MW)
50
45
40
35
30
25
20
15
10
5
0
-0.5
0
0.5
1
1.5
2
2.5
3
Time (ms)
OCC02
OCC06
OCC10


Alternate Propellants
OCC Series
Power (MW)
0
10
20
30
40
50
60
70
80
Time (ms)
-0.5
0
0.5
1
1.5
2
2.5
3
OCC05
OCC06
OCC08

IBHVG2 PREDICTIONS FOR CENTER CORE BURNING JA2 MONOLITHS

CHARGE	P(KSI)	V(M/S)	%BURNT
1/4	2	146	0.4
1/2	6	221	0.6
1	13	334	0.7

JA-2 PRESHOT IBHVG2 RESULTS
2.4 MSEC AT 0.5 MJ/KG EE



Firing Schedule
As Fired

May 3, 1993

Shot Number	/Date	Charge Weight	Power Pulse Length (ms)	Energy Density (kJ/gm)	(kV)	
1	4/08/93	1/4	2.2	.75	2.6 -LB+RB	
2	4/08/93	1/2	2.2	.75	3.7 -LB+RB	
3	4/14/93	3/4	2.2	.75	4.6 -LB+RB	
4	4/14/93	F	2.2	.75	5.3 -LB+RB	
5	4/15/93	1/4	1.1	.37	2.6 -LB	
6	4/15/93	1/2	1.1	.37	3.7 -LB	
7	4/16/93	1/4	1.1	0.75	3.7 -LB	
8	4/16/93	1/2	1.1	0.75	5.2 -LB	
9	4/20/93	1/4	0.6	.2	2.6 -½LB	
10	4/20/93	1/2	0.6	.2	3.7 -½LB	
11	4/21/93	1/4	1.1	0.75	3.7 -½LB	Mod Tube
12	4/21/93	1/2	1.1	0.75	5.2 -½LB	Mod Tube
13	4/22/93	1/2	2.2	0.75	3.7 -½LB	Mod Tube
14	4/22/93	1/4	0.6	0.75	5.2 -½LB	Mod Tube
15	4/27/93	3/4	2.2	0.75	4.6 -LB+RB	Mod Tube
16	4/27/93	F	2.2	0.75	5.3 -LB+RB	Mod Tube
17	4/28/93	3/4	2.2	0.37	3.25-LB+RB	Mod Tube
18	4/28/93	F	2.2	0.37	3.7 -LB+RB	Mod Tube

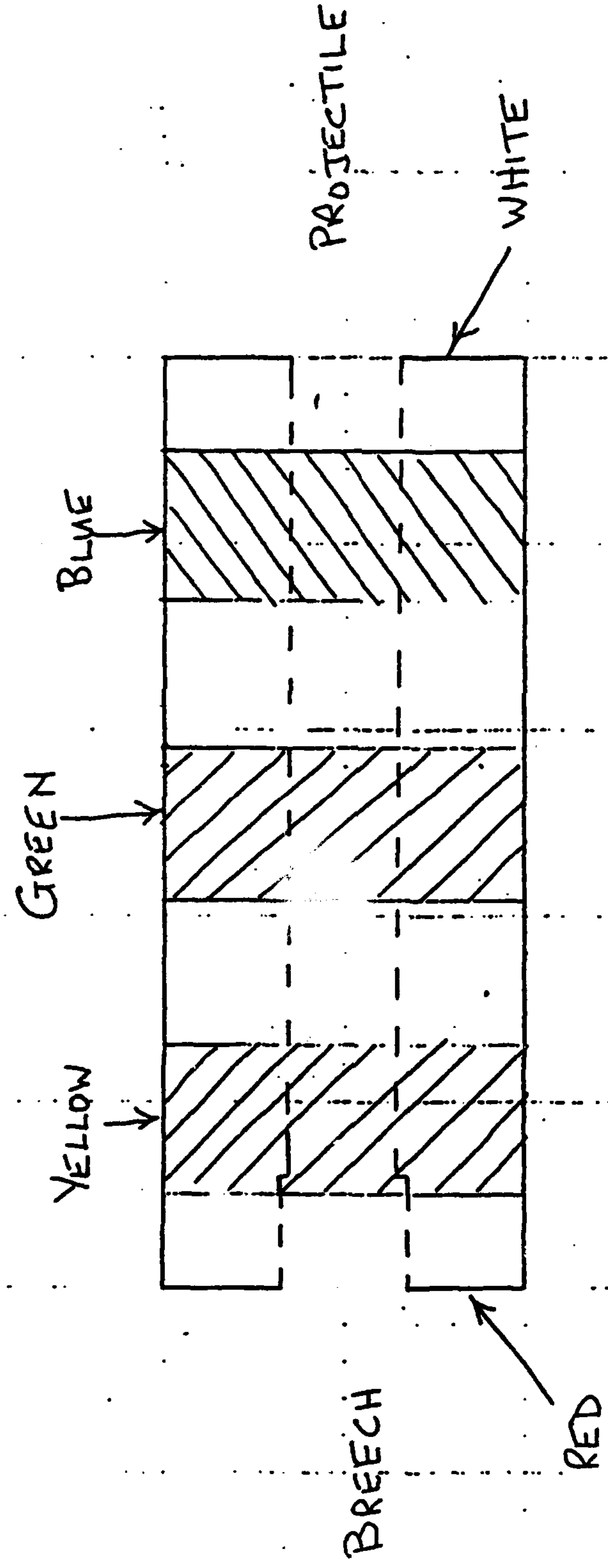
LB - 30mm Left Bank
RB - 30mm Roght Bank

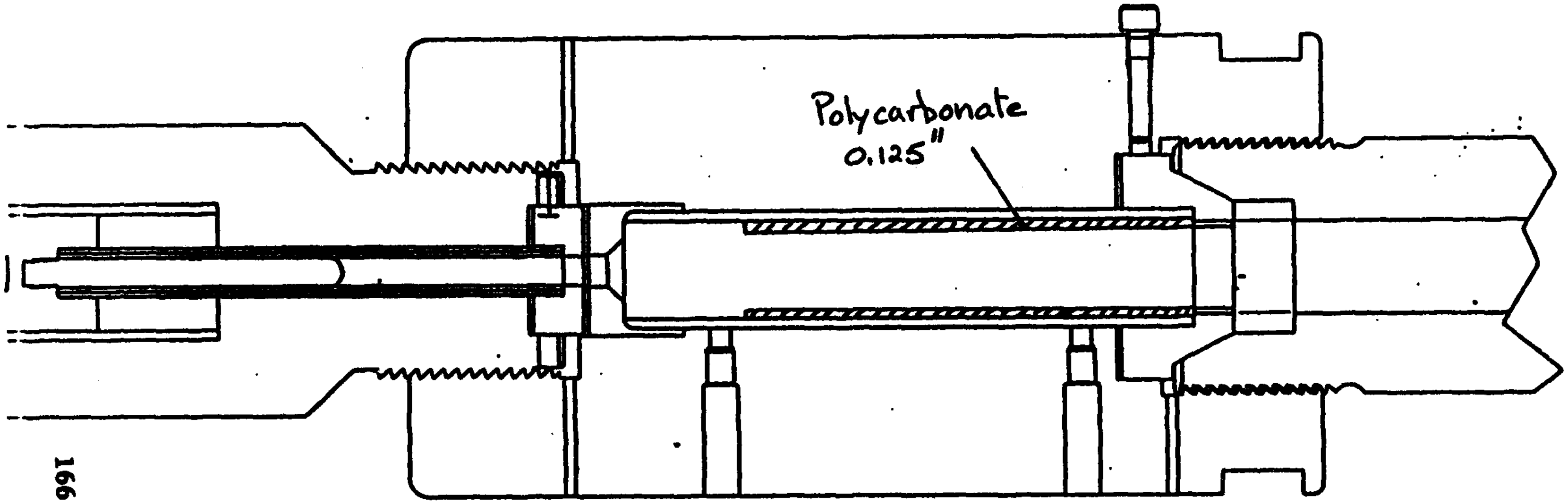
LB+RB - LB fired first, RB fired after delay of 1050μs.
LB - LB alone.
½LB - LB with LL9 disconnected from LC8.

DATE 04/30/93
08:52 AM

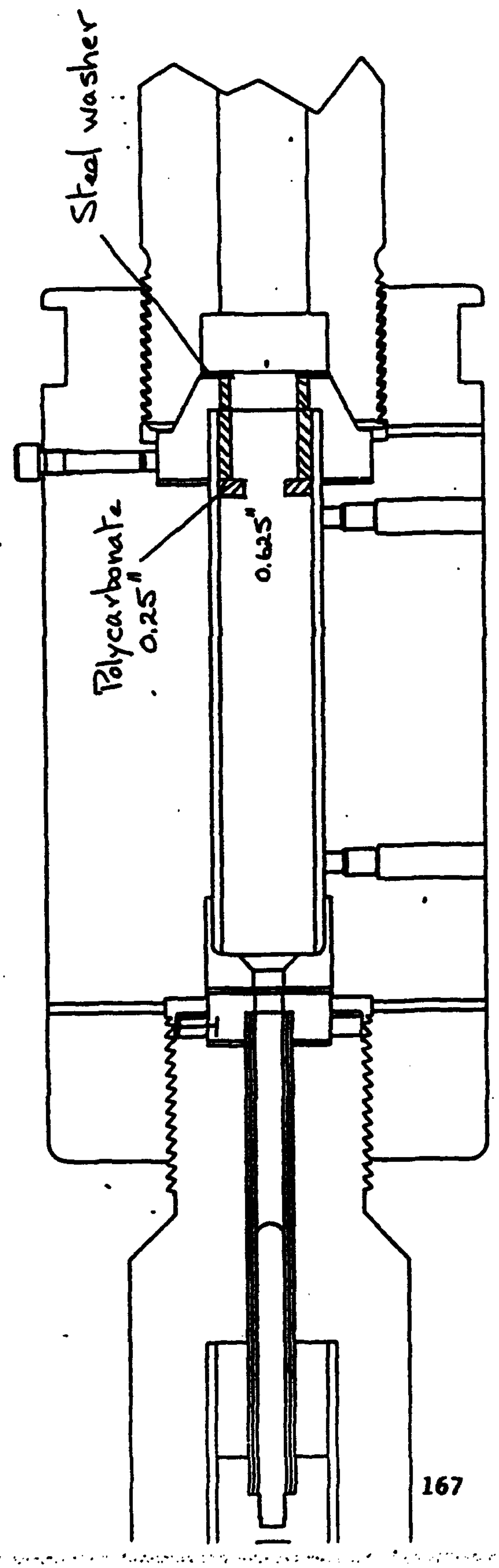
30MM AXIAL CARTRIDGE DATA BASE
REVISED 4/93 FOR OLIN 'C' SERIES DATA

SHOT NUMB	DATE	PROJ MASS GM	PROP FILL GM.	CART ENER KJ	PROJ VEL KM/SEC	COMPRESS VEL KM/SEC	VOLTS KV	PEAK POWER MEG W	CHBR PRESS KPSI	EXTENDED NOTES AND COMMENTS	CHAMBER VOLUME (CM3)	ENERGY DENSITY KJ/GM	SHOT NUMB
1	04/08/93	332.3	41.3	30	0.319		2.60	16	10	JA-3 SINGLE PERF SINGLE GRAIN 1/4 CHARGE; 0.75KJ/GM 2.2ms PULSE	161.0	0.74	1
2	04/08/93	332.3	83.8	58	0.478		3.68	33	18	JA-2 (SPSG) 1/2 CHARGE; 0.75KJ/GM 2.2ms PULSE	161.0	0.70	2
3	04/14/93	332.6	130.8	77	0.480		4.60	47	27	JA-2 (SPSG) 3/4 CHARGE; 0.75KJ/GM 2.2ms PULSE; MODS. TO HOLD GRAIN	161.0	0.59	3
4	04/14/93	331.9	176.1	111	0.547		5.30	68	30	JA-2 (SPSG) FULL CHARGE; 0.75KJ/GM 2.2ms PULSE	161.0	0.63	4
5	04/15/93	333.1	41.3	15	0.271		2.60	15	10	JA-2 (SPSG) 1/4 CHARGE; 0.37KJ/GM 1.1ms PULSE (LEFT BANK)	161.0	0.37	5
6	04/15/93	332.1	85.1	28	0.386		3.70	30	17	JA-2 (SPSG) 1/2 CHARGE; 0.37KJ/GM 1.1ms PULSE; SM PROP LEFT IN CHBR	161.0	0.33	6
7	04/16/93	329.1	41.2	29	0.342		3.70	30	11	JA-2 (SPSG) 1/4 CHARGE; 0.75KJ/GM 1.1ms PULSE (OCC01 W/SHORT PULSE)	161.0	0.70	7
8	04/16/93	328.6	84.9	54	0.433		5.20	60	19	JA-2 (SPSG) 1/2 CHARGE; 0.75KJ/GM 1.1ms PULSE (OCC02 W/SHORT PULSE)	161.0	0.63	8
9	04/20/93	329.2	41.0	8	0.192		2.60	12	7	JA-2 (SPSG) 1/4 CHARGE; 0.2KJ/GM 0.6ms PULSE; PAINTED PROPELLANT	161.0	0.20	9
10	04/20/93	329.5	84.7	15	-.260		3.70	22	17	JA-2 (SPSG) 1/2 CHARGE; 0.2KJ/GM 0.6ms PULSE; BAD VELOCITY DATA	161.0	0.18	10
11	04/21/93	329.1	38.5	30	0.162		3.70	32	5	JA-2 (SPSG) 1/4 CHARGE; 0.75KJ/GM 1.1ms PULSE W/MOD TUBE; NO VEL 3	161.0	0.78	11
12	04/21/93	328.8	78.9	54	0.358		5.20	55	20	JA-2 (SPSG) 1/2 CHARGE; 0.75KJ/GM 1.1ms PULSE W/MOD TUBE	161.0	0.69	12
13	04/22/93	329.0	78.0	57	0.365		3.70	31	18	JA-2 (SPSG) 1/2 CHARGE; 0.75KJ/GM 2.2ms PULSE; MOD TUBE;PROP INTACT	161.0	0.73	13
14	04/22/93	329.5	38.5	30	0.218		5.20	47	6	JA-2 (SPSG) 1/4 CHARGE; 0.75KJ/GM 0.6ms PULSE MOD TUBE;PROJ TUMBLED	161.0	0.77	14
15	04/27/93	328.3	120.5	86	0.426		4.60	48	13	JA-2 (SPSG) 3/4 CHARGE; 0.75KJ/GM 2.2ms PULSE MOD TUBE;GRAIN RECOV.	161.0	0.71	15
16	04/27/93	328.9	162.5	102	0.554		5.30	64	31	JA-2 (SPSG) FULL CHARGE; 0.75KJ/GM 2.2ms PULSE; W/ MODERATOR TUBE	161.0	0.63	16
17	04/28/93	329.0	121.4	46	0.322		3.25	26	11	JA-2 (SPSG) 3/4 CHARGE; 0.37KJ/GM 2.2ms PULSE W/ MODERATOR TUBE	161.0	0.38	17
18	04/28/93	328.9	156.2	59	-.330		3.70	32	16	JA-2 (SPSG) FULL CHARGE; 0.37KJ/GM 2.2ms PULSE MOD TUBE; BAD VELOC.	161.0	0.37	18

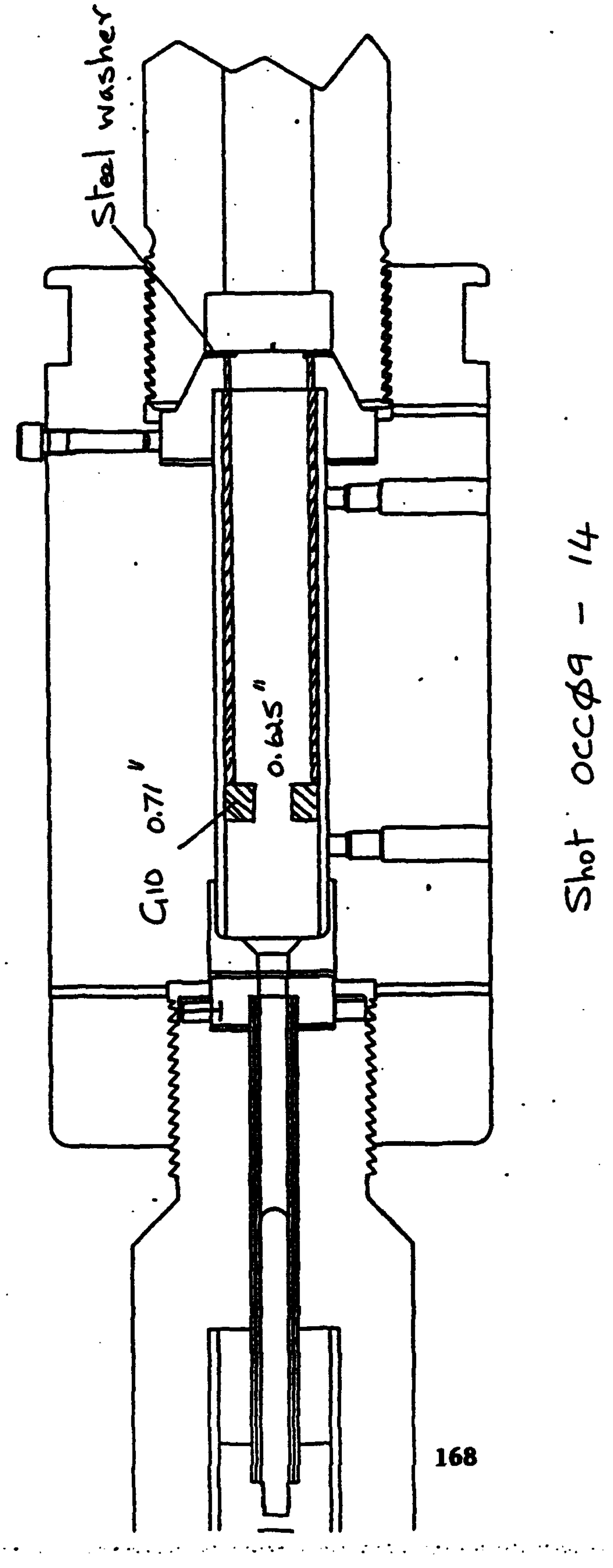

PROJECTILE
WHITE
BLUE
GREEN
YELLOW
BREECH
RED

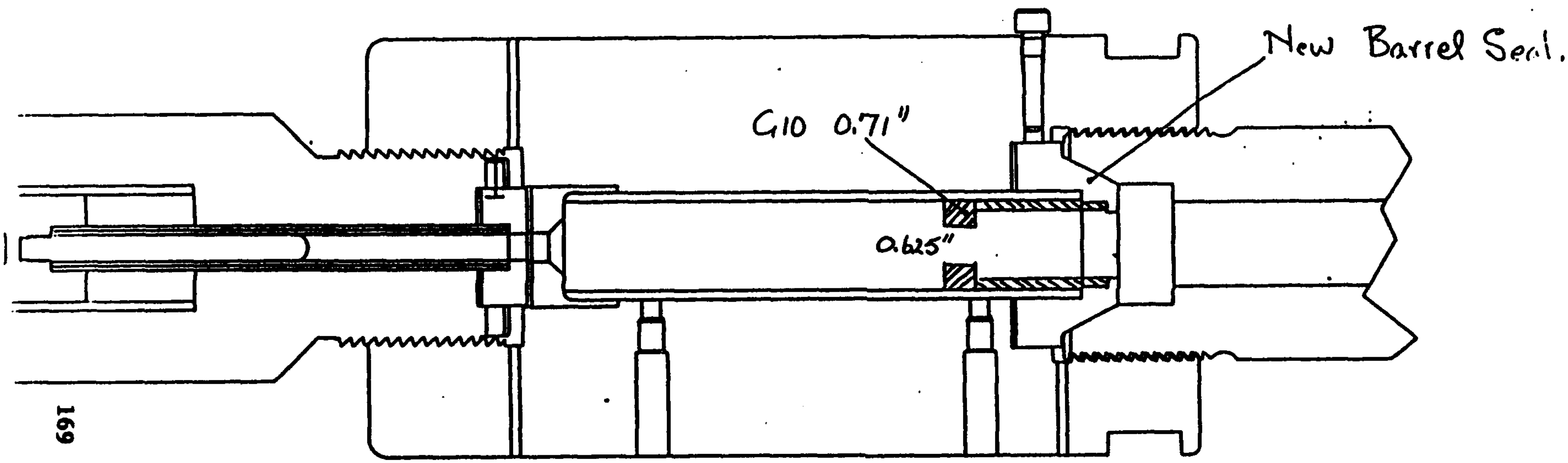


Shot OCCΦ1 and Φ2.



Shots OCC Ø3 – Ø8


Steel washer
G10 0.71"
0.625"
Shot OCC09 - 14

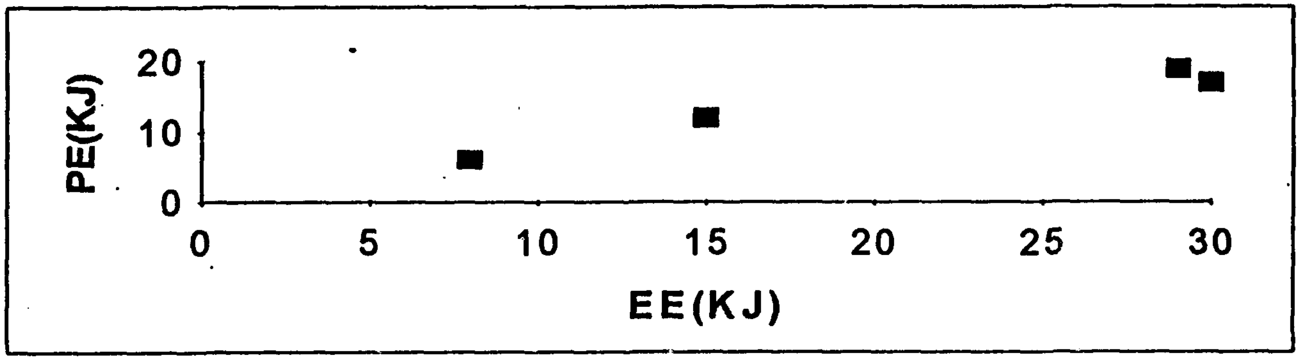


Shots OCC 15 - 18

SHOT NUMB	Notes on retainer system	Retainer System
1	Insert tube pushed slightly into barrel.	I
2	Insert tube stuck in barrel, > 1 inch.	I
3	All retainers launched.	II
4	All retainers launched.	II
5	Nozzle melted, tube in place, melted.	II
6	Ring launched, tube in chamber.	II
7	Ring launched, tube moved forward.	II
8	Ring launched, tube pushed into barrel.	II
9	Nozzle melted, tube in place, ring launched.	III
10	G10 retainer pushed into barrel seal.	III
11	Inserts in place.	III
12	Melt down. Liquid in barrel.	III
13	G10 ring in chamber, tube pushed into barrel seal.	III
14	All retainers in place.	III
15	All retainers in place.	IV
16	Retainers launched.	IV
17	G10 ring pushed into barrel seal, tube launched.	IV
18	Steel ring in place.	IV

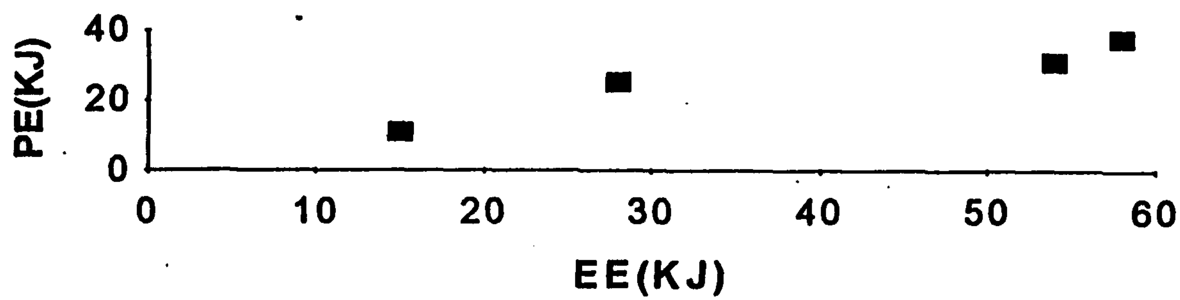
JA2 MONOLITHS
QUARTER CHARGE

SHOT	P(MW)	EE(KJ)	V(M/S)	PE(KJ)
1	16	30	316	17
5	15	15	271	12
7	30	29	342	19
9	12	8	192	6.1
11 MT	32	30	162	4.4
14 MT	47	30	218	7.9



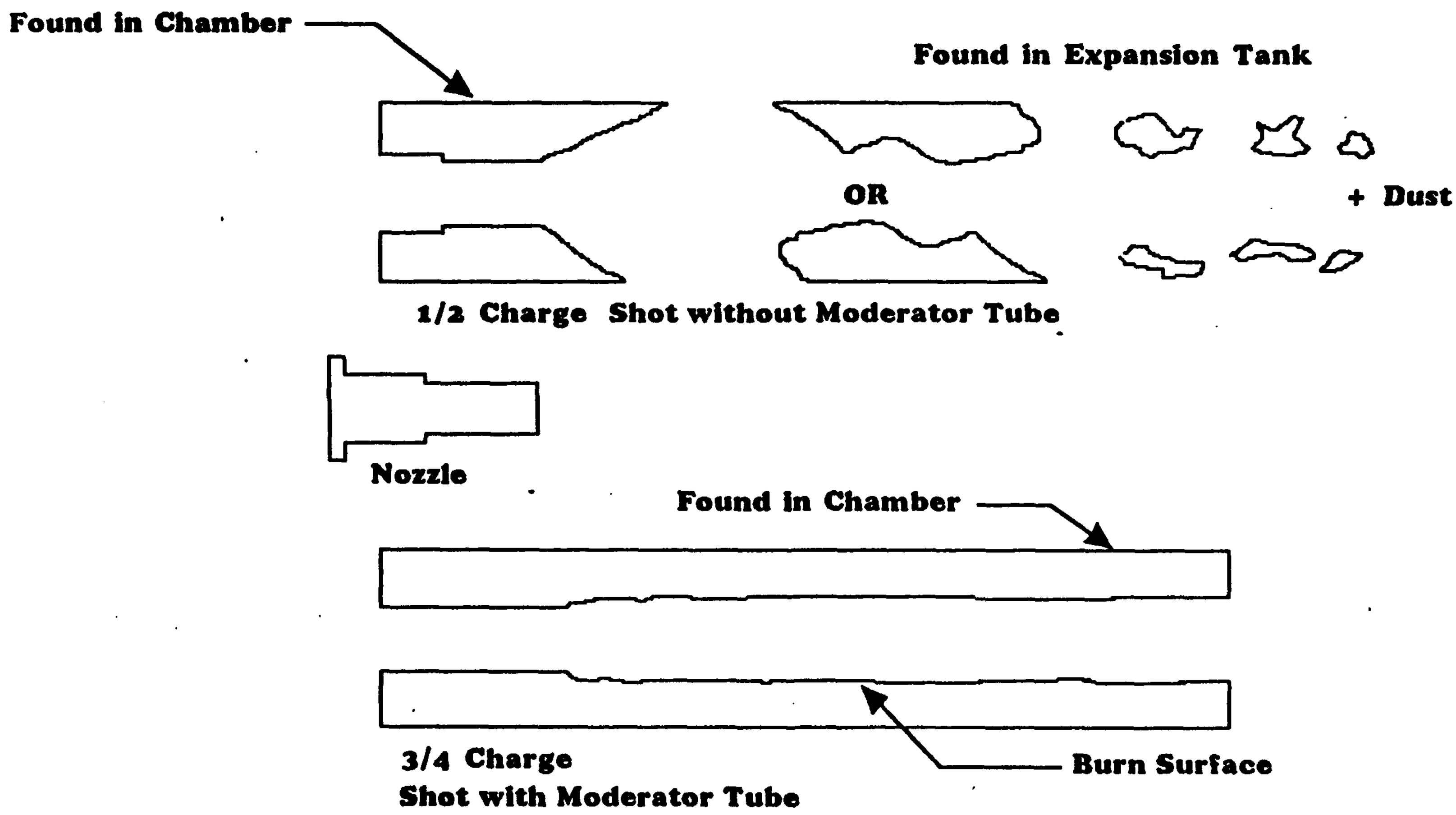
JA2 MONOLITHS HALF CHARGE

SHOT	P(MW)	EE(KJ)	V(M/S)	PE(KJ)
2	33	58	478	38
6	30	28	386	25
8	60	54	433	31
10	22	15	260	11
12	55	54	358	21
15	31	57	365	22



SHOT NUMB	PROP FILL GM	TANK RESIDUE GM		Chamber Residue gm		Barrel Residue gm
1	41.3	18.4	Broken not burned	TRACE		0.9
2	83.8	32.5	Some burned	2.2	one piece, burned	TRACE
3	130.8	57.8	18 chunks, 40 dust	TRACE		0.6
4	176.1	27.1	powder	3.9	pieces, burned	0.1
5	41.3	10.0	powder	TRACE	melt down	0.1
6	85.1	48.4	28 chunks, 20 powder	17.3	cracked, burned	0.9
7	41.2	20.8	11 chunks, 10 dust	18.0	cracked, burned	0.1
8	84.9	55.0	22 chunks, 33 dust	16.6	large pieces, burned	TRACE
9	41.0	21.0	few chunks, rest dust	TRACE		0.4
10	84.7	44.7	5 chunks, 40 dust	10.0	pieces, burned	0.0
11	38.5	7.[illegible]	dust	37.8	whole	0.1
12	78.9	6.3	dust	TRACE		LIQUID
13	78.0	10.9	dust	66.8	cracked, burned	0.1
14	38.5	8.9	dust	32.9	cracked, burned	TRACE
15	120.5	18.0	few chunks, rest dust	109.9	whole	0.2
16	162.5	69.0	26 chunks, 43 dust	0.2		0.7
17	121.4	65.1	dust	NONE		NONE
18	156.2	87.4	27 chunks, 61 dust	NONE		1.3

Residue



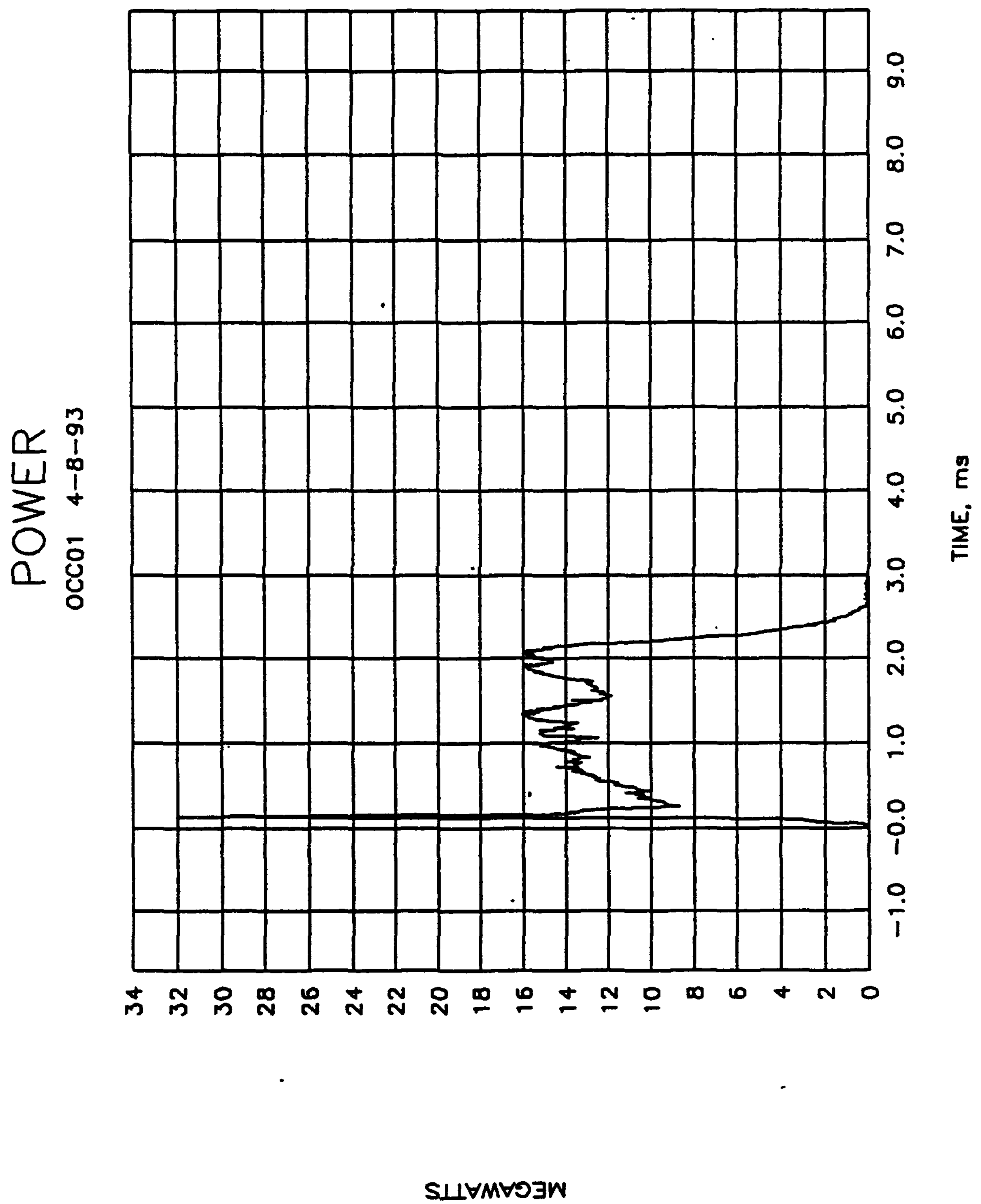
Found in Chamber
Found in Expansion Tank
OR
+ Dust
1/2 Charge Shot without Moderator Tube
Nozzle
Found in Chamber
3/4 Charge
Shot with Moderator Tube
Burn Surface

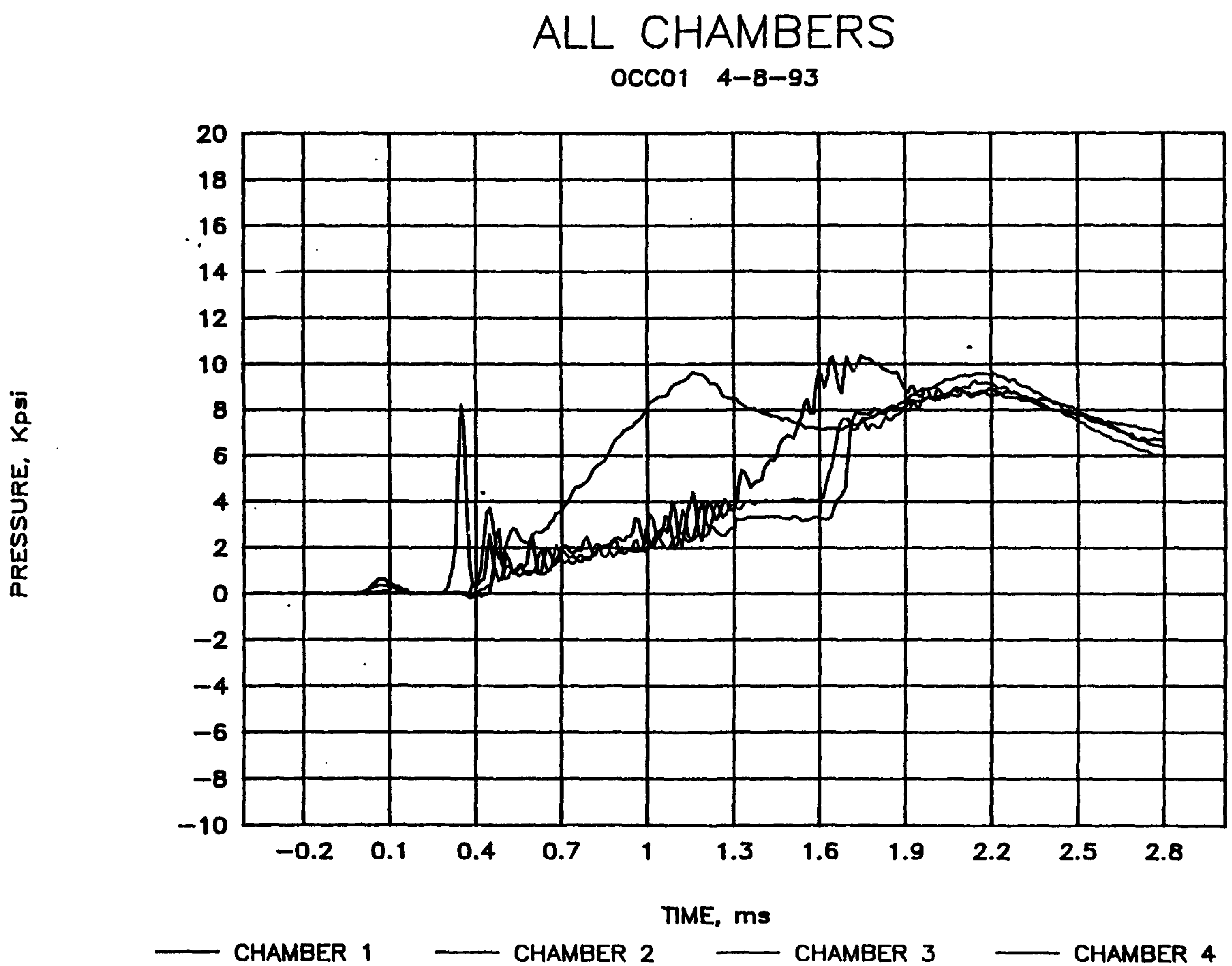
JA2 MONOLITHS BURNING RATES

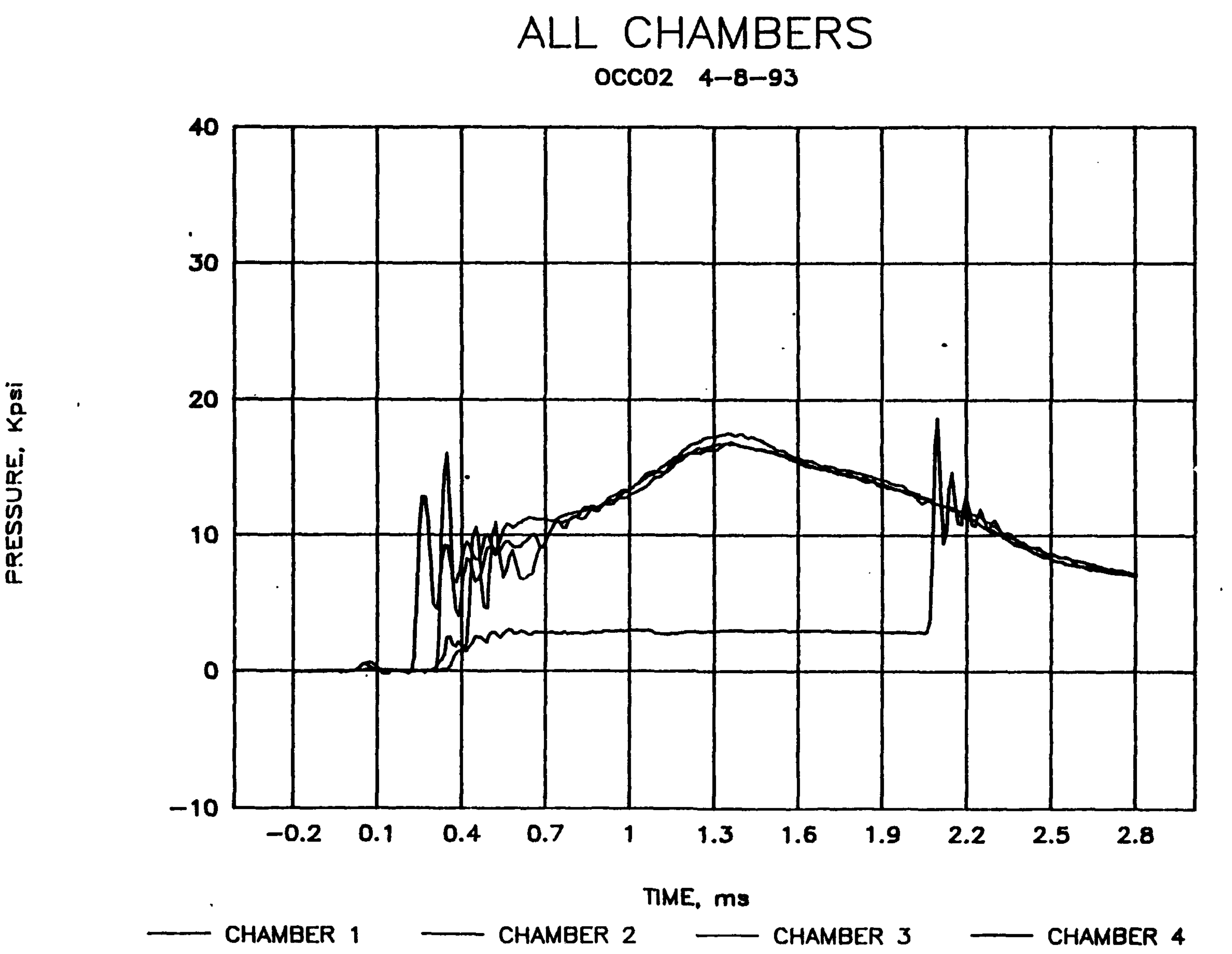
$r = b\,[P_{mean}]^{a} + c\,v$

$v = v_P$ proj velocity for prop/gas surface

$v = v_J$ plasma velocity for prop/plasma surface

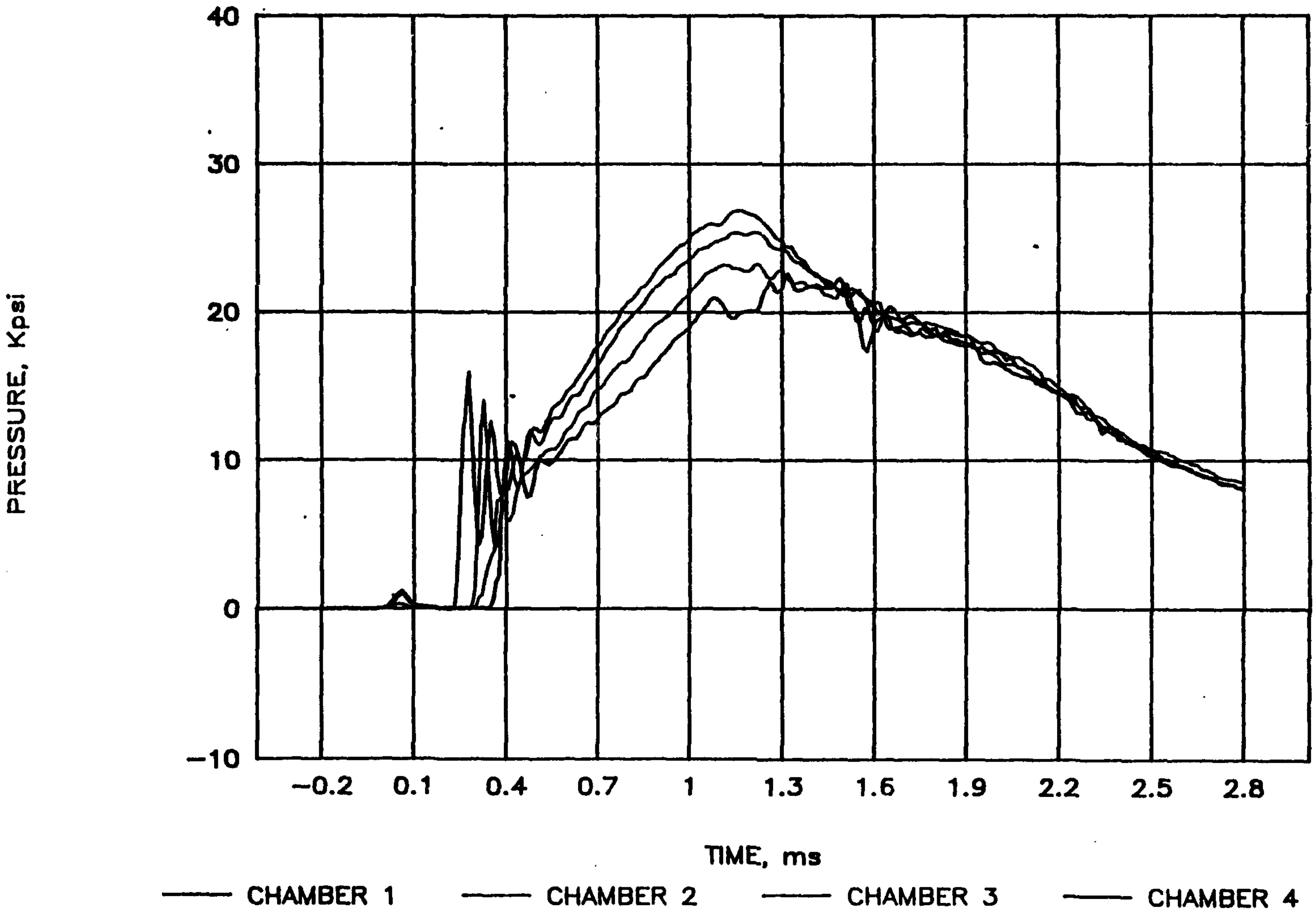

POWER
OCC01 4-8-93
MEGAWATTS
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
TIME, ms
-1.0
-0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0


ALL CHAMBERS
OCC01 4-8-93
20
18
16
14
12
10
8
6
4
2
0
−2
−4
−6
−8
−10
PRESSURE, Kpsi
−0.2
0.1
0.4
0.7
1
1.3
1.6
1.9
2.2
2.5
2.8
TIME, ms
CHAMBER 1
CHAMBER 2
CHAMBER 3
CHAMBER 4


ALL CHAMBERS
OCC02 4-8-93
PRESSURE, Kpsi
40
30
20
10
0
-10
-0.2
0.1
0.4
0.7
1
1.3
1.6
1.9
2.2
2.5
2.8
TIME, ms
CHAMBER 1
CHAMBER 2
CHAMBER 3
CHAMBER 4

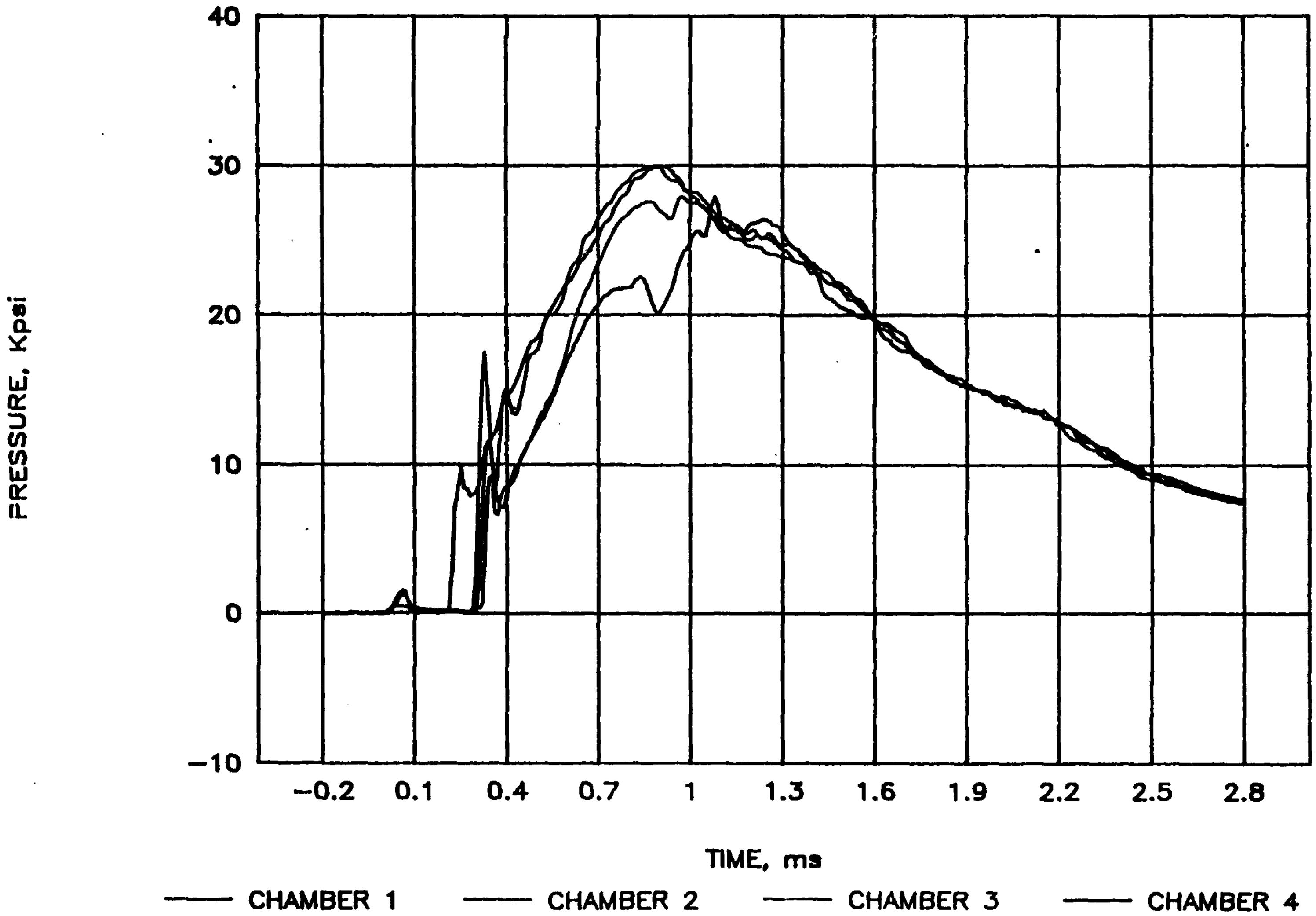
ALL CHAMBERS

OCC03 4-14-93



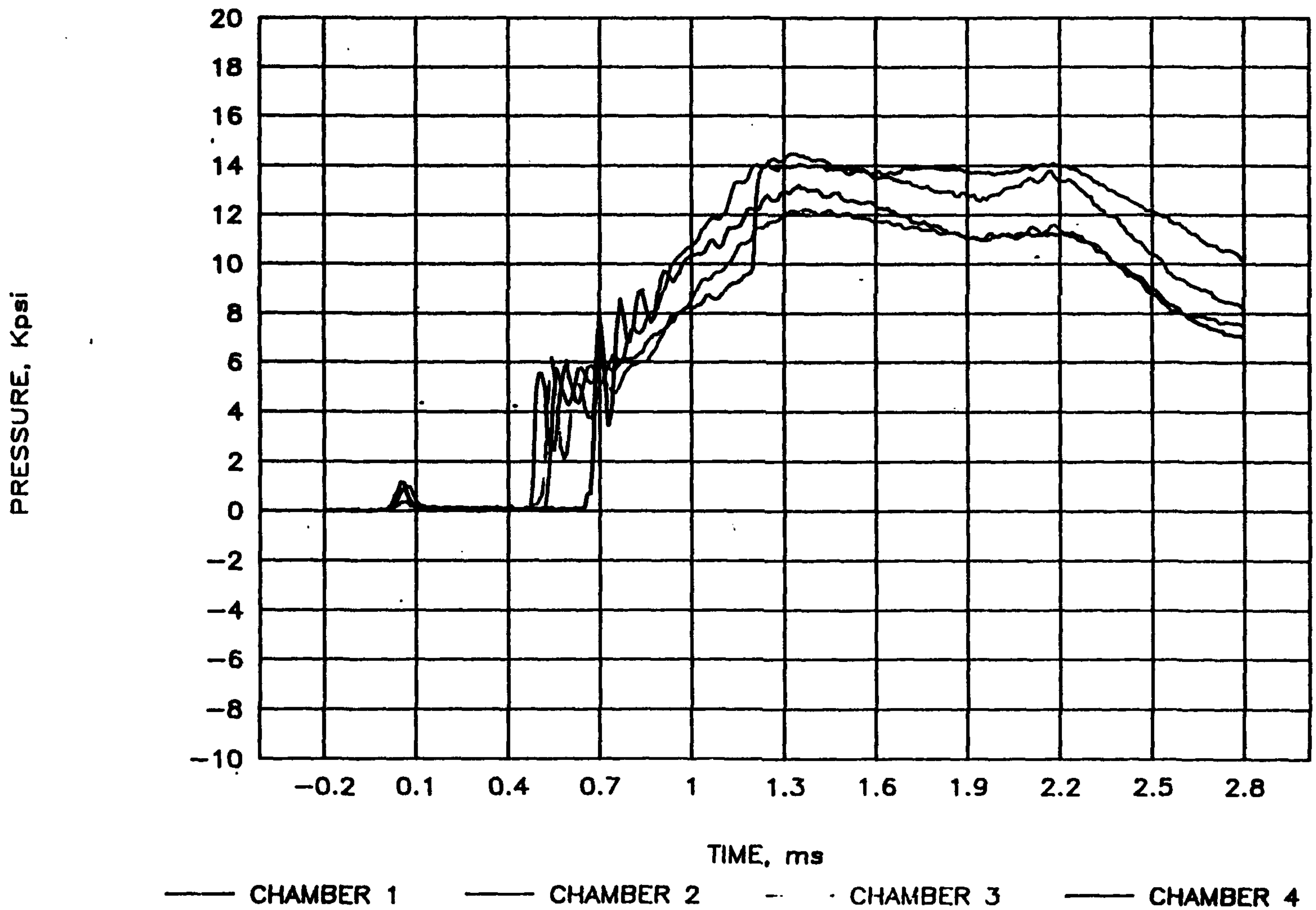
ALL CHAMBERS

OCC04 4-14-93



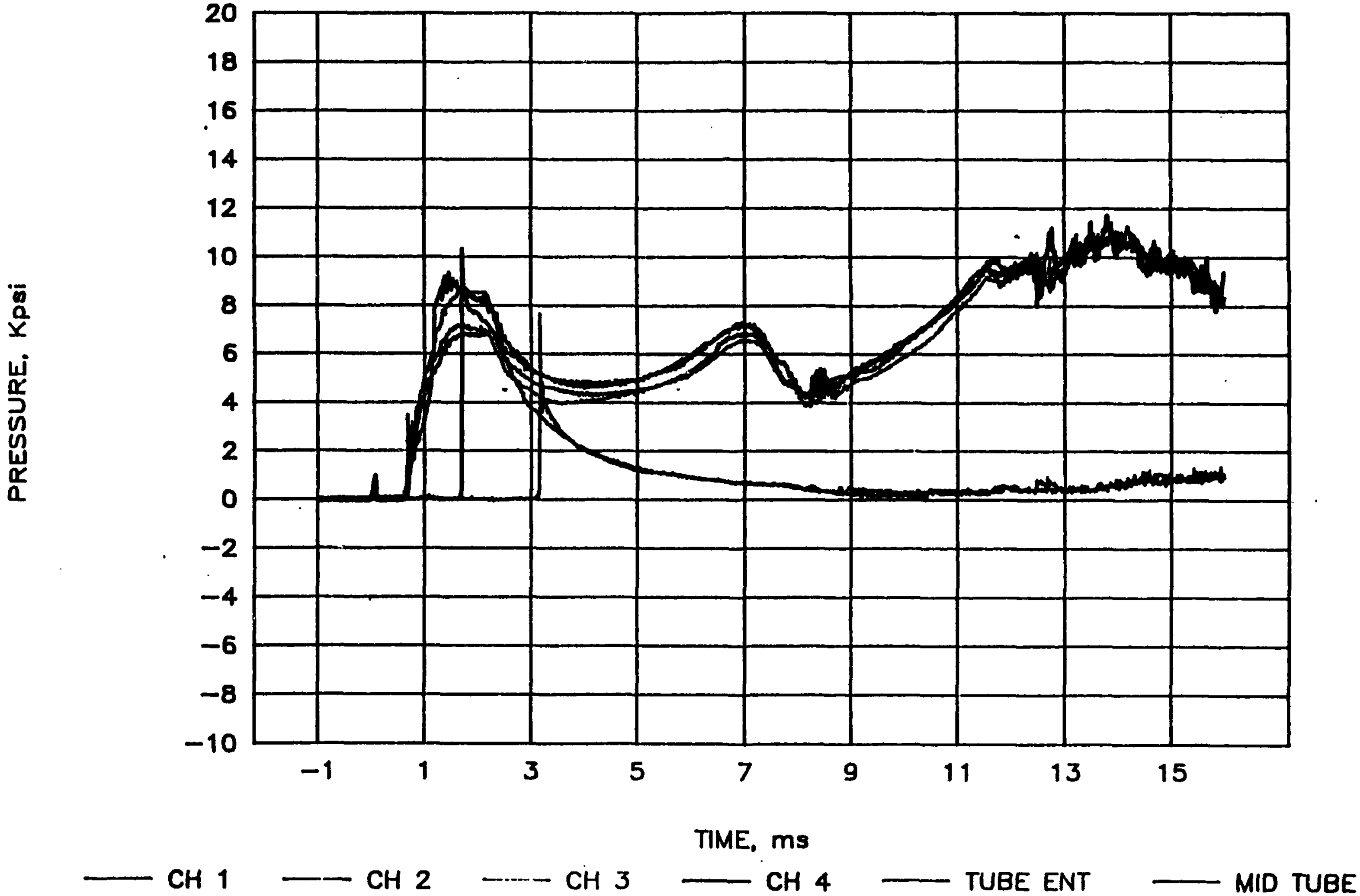
ALL CHAMBERS

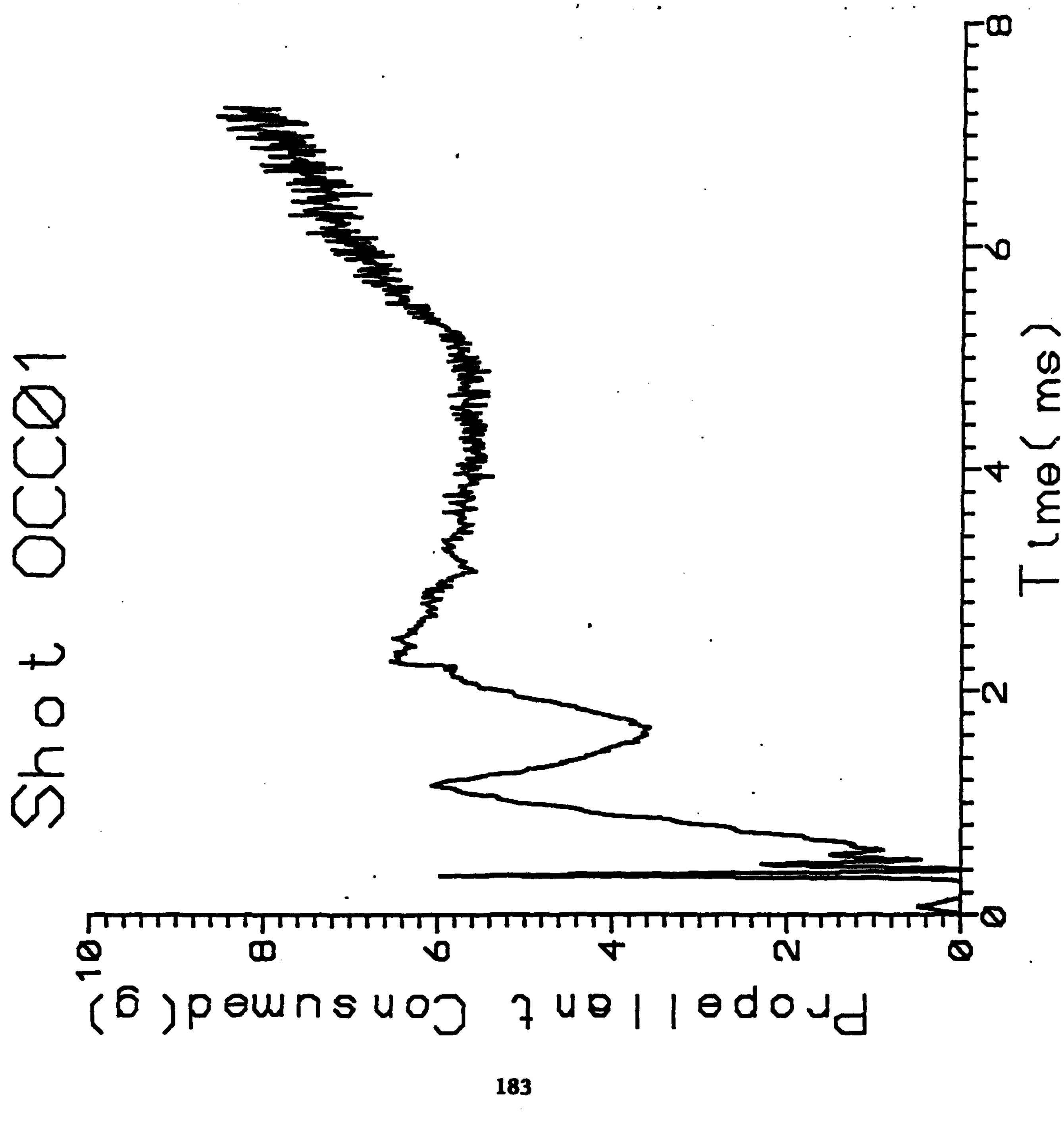
OCC15 4-27-93



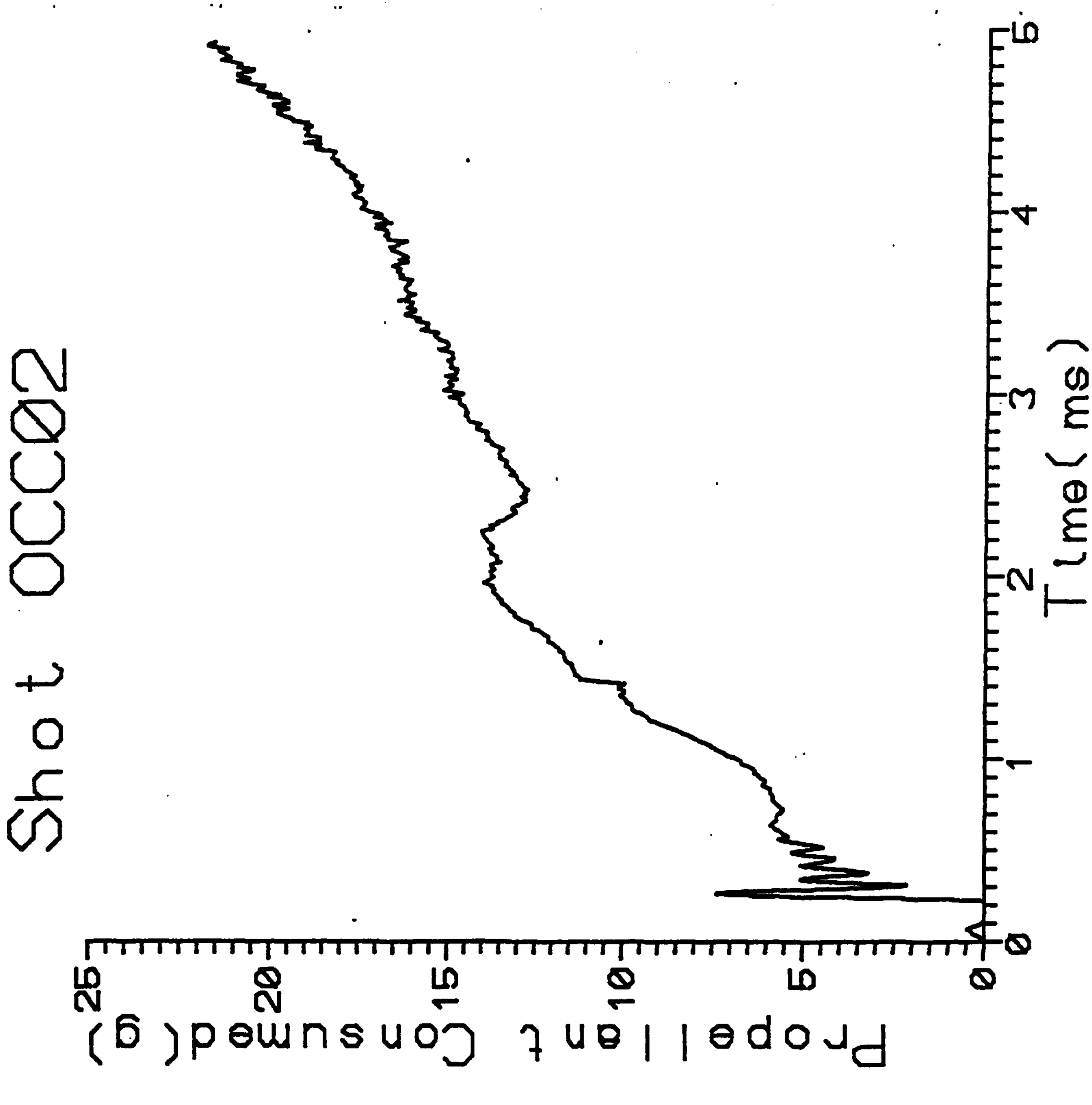
ALL PRESSURES

OCC17 4-28-93





Shot OCC01
Propellant Consumed (g)
Time (ms)
0
2
4
6
8
10


Shot OCC02
Propellant Consumed (g)
Time (ms)
0
5
10
15
20
25
0
1
2
3
4
5

Evidence Concerning Plasma Enhanced Erosive Burning

- For
  - Shape of large residual grains
  - Smooth pt and inverse cp traces
  - Higher than predicted pressure and velocity
- Against
  - residue
  - Some cracking in larger grains
- More data will be obtained in the at least six remaining shots

INTENTIONALLY LEFT BLANK.

DROPLET ENTRAINMENT AND BREAKUP BY SHEAR FLOWS*

Kenneth K. Kuo and F. Bill Cheung

(Presented in the ETC Modeling Workshop at the Army Research Laboratory, Aberdeen Proving Ground, MD)

May 12, 1993

* Work sponsored by the U. S. Army Research Laboratory under Contract No. DAAA15-92-D-0011. The support and encouragement of Gloria P. Wren are highly appreciated.

OBJECTIVES

- To evaluate the applicability of existing correlations for describing the entrainment and subsequent breakup of the liquid propellant droplets caused by the discharge of a plasma jet from a plasma generating cartridge.

- To identify the key elements of plasma/liquid propellants interaction that are not fully understood.

- To summarize the findings of this critical review and to define basic research needs for future modeling and diagnostic activities in this subject area.

- To perform a theoretical analysis to provide guidance in the development of a suitable correlation applicable to ETC gun conditions.

CHARACTERISTIC LENGTH AND VELOCITY SCALES

- Two Macro-Length Scales

d_h — Hydraulic Diameter of the Core Region (Associated with phenomena of the Interfacial Shear Action and Inertia of the Core Flow)

δ — Liquid Film Thickness (Associated with Phenomena of Liquid-Film Motion and Induced Surface Wave Form)

- One Micro-Length Scale

l_{TW} — Taylor Wavelength (On the same Order as Ligament or Initial Droplet Size Before Secondary Breakup)

$$l_{TW} \equiv \left[\frac{\sigma}{g\ (\rho_f - \rho_g)}\right]^{1/2}$$

- Two Independent Velocity Scales

V_f — Bulk Liquid Film Velocity

V_r — Relative Velocity Between Gas and Liquid Phases ($V_r = V_g - V_f$)

or

V_f and V_g

OBSERVATIONS OF ENTRAINMENT PHENOMENA

- Similarities exist between the entrainment of liquid propellant by a plasma jet in an ETC gun and entrainment of droplets in two-phase annular mist flow.

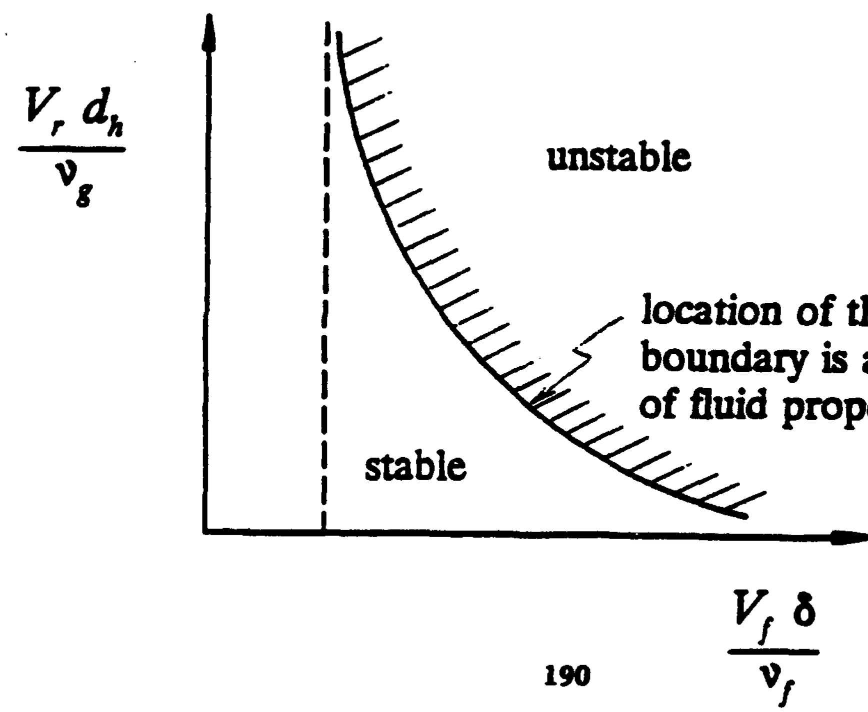
- The interface of the two fluids i- inherently unstable.

- When $V_r > (V_r)_{critical}$ or $V_f > (V_f)_{critical}$, instabilities set in and grow in the interfacial region.

  - formation of wavy interface and large amplitude roll wave (so-called Kelvin-Helmholtz instability)

  - ligaments and droplets torn off from the interface dynamic interaction

- Critical Conditions for the Onset of Entrainment:



OBSERVATIONS OF ENTRAINMENT PHENOMENA (continued)

- Detailed studies of entrainment mechanism have been performed by Newitt et al. (1954), Hanratty and Hershman (1961), Chung and Murgatroyd (1965), and Ishii and Grolmes (1975).

- In general, entrainment may take place in a number of different ways, depending on the flow situation.

- Hydrodynamic and surface tension forces govern the motion and deformation of the wave crests. Under certain conditions, these forces lead to an extreme deformation of the interface that results in the breakup of a portion of a wave into liquid droplets. The forces acting on the wave crests depend on the flow pattern around them as well as on the shape of the interface.

RELEVANT ARTICLES ON ENTRAINMENT MECHANISM STUDIES

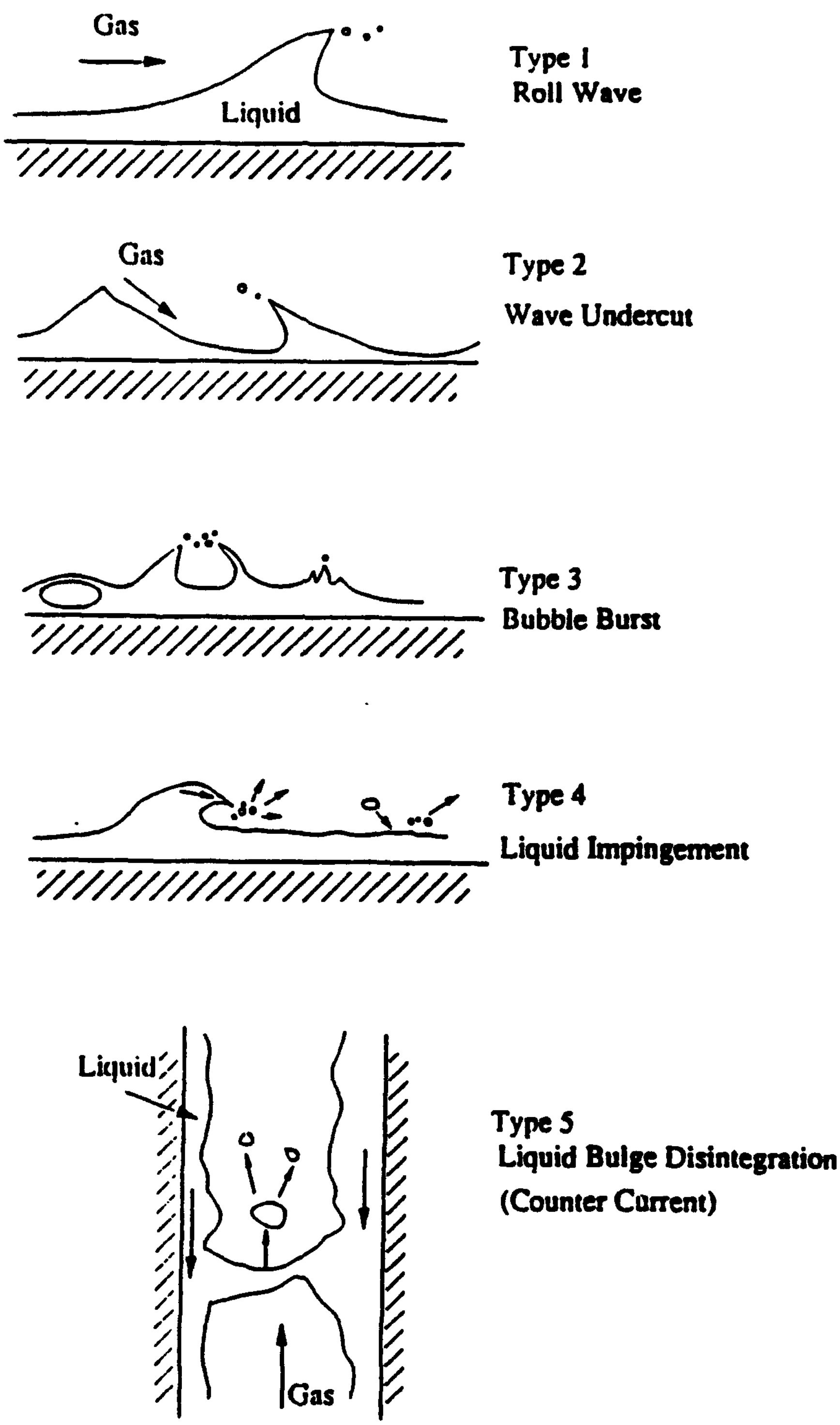
- "Liquid Entrainment: The Mechanism of Drop Formation from Gas or Vapor Bubbles," Newitt, D. M., Dombrowski, N. and Knelman, F. H., *Tran. Inst. Chem. Engng.*, Vol. 32, p. 244, 1954.

- "Fundamentals of the Hydrodynamic Mechanism of Splitting in Dispersion Process," Hinze, J. O., *AIChE J.*, Vol. 1, p. 289, 1955.

- "Initiation of Roll Wave," Hanratty, T. J. and Hershman, A., *AIChE J.*, Vol. 7, p. 488, 1961.

- "Studies of the Mechanism of Roll Wave Formation on Thin Liquid Films," Chung, H. S. and Murgatroyd, W., *Symp. on Two-Phase Flow*, Vol. 2, Paper A2, Exeter, UK, 1965

- "Prediction of Onset of Entrainment for Liquid Metals," Ishii, M. and Grolmes, M., *Trans. Am. Nucl. Soc.*, Vol. 21, p. 325, 1975



A Schematic Diagram Showing the Five Types of Entrainment Mechanisms

FIVE BASIC TYPES OF ENTRAINMENT MECHANISMS FOR TWO-PHASE ANNULAR MIST FLOW [ISHII AND GROLMES (1975)]

ROLL WAVE:

The drag force acting on the wave tops deforms the interface against the retaining force of the liquid surface tension. The tops of the large amplitude roll waves are sheared off from the wave crest by the gas flow and then broken into small droplets. (most relevant to ETC gun conditions)

WAVE UNDERCUT:

Entrainment is caused by the undercutting of the liquid film by the gas flow. This mechanism is similar to droplet disintegration by the gas stream. (could also happen in ETC gun condition)

BUBBLE BURST:

Associated with the bursting of gas bubbles. The droplets may be generated by the bubble rising to the surface of a liquid.

LIQUID IMPINGEMENT:

This is caused by the impingement of relatively large liquid droplets to the film interface for production of small droplets.

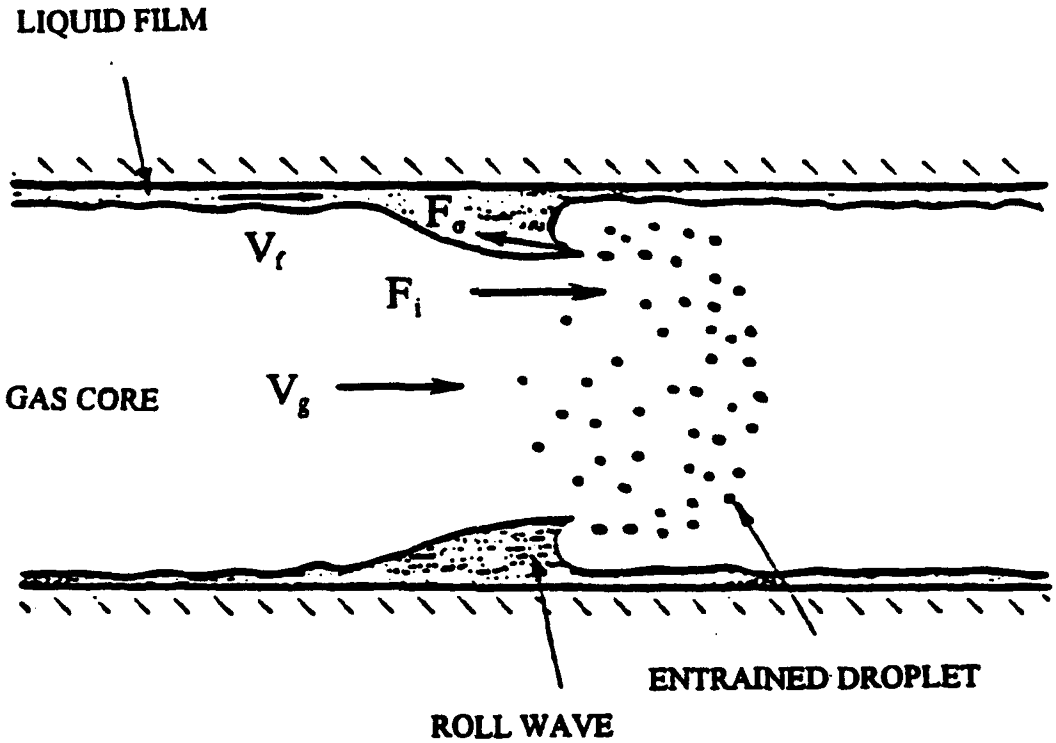
LIQUID BULGE DISINTEGRATION:

When a counter-current flow reaches the flooding condition, large amplitude waves can emerge from the liquid film and coalesce to from a bridge. Bulged regions of the bridge can then disintegrate into small droplets due to the gas dynamics. (not relevant to ETC gun conditions)

ONSET OF KELVIN-HELMHOLTZ INSTABILITY

- When both the gas flow and the induced liquid film motion are sufficiently high, the interfacial waves transform into large amplitude roll waves.

- Beyond this critical point, the interfacial shear forces become greater than the surface tension forces, and the onset of entrainment occurs.



ONSET OF ENTRAINMENT

- The criterion developed by Ishii and Grolmes (1975) was based upon a force balance at the crest of roll waves. Droplet entrainment starts when

$$F_i > F_\sigma$$

$$\begin{bmatrix}\text{interfacial} \\ \text{shear force}\end{bmatrix} \quad \begin{bmatrix}\text{surface tension} \\ \text{retaining force}\end{bmatrix}$$

- The dimensionless critical superficial gas velocity at the onset of entrainment was found to depend on the film Reynolds number and the viscosity number of the fluids, i. e.

$$(J_g)_{critical} = f\,(Re_f, N_\mu)$$

$$Re_f \equiv \frac{\rho_f\, j_f\, d_h}{\mu_f}$$

$$N_\mu \equiv \frac{\mu_f}{[\,\rho_f\, \sigma\, l_{TW}]^{\frac{1}{2}}} = \frac{\mu_f}{\left[\rho_f\, \sigma \left(\dfrac{\sigma}{g\,(\rho_f - \rho_g)}\right)^{\frac{1}{2}}\right]^{\frac{1}{2}}}$$

where ρ_f and μ_f are the density and viscosity of the liquid, d_h the hydraulic diameter of the cone, and j_f the superficial velocity of the liquid (including liquid film and droplets).

- J_g is defined as

$$J_g \equiv \frac{j_g}{(\sigma/\mu_f)} \left(\frac{\rho_g}{\rho_f}\right)^{\frac{1}{2}} = \left(\frac{\rho_g\, j_g^{\,2}\, d_h}{\sigma}\right) \left(\frac{\mu_g}{\rho_g\, j_g\, d_h}\right) \left(\frac{\mu_f}{\mu_g}\right) \left(\frac{\rho_g}{\rho_f}\right)^{\frac{1}{2}}$$

$$= We_g \quad (Re_g)^{-1} \left(\frac{\mu_f}{\mu_g}\right) \left(\frac{\rho_g}{\rho_f}\right)^{\frac{1}{2}}$$

ONSET OF ENTRAINMENT (continued)

- For a horizontal two-phase annular flow with $160 < Re_f < 1635$, the criterion of Ishii and Grolmes (1975) gives

$$J_g \geq 11.78\, N_\mu^{0.8}\, Re_f^{-1/3} \qquad \textit{for } N_\mu \leq \frac{1}{15}$$

and

$$J_g \geq 1.35\, Re_f^{-1/3} \qquad \textit{for } N_\mu > \frac{1}{15}$$

- For values of Re_f that are above 1635, a so-called completely rough turbulent regime occurs in which the critical superficial gas velocity becomes independent of the film Reynolds number. According to Ishii and Grolmes (1975), the inception criterion for this flow regime is given by

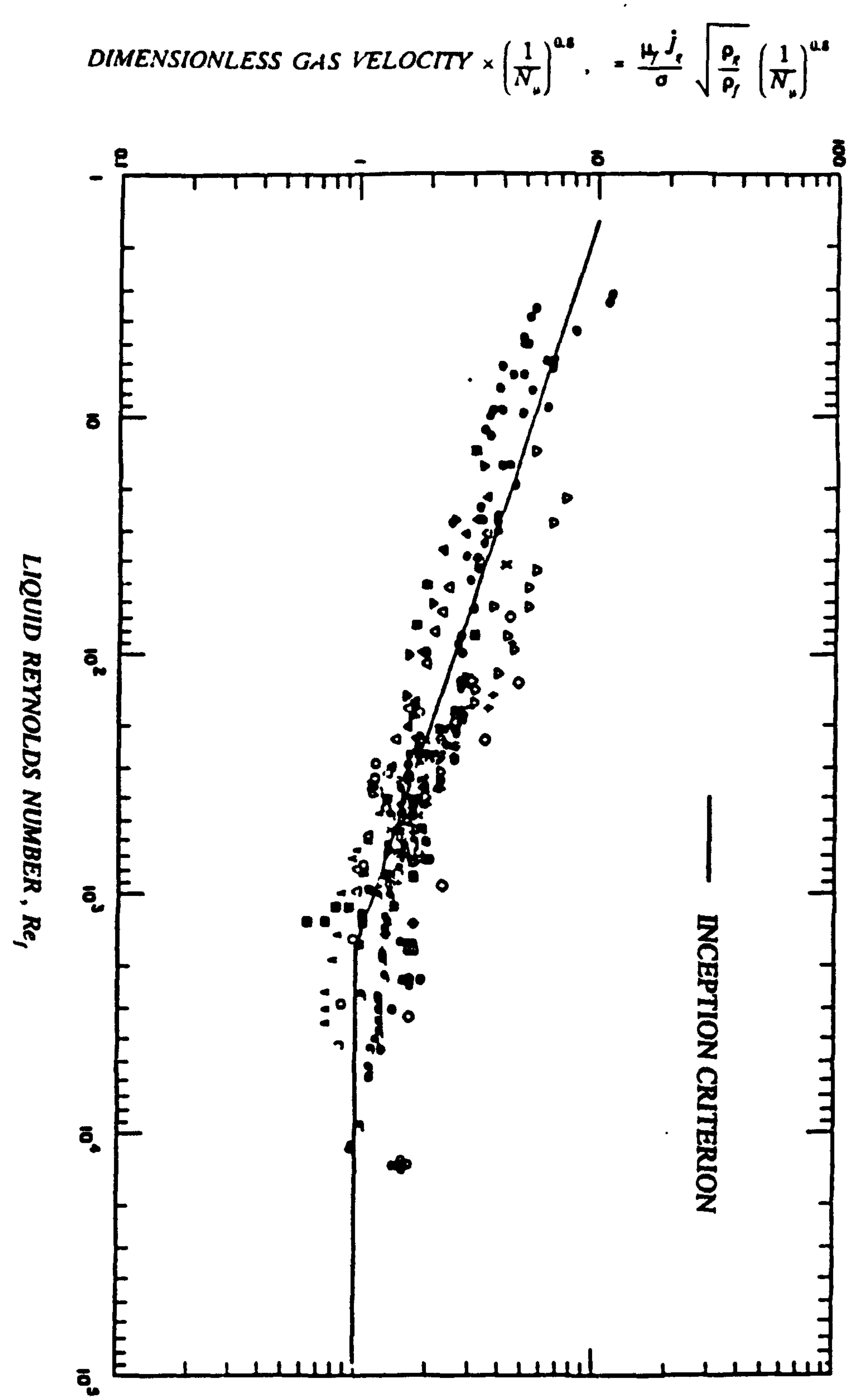
$$J_g \geq N_\mu^{0.8} \qquad \textit{for } N_\mu \leq \frac{1}{15}$$

and

$$J_g \geq 0.1146 \qquad \textit{for } N_\mu > \frac{1}{15}$$

- The inception criterion compares favorably with a large number of experimental data for various types of fluids covering a wide range of the film Reynolds numbers and the viscosity number.

- The inception criterion of Ishii and Grolmes should be applicable to the case of plasma/liquid propellants interaction provided that fluid properties are known.



Comparison of the Inception Criterion of Ishii and Grolmes with Data

METHODS FOR MEASURING THE FRACTION OF LIQUID MASS FLUX ENTRAINED IN THE GAS CORE

- Local Probe Measurements

  — To determine the axial liquid mass flux at the location of the sampling probe.

  — Used with limited success by Wicks and Dukler (1960), Magiros and Dukler (1961), Wallis (1962), Steen and Wallis (1964), Cousins et al. (1965), Gill and Hewitt (1968), and Yablonik and Khaimov (1972).

  — Measurement along the centerline with the assumption that the mass flux is radially uniform.

- Liquid Film Flow Measurements

  — Flow rate determined by removing liquid film completely from the test section.

  — This method, which eliminates those uncertainties associated with the local probe measurement, is probably a more accurate measurement technique.

  — Successfully employed by a number of investigators including Paleev and co-workers (1962, 1966), Cousins and Hewitt (1968), Petrovichev et al. (1971), and Ishii and Mishima (1981).

ENTRAINMENT CORRELATIONS

- Purely Empirical Approach
  - Wicks and Dukler (1960)
  - Minh and Huyghe (1965)
  - Paleev and Filipovich (1966)
  - Wallis (1968)
- Semi-Empirical Approach Based Upon Mechanistic Models
  - Hutchinson and Whalley (1973)
  - Dallman, Laurinat, and Hanratty (1984)
  - Ishii and Mishima (1989)

ENTRAINMENT CORRELATION OF WICKS AND DUKLER (1960)

- Developed a correlation that relates the entrainment parameter, R, to the Martinelli parameter X, i. e.

$$R = R(X)$$

- Entrainment Parameter:

$$R \equiv \frac{We_c \, (j_f / j_g)}{(dP/dz)_g} W_d$$

where W_d is the liquid drop mass flow rate, and We_c the critical Weber number defined in terms of the film thickness δ by

$$We_c \equiv \frac{\rho_g \, v_g^2 \, \delta}{\sigma}$$

where v_g is the velocity of the gas phase.

- Martinelli Parameter

$$X \equiv \left[\frac{(dP/dz)_f}{(dP/dz)_g} \right]^{1/2}$$

where quantities in the numerator and denominator represent the single-phase pressure drops which would exist if each phase flowed alone.

- Two Major Drawbacks
  - The dependence of the entrainment on various controlling factors is hidden by the use of the Martinelli parameter.
  - The correlation is dimensional which severely limits the range of applicability.

ENTRAINMENT CORRELATION OF MINH AND HUYGHE (1965)

- Empirical correlation relates the entrained fraction, E, to the gas core momentum, i. e.

$$E = E\left(\bar{\rho}_g j_g^2 \right)$$

where $\bar{\rho}_g$ is the homogeneous density of the gas core given by

$$\bar{\rho}_g = \rho_g \left(1 + \frac{\rho_f j_d}{\rho_g j_g} \right)$$

where j_d is the superficial velocity of the entrained liquid droplets.

- Entrained Fraction:

$$E = \frac{W_d}{W_f} = \frac{j_d}{j_f}$$

where W_d is the mass flow rate of the droplets and W_f the total liquid mass flow rate including both the liquid film and the droplets.

- Two Major Drawbacks

  - The use of the dimensional parameters results in uncertainties regarding the dependence of the correlation on the fluid properties.

  - The range of applicability is virtually unknown as the effects of many important factors such as the liquid Reynolds number are not included.

ENTRAINMENT CORRELATION OF PALEEV AND FILIPOVICH (1966)

- The shortcoming in the Minh and Huyghe correlation (1965) was eliminated by introducing a dimensionless gas flux* in correlating the entrained fraction in the following form.

$$\frac{W_{ff}}{W_f} = 0.985 - 0.44 \log \left[\frac{\bar{\rho}}{\rho_f} \left(\frac{\mu_f j_g}{\sigma} \right)^2 \times 10^4 \right]$$

where W_{ff} is the mass flow rate of the film and W_f the total liquid flow rate including the film and droplets.

- Entrained Fraction:

$$E = 1 - \frac{W_{ff}}{W_f}$$

- This correlation showed fairly good agreement with a limited number of data.

- Major Drawback

  - The range of applicability is not well defined as the important effects of the hydraulic diameter and the Reynolds number were not included.

---

* The dimensionless gas flux is very similar to J_g used in the onset of entrainment.

ENTRAINMENT CORRELATION OF WALLIS (1968)

- In an effort to improve the correlation of Paleev and Filipovich (1966), Wallis introduced a modified dimensionless gas flux (π) by replacing the liquid viscosity by the gas viscosity in the Paleev and Filipovich correlation, i. e.

$$E = E(\pi)$$

  where

$$\pi = \left(\frac{v_g \, \mu_g}{\sigma} \right) \left(\frac{\rho_g}{\rho_f} \right)^{\frac{1}{2}}$$

- Major Drawbacks
  - The range of applicability is not well defined.
  - The dimensionless gas flux is not general enough to account for the effect of fluid properties.

ENTRAINMENT CORRELATION OF HUTCHINSON AND WHALLEY (1973)

- Proposed a mechanistic model to correlate the rates of entrainment and deposition of droplets to the liquid film.

- The deposition rate is taken to be a linear function of the droplet concentration in the gas core, i. e.,

$$\dot{D} = k\,C$$

where k is the mass transfer coefficient.

- The entrainment rate is considered proportional to the equilibrium concentration, i. e.

$$\dot{E} = k\,C_e$$

The equilibrium concentration is correlated in a functional form given by

$$C_e = C_e\left(\frac{\tau_i\,\delta}{\sigma}\right)$$

where τ_i is the interfacial shear of the two-phase flow and δ the liquid film thickness.

- Major Drawbacks

  - It is difficult to accurately determine the equilibrium concentration. The data for this quantity showed considerable scattering, sometimes up to more than an order of magnitude.

  - In order to estimate the entrainment, two different correlations, i. e., one for the entrainment rate and the other for the deposition rate, need to be employed. Any error in determining the deposition would add to the error associated with the entrainment rate.

  - Conceptually, the entrainment rate is not dictated by the equilibrium concentration.

ENTRAINMENT CORRELATION OF DALLMAN, LAURINAT AND HANRATTY (1984)

- Conducted an experimental study of horizontal annular two-phase flow using air and water.

- The amount of liquid entrained in the gas flow is assumed to be governed by a dynamic balance between the rate of atomization of the liquid film and the rate of deposition of droplets from the gas core.

- The rate of deposition of liquid droplets was considered to vary linearly with the concentration of the droplets whereas the rate of atomization of the liquid film was assumed to vary linearly with the liquid film flow rate.

- Entrainment Correlation Developed:

$$\frac{E}{E_m} = \frac{A\left[(d_h - 2\delta)\,\rho_g^{1/2}\,\rho_f^{1/2}\,V_g^3\right]^{1.5}}{1 + A\left[(d_h - 2\delta)\,\rho_g^{1/2}\,\rho_f^{1/2}\,V_g^3\right]^{1.5}}$$

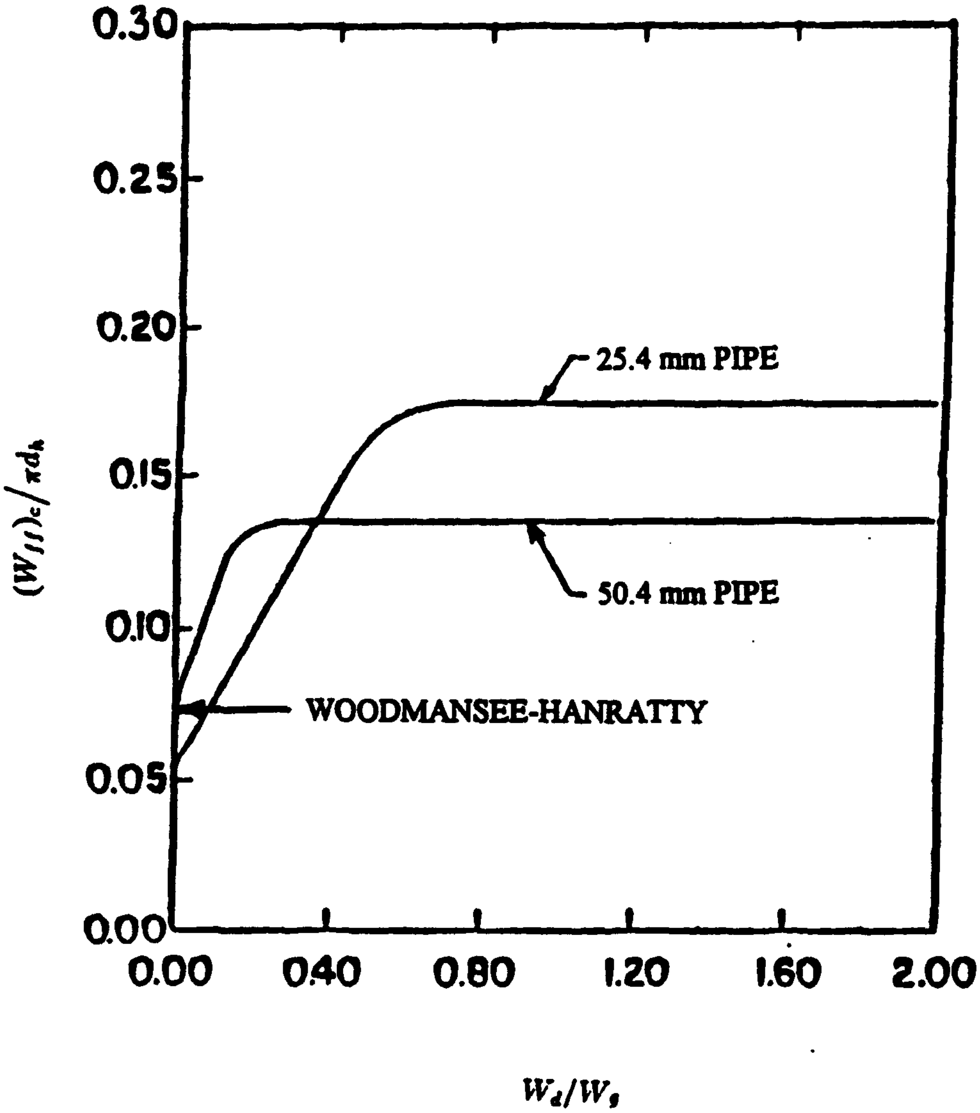
  where A is a dimensional constant having the value of 3.6×10^{-8} in SI unit and E_m the maximum entrainment fraction. The latter quantity is given by

$$E_m = 1 - \frac{(W_{ff})_c}{W_f}$$

  where $(W_{ff})_c$ is the so-called critical film flow rate.

- Critical Film Flowrate

  - The critical film flow rate has been determined by Dallman et al. (1984) as a function of the ratio between the droplet mass flow rate and the mass flow rate of the gas.



Variation of the Critical Film Flow Rate with the Mass-Flow-Rate Ratio

ENTRAINMENT CORRELATION OF DALLMAN, LAURINAT AND HANRATTY (1984)
(continued)

- Major Drawbacks:
  - The correlation is given in dimensional form; thus, the applicability is limited.
  - The effect of fluid properties are not included.
  - While the concept of critical film flow rate is correct, the functional dependence of $(W_{ff})_c$ is generally unknown.
  - The correlation is cumbersome as E_m and δ are unknown quantities.

ENTRAINMENT CORRELATION OF ISHII AND MISHIMA (1989)

- Based upon the mechanism of roll wave entrainment: The shearing off of roll wave crests was considered to be the dominant mechanism of liquid entrainment.

- Droplet entrainment would result whenever the retaining force of surface tension is exceeded by the interfacial shear force.

- The same forces controlling the onset of entrainment were assumed to control the entrainment itself. However, a modification of the inertia of the gas core flow was made to account for the effect of droplet inertia, since there are many droplets flowing in the gas core.

- Under an equilibrium condition in which the deposition rate exactly balances the entrainment rate, the entrained fraction was correlated in the following form:

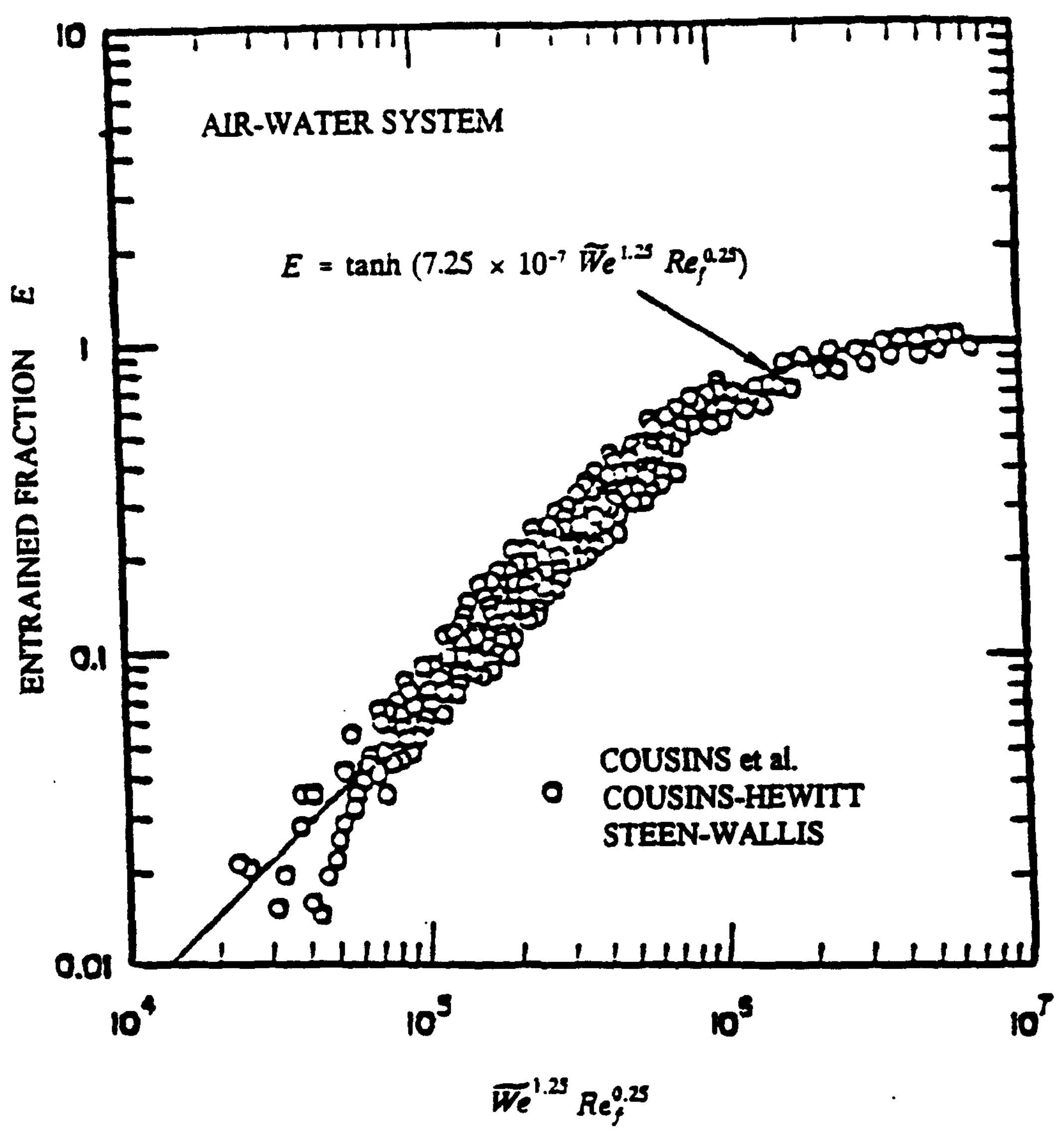
$$E = \tanh\left(7.25 \times 10^{-7}\, \widetilde{We}^{1.25}\, Re_f^{-.25}\right)$$

where $\widetilde{We}$ is an effective gas-phase Weber number defined by

$$\widetilde{We} \equiv \frac{\rho_g\, j_g^2\, d_h}{\sigma} \left(\frac{\rho_f - \rho_g}{\rho_g} \right)^{\frac{1}{3}}$$

- The Ishii and Mishima correlation, which compares favorably with a large number of data , is probably the best correlation available today.

- Unfortunately, the entrained fraction represents the equilibrium value that includes the contribution due to droplet deposition. Thus, this correlation tends to underestimate the actual entrainment rate in the ETC gun environment.



Comparison of the Entrainment Correlation of Ishii and Mishima with Data

SPECIAL FEATURES OF DROPLET ENTRAINMENT IN AN ETC GUN ENVIRONMENT

- Droplet life times are relatively short due to
  - High rates of heat transfer
  - Evaporation, thermal decomposition, and combustion
  - Secondary breakup to smaller droplets by highly turbulent flow conditions
- The deposition rate is negligible since the droplets have very little chance to return to liquid film before they are totally consumed. The absence of the deposition process in an ETC gun represents a unique feature which is different from all annular two-phase flows studied by previous researchers.
- For ETC guns utilizing piccolo igniters, the phenomena of mixing of plasma and liquid propellants involve two sequential stages.
  1) Development of numerous mini-Taylor cavities and subsequent expansion of cavity sizes.
  2) Merging of mini-Taylor cavities onto a single large cavity.

RESEARCH NEEDS ON DROPLET ENTRAINMENT

- The single most important element in accurate prediction of the performance of ETC guns is the droplet entrainment rate, since it controls the rate of conversion of chemical energy into propulsive energy.

- A suitable entrainment correlation, excluding the effect of droplet deposition, should be developed for ETC gun application. This can be accomplished by performing an experimental study to measure the rate of entrainment for the case without the effect of deposition.

- In order to develop a realistic model for simulating the mixing phenomena of plasma jets and liquid propellants in ETC guns using piccolo igniters, it is useful to conduct detailed observations of the evolution of mini-Taylor cavities.

THEORETICAL ANALYSIS OF DROPLET ENTRAINMENT IN AN ETC GUN ENVIRONMENT

- The starting point of the analysis is the selection of an appropriate inception criterion. Since the roll wave mechanism is the prevailing mechanism of entrainment during plasma/liquid propellant interaction in an ETC gun, it is deemed appropriate to adopt the inception criterion of Ishii and Grolmes (1975) in the present analysis.

- Owing to the relatively high velocity of the plasma jet, the plasma/liquid propellant system in an ETC gun is likely to be significantly above the inception criterion. However, there is a potential for the liquid film Reynolds number to be reduced to a critical value as the liquid film thickness decreases. Below this critical Re_f, no further entrainment is possible.

THEORETICAL ANALYSIS OF DROPLET ENTRAINMENT IN AN ETC GUN ENVIRONMENT
(continued)

- An upper theoretical limit for the entrained fraction may thus be determined by assuming that the liquid film flow rate is given by the critical condition for the onset of entrainment:

$$(Re_f)_c^{1/3} = 11.78\, N_\mu^{0.8} \left(\frac{\sigma}{\mu_f\, j_g} \right) \left(\frac{\rho_f}{\rho_g} \right)^{1/2}$$

where $(Re_f)_c$ is now the critical Reynolds number on the critical film flow rate introduced initially by Dallman, Laurinat and Hanratty (1984).

- The critical Reynolds number is defined by

$$(Re_f)_c = \frac{\rho_f\, (j_{ff})_c\, d_h}{\mu_f}$$

where $(j_{ff})_c$ is the critical superficial velocity of the liquid film. The use of this definition in the above equation is equivalent to ignoring the effect of droplets in determining the critical condition.

- In terms of the liquid film Reynolds number (Re_f), the critical superficial velocity of the liquid film is given by

$$(j_{ff})_c = \frac{j_f}{Re_f} \left[11.78\, N_\mu^{0.8} \left(\frac{\sigma}{\mu_f\, j_g} \right) \left(\frac{\rho_f}{\rho_g} \right)^{1/2} \right]^3$$

THEORETICAL ANALYSIS OF DROPLET ENTRAINMENT IN AN ETC GUN ENVIRONMENT (continued)

- Following the conventional definition, the entrained fraction, E, can be expressed in terms of the superficial velocities of the total liquid (including the liquid film and the entrained droplets) and the liquid film alone, i. e.,

$$E = \frac{j_d}{j_f} = \frac{j_f - j_{ff}}{j_f} = 1 - \frac{j_{ff}}{j_f}$$

- The upper limit of the entrained fraction is given by

$$E_{up} = 1 - \frac{(j_{ff})_c}{j_f}$$

After substituting the expression of $(j_{ff})_c$ into the above equation, E_{up} can be expressed as

$$E_{up} = 1 - \frac{1}{Re_f}\left[11.78\, N_\mu^{0.8}\left(\frac{\sigma}{\mu_f\, j_g}\right)\left(\frac{\rho_f}{\rho_g}\right)^{1/2}\right]^3$$

- Theoretically, the actual entrainment during the mixing of plasma and liquid propellants in an ETC gun should be bounded by the above upper limit and the lower limit given by Ishii and Mishima (1989), i. e.

$$(E)_{IM} < E < E_{up}$$

THEORETICAL ANALYSIS OF DROPLET ENTRAINMENT IN AN ETC GUN ENVIRONMENT
(continued)

- From the above equations, a functional form can be postulated for the actual entrained fraction as

$$E = 1 - B\, Re_f^{-1}\, N_\mu^{2.4} \left(\frac{\sigma}{\mu_f\, J_g} \right)^3 \left(\frac{\rho_f}{\rho_g} \right)^{3/2}$$

  where B is a coefficient that needs to be determined experimentally.

- In view of the fact that the critical superficial velocity of the liquid film represents the lower limit of the liquid film flow, the value of B should be bounded by

$$B \geq 1.635 \times 10^3$$

- In terms of the dimensionless characteristic gas velocity as

$$J_g = j_g \left(\frac{\mu_f}{\sigma \sqrt{\rho_f / \rho_g}} \right)$$

  a more general expression for the entrained fraction can be postulated. This is

$$E = 1 - B\, N_\mu^a\, Re_f^b\, J_g^c$$

- Based upon the preceding physical arguments, the values of the exponents should be approximately equal to: a = 2.4, b = -1, and c = -3. Experimental data to be obtained in the proposed experiments will be used to obtain a final expression for the entrainment correlation.

ENTRAINED DROPLET SIZE DISTRIBUTION

- In an ETC gun environment, the chemical reactions that are directly responsible for the transfer of chemical energy to propulsive energy are controlled not only by the entrainment rate but also by the entrained droplet size distribution.

- In an ETC gun chamber, the majority of droplets are generated by entrainment and not by secondary breakup mechanisms. Examples of secondary breakup are turbulence eddy-induced breakup and particle/particle collision generated breakup.

- The size distribution should be governed by the process of the droplet entrainment based on shearing off of the roll waves.

- Studies of droplet sizes have been performed by Hinze (1955), Hass (1964), Wicks and Dukler (1966), Cousins and Hewitt (1968), Tatterson et al. (1977), and Kataoka, Ishii, and Mishima (1983).

- A correlation of droplet size distribution, which could be applied to the interior ballistic processes of an ETC gun, was obtained by Kataoka, Ishii, and Mishima (1983).

DROPLET SIZE CORRELATION BY TATTERSON DALLMAN AND HANRATTY (1977)

- An experimental study was performed to measure the entrained droplet size in an annular two-phase flow using a log-normal distribution function to simulate the droplet size distribution:

$$We(d_{vm}) = 0.106\, Re_g^{1.1} \left(\frac{\mu_g^2}{d_h\ \sigma\ \rho_g} \right)^{1/2}$$

where μ_g is the gas viscosity, Re_g the gas Reynolds number, and $We(d_{vm})$ the characteristic Weber number based on the volume median diameter.

- The gas Reynolds number and the characteristic Weber number are defined respectively by

$$Re_g = \frac{\rho_g\, j_g\, d_h}{\mu_g} \quad and \quad We\,(d_{vm}) = \frac{\rho_g\, j_g^2\, d_{vm}}{\sigma}$$

where d_{vm} is the volume median diameter. Physically, d_{vm} is defined such that droplets having diameters greater than the volume median diameter would occupy exactly half of the total droplet volume in the gas core.

- Major Drawback:

  Their assumption of a potential flow is not strictly valid for two-phase annular-mist flow with a highly turbulent gas core. As a result, the correlation of Tatterson et al. does not compare favorably with experimental data over a wide range of gas Reynolds number.

DROPLET SIZE CORRELATION BY KATAOKA ISHII AND MISHIMA (1983)

- A mechanistic model was developed that was based on the mechanism of shearing off of the roll-wave crest for generation of liquid droplets by a viscous shear flow. The potential flow assumption employed in the standard Weber number criterion was eliminated in developing the model development.

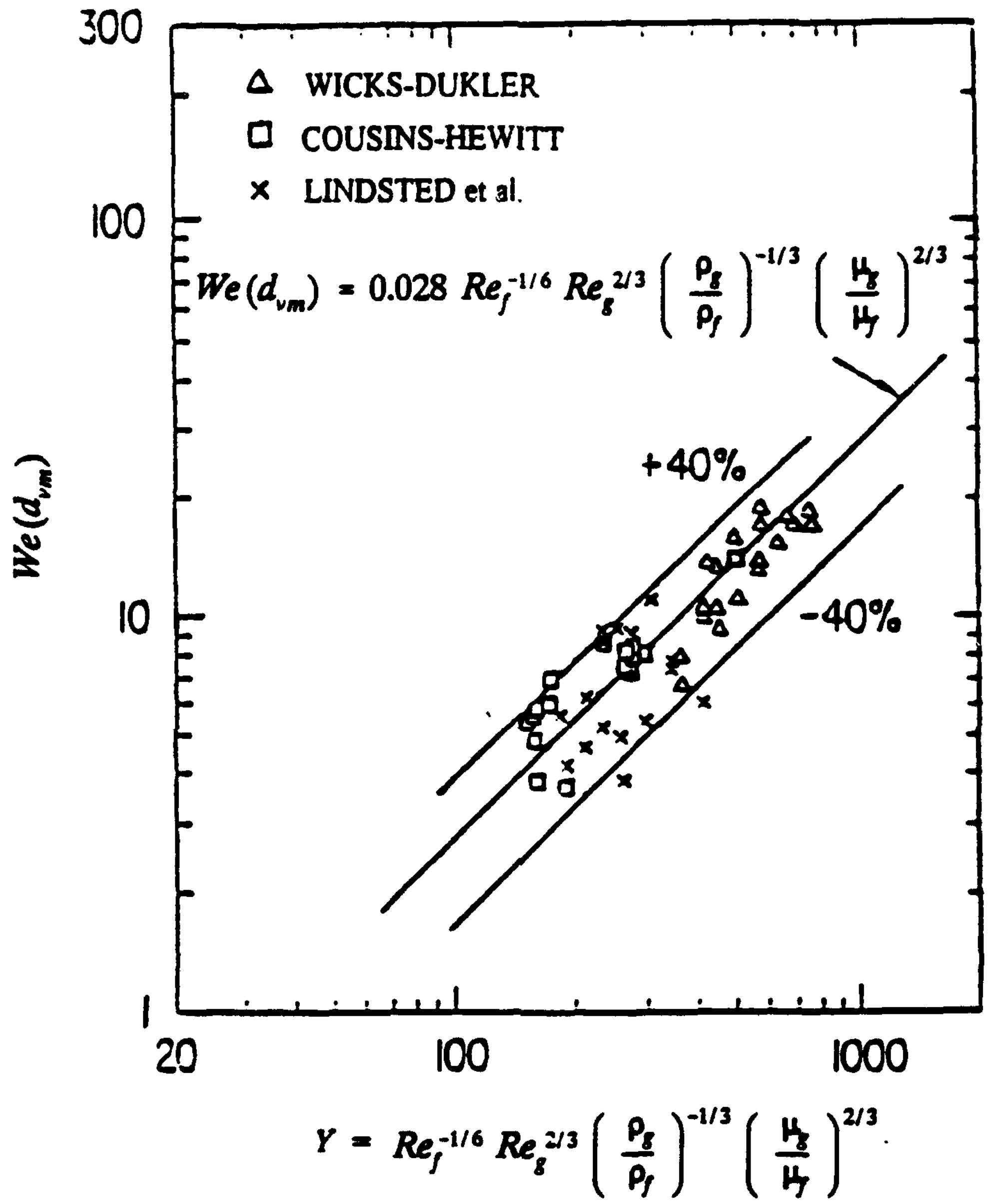
- By incorporating the mechanistic model with test data, Kataoka, Ishii, and Mishima (1983) successfully derived a correlation for deducing the volume median diameter from the Weber number

$$We(d_{vm}) = 0.028\, Re_f^{-1/6}\, Re_g^{2/3} \left(\frac{\rho_g}{\rho_f} \right)^{-1/3} \left(\frac{\mu_g}{\mu_f} \right)^{2/3}$$

- In terms of the characteristic Weber number, the volume median diameter is given by

$$d_{vm} = \frac{\sigma\, We(d_{vm})}{\rho_g\, j_g^2}$$

The above expression correlates the experimental data of volume median diameter within ± 40% errors.



Correlation of the Volume Median Diameter by Kataoka, Ishii and Mishima

DROPLET SIZE CORRELATION BY KATAOKA ISHII AND MISHIMA (1983) (continued)

- The mean values of the data on drop size distribution were fitted by Kataoka, Ishii, Mishima (1983) to the upper limit log-normal distribution:

$$\frac{d\Delta}{dy} = -\frac{\xi}{\sqrt{\pi}} \exp\left[-(\xi y)^2\right]$$

where Δ is the volume fraction oversize defined as the volume fraction of droplets having a diameter larger than a given diameter, d.

- In the above equation, ξ is a distribution parameter and y is defined in terms of the maximum diameter d_m and volume mean diameter d_{vm} as

$$y = \ln\left[\frac{k\,d}{(d_m - d)}\right] \quad and \quad k = \frac{(d_m - d_{vm})}{d_{vm}}$$

- Based upon the experimental results, the values of ξ and k were found to be $\xi = 0.884$ and $k = 2.13$ whereas using the upper limit log-normal distribution, the maximum diameter was related to the volume mean diameter by

$$d_m = 3.13\, d_{vm}$$

DROPLET SIZE CORRELATION BY KATAOKA ISHII AND MISHIMA (1983)
(continued)

- The correlation of drop size distribution developed by Kataoka, Ishii, and Mishima (1983) is probably the most suitable one among the existing correlations for use in simulating the phenomena of mixing of plasma and liquid propellants in the ETC gun environment.

- It is recommended that the correlation be used in future modeling. The reasons are:

  - The correlation is based upon a sound physical model, taking full account of key elements involved in the droplet formation process

  - The use of the upper limit log-normal distribution function is evidently appropriate for annular-mist flow

  - The correlation compares very well with available experimental data on drop size distribution covering a wide range of conditions

  - The correlation is easy to use since the primary quantity that needs to be determined is the volume median diameter.

Electrothermal-Chemical Gun Interior Ballistic Modeling

Gloria P. Wren
U.S. Army Research Laboratory
Attn: AMSRL-WT-PA
Weapons Technology Directorate
Aberdeen Proving Ground, Maryland
(410) 278-6199, DSN 298-6199

ARL

Interior Ballistic Component Processes

	LPETC	SPETC
Plasma generation:	Variety of plasma generation concepts. Not dependent on propellant type. Generates little mass; temperatures 10 - 30,000 K. Coupled to combustion chamber.	
Ignition:	Little or no ignition delay. No detailed information.	
Gas flow and flamespread:	Similar to bulk-loaded LPG. Moving to higher ullage charge designs.	Appears similar to conventional SP charges. More influence from radial convection & radiation in designs with chamber burst tube.
Combustion: & Mixing	Complex process. Propellant surface area not well defined. Similar to processes in BLPG. Droplet entrainment & breakup at high shear flows.	Data suggests plasma does not directly affect SP combustion process in a major way. Impact on gas internal energy & pressure.
Expansion:	Anticipate diminishing plasma influence with increasing projectile travel for breech/chamber injected plasmas.	

Appropriate Dimensionality

- **Practical motivation to utilize codes with lowest dimension to obtain desired information**
  - reduce complexity, decrease run time, decrease post processing
  - reduce need for specialized personnel
  - 'user friendly' models needed for the larger ballistics community
- ***Lumped parameter IB codes***
  - macroscopic parameters such as max pressure & muzzle velocity
  - mean IB history
  - ETC applications currently require empiricism, especially for liquids
- **quasi 1D, multi-phase, IB codes**
  - axial structure of flamespreading
  - energy, mass & momentum of plasma at various axial locations
  - details of multi-phase flow
  - investigate sources of longitudinal pressure waves
- **2D / 3D, multi-phase IB codes**
  - radial structure of flamespreading
  - influence of turbulence
  - radial structure of plasma in combustion chamber
  - investigate sources of radial, tangential & longitudinal pressure waves
  - detailed interaction of multiple plasma sources
  - influence of complex geometries

ARL

Dimensionality for IB Simulations

	Plasma	LPETC	SPETC
0D (Lumped parameter)	Not generally utilized.	Models available. Require specification of mass generation rate. e.g. as function of injected plasma energy. Closely coupled to experiment. Both 0D & 1D models can be used to simulate experiment, but predictive capability is limited.	Adaptations of existing IB models. Reasonable agreement with experiment using traditional assumptions at modest electrical energy densities & breech plasma capillaries.
1D	Ideal & nonideal, quasi-steady & transient models provide good agreement with macroscopic measurables. Has been coupled to 2D/3D IB model .		Adaptations of existing IB models available. Reasonable agreement with experiment. Design of plasma generator (e.g. internal, burst tube,) may have large effect; currently not explicitly modeled.
2D/3D	Some indications of significant radial structure in capillary May influence plasma characteristics. Model development underway.	IB process appears to be at least 2D. Macroscopic agreement good. Microscopically complex. Research in turbulence submodels. Uniqueness?	Initial efforts to develop multi-phase, CFD, solid propellant IB models.

ETC IB Models

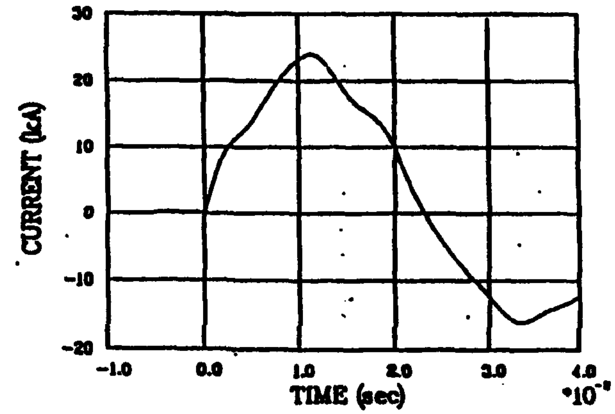
Model	Description	Status
P2SIM	0D, power systems for electric guns, includes mission scenarios	Complete
Plasma	1D steady state capillary 1D transient capillary - treats metals (In Progress) 1D piccolo tube 2D capillary	Complete Complete In Progress In Progress (SNL)
BLAKE-ETC	Thermochemical code, treats electrical energy as a constituent	Complete
IBHVG2 -ETC	0D, EE source term Input power - coupled to plasma (In Progress)	Complete
SPETC	0D, SP, Determines power pulse for given performance - optimization (In Progress)	Complete
LUMPET	0D, LP, Arrehenius EOS EE source term	Complete
Conpress	0D, Constant pressure solution, EE source term	Complete
XKTC-ETC	1D, Solid propellant code, EE source term	Complete
CRAFT	1D/2D/3D research code, fundamental physics, state-of-the-art numerics - gas/gas (Complete) - gas/liquid (Complete) - gas/liquid/solid (In Progress).	In Progress

Power Model

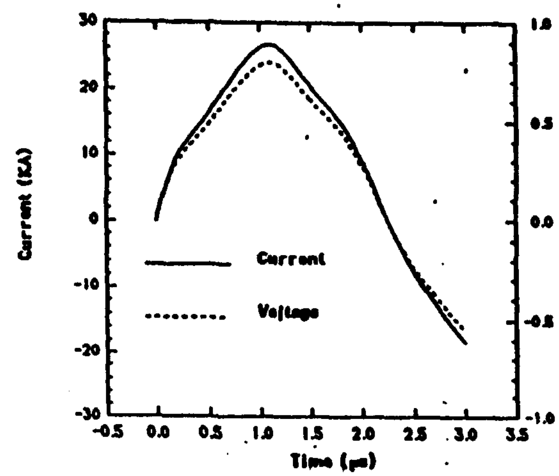
- Virtually all electric gun power systems
- Includes mission scenarios
- Developed by PCRL
- Application by P. Tran

FMC Pulse-Power Module for 9MJ ET Skid Gun: Verification Test 1

EEF FOLLOW-ON PROGRAM
10kV PFN TESTS #1-10



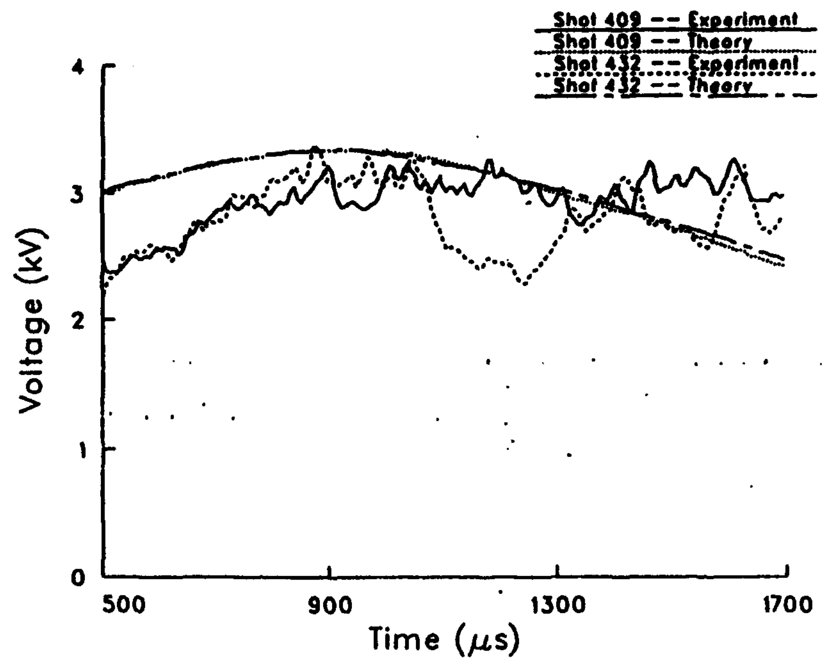
P2SIM PREDICTION



Plasma Models

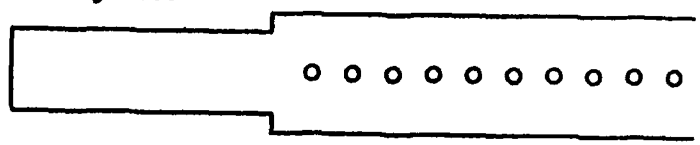
- **Past Accomplishments:**
  - Develop 1D, steady-state, capillary model for breech-fed mixing chamber
  - Included nonideal effects for relatively high-density, low-temperature plasmas
  - Extended solution to 1D, fully transient case
  - Effected comparison with various sets of experimental data
- **Present Activities:**
  - Develop capability for treating mixture of several different species

    Account for electrode ablation
    Account for fuse vaporization
  - Extend model to treat "piccolo" injector
  - Couple plasma model to 2D, Interior Ballistic, CFD models



Status of Plasma Activities

- Piccolo
  - Developed 1D, transient model for piccolo extension to breech-fed injector
  - Performing calculations to compare with FMC experimental data



- Coupling to CFD models
  - Isothermal, steady-state, breech-fed plasma code included in CRAFT
  - Coupled calculations performed for FMC and GDLS data

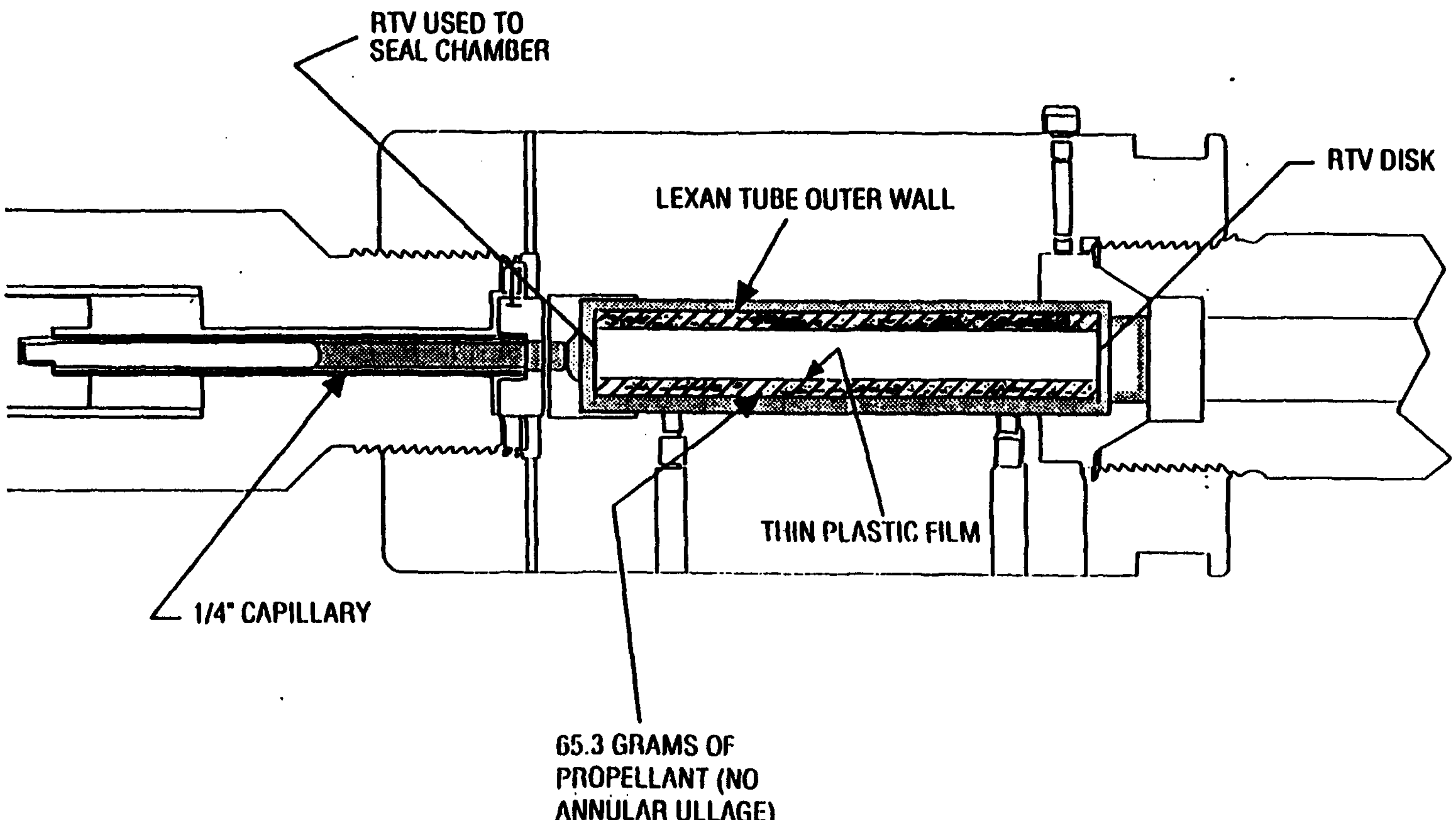
- Mixtures
  - Formulated equations for calculating EOS's and conductivity for arbitrary mixture of C, H, Cu, Al, Fe, O, and N
  - Developed stand-alone code and subroutine for performing calculations
  - Initiated calculations for breech-fed injector accounting for vaporization of Al fuse

* Much of work done in collaboration with SAIC – Atlanta, Ft. Washington

Experimental Fixture

ARMY RESEARCH LABORATORY
WEAPONS TECHNOLOGY DIRECTORATE

Bore diameter: 30mm
Chamber volume: 160 cc
Chamber diameter: 3.175 cm
Chamber L/D: 6.15
Travel: 16.1 cm
Projectile mass: 328.8 g



Ignition Characteristics

- Ignition time delays close for same material (Average 0.35 ms)
- Plasma driven propellants appear to exhibit reduced variability in ignition

Shot	Propellant	Ignition delay
1	LGP1846	0.36
2	LGP1846	0.24
3	LGP1846	0.28
4	LGP1846	0.24
5	LGP1846	0.20
6	LGP1846	0.17
8	N2H4/HN	0.28
9	HAN/DEG/H2O	0.26
10	HAN/DEG/H2O	0.30
11	HAN/DEG/H2O	0.29
12	HAN/NMP/H2O	0.26
13	HAN/NMP/H2O	0.32
14	M43	0.24
15	M43	0.24
16	DINA/NC	0.23
20	DINA/NC	0.25

Shot	Propellant	Ignition delay
17	RDX/NC/NG	0.30
19	RDX/NC/NG	0.33
22	AN/Cyanoguanidine	1.68
23	AN/MEAN/H2O	0.27
24	AN/MEAN/H2O	0.30
25	AN/5AT/H2O	0.94
26	AN/5AT/H2O	0.82
27	JA2	0.24
28	JA2	0.30
29	JA2 - X	0.23
30	JA2 - X	0.30
31	JA2	0.27
32	JA2	0.27
33	Compacted CAB	0.87
34	Compacted CAB	0.12
35	Loose CAB	0.23
36	Loose CAB	0.20
37	Loose CAB	0.16
38	Loose CAB	0.16

Pressurization Rate

ARMY RESEARCH LABORATORY
WEAPONS TECHNOLOGY DIRECTORATE

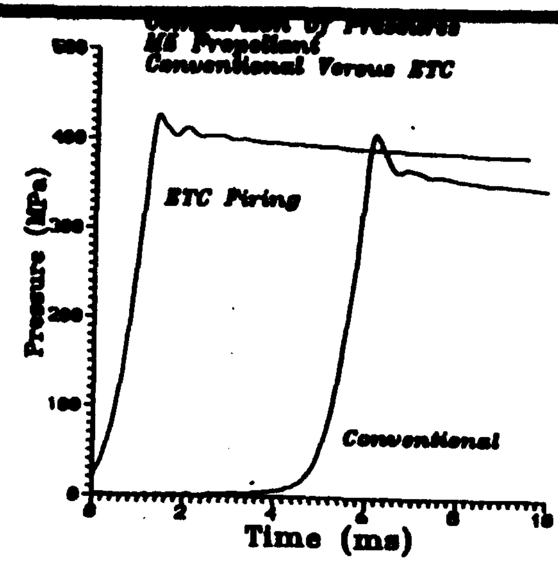
- 'Runaway' combustion does not occur
- 120mm tank round: dP/dt = 0.4 MMPa/s
- 155mm artillery round: dP/dt = 0.09 MMPa/s

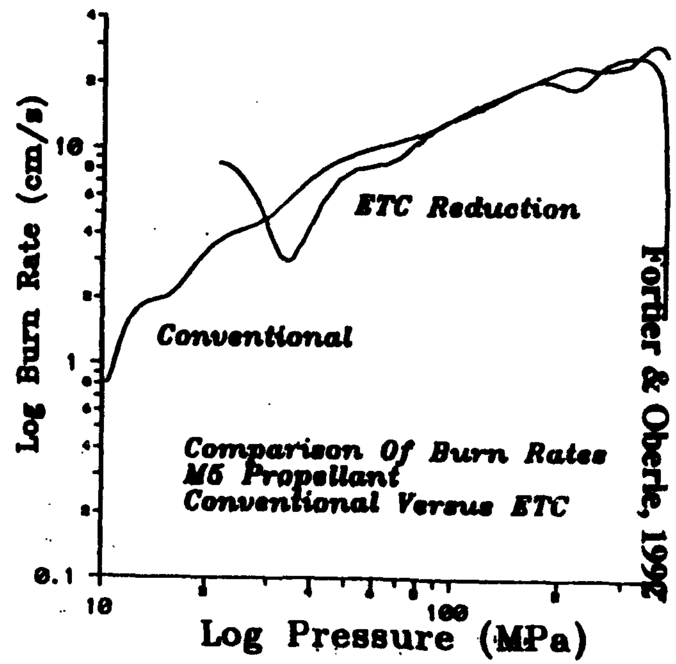
Shot	Propellant	Derivative (MMPa/s)
1	LGP1846	3.820
2	LGP1846	3.670
3	LGP1846	0.134
4	LGP1846	0.084
5	LGP1846	0.327
6	LGP1846	0.121
8	N2H4/HN	0.151
9	HAN/DEG/H2O	0.124
10	HAN/DEG/H2O	0.133
11	HAN/DEG/H2O	0.119
12	HAN/NMP/H2O	0.122
13	HAN/NMP/H2O	0.137
14	M43	0.117
15	M43	0.136
16	DINA/NC	0.108
20	DINA/NC	0.153

Shot	Propellant	Derivative (MMPa/s)
17	RDX/NC/NG	0.129
19	RDX/NC/NG	0.123
22	AN/Cyanoguanidine	0.113
23	AN/MEAN/H2O	0.150
24	AN/MEAN/H2O	0.180
25	AN/5AT/H2O	0.338
26	AN/5AT/H2O	0.272
27	JA2	0.198
28	JA2	0.186
29	JA2 - X	0.161
30	JA2 - X	0.183
31	JA2	0.179
32	JA2	0.172
33	Compacted CAB	0.075
34	Compacted CAB	0.218
35	Loose CAB	0.119
36	Loose CAB	0.112
37	Loose CAB	0.203
38	Loose CAB	0.228

Closed Chamber Burn R[illegible]e

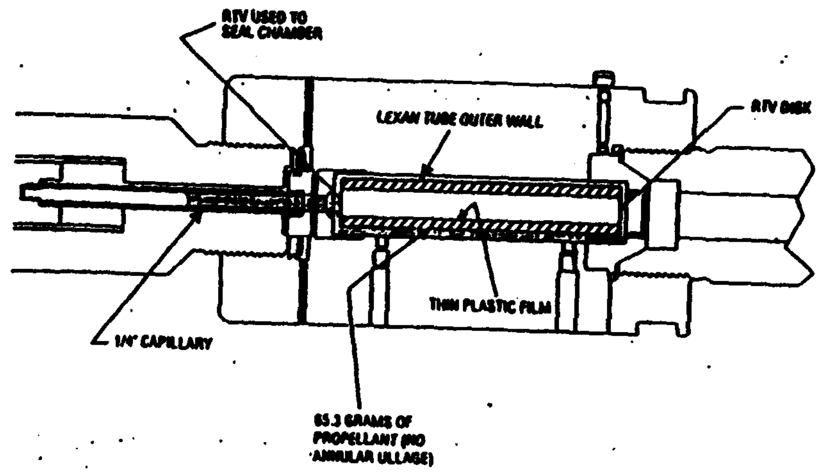
- **Research at ARL in SP combustion with plasma**
  - ETC diagnostic closed chamber/gun fixture
  - Specialized ETC closed chamber data analysis code
- **M5 solid propellant with conventional ignition vs plasma augmented**
  - 50 cc closed chamber data
  - Plasma pulse 1.2 ms, 125 kJ
  - Analyzed using BRLCB
- **Prompt ignition with plasma**
- **In closed chamber plasma does not appear to influence burn rate of SP**

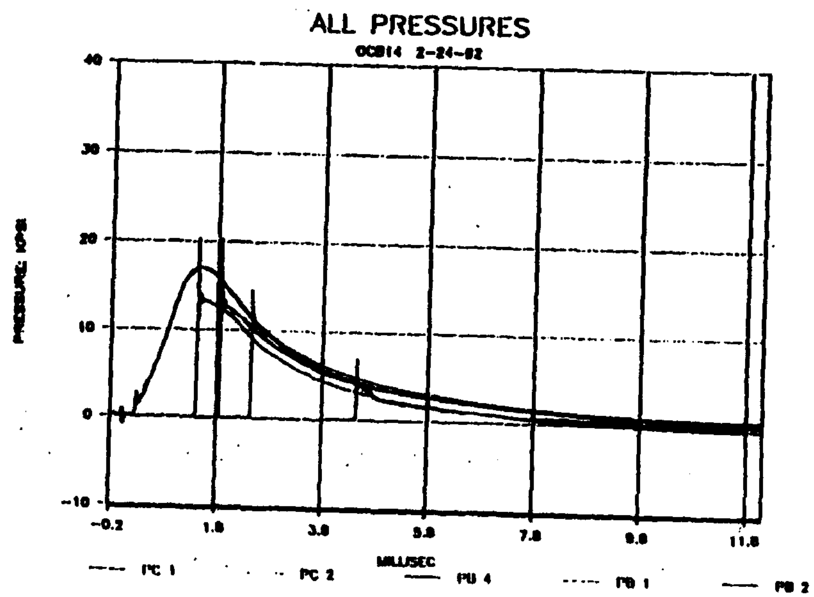




Experiment OCB14

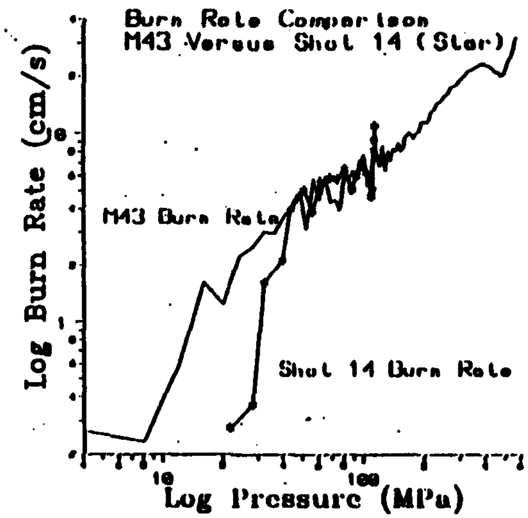
- **30mm fixture**
  - Chamber volume: 160 cc
  - Propellant mass: 65.3 g
  - Chamber diameter: 3.175 cm
  - Chamber L/D: 6.15
  - Travel: 161 cm
  - Projectile mass: 324.36 g
- **M43 solid propellant**
  - Number of perfs: 7
  - Outer diameter 0.2895 cm
  - Diameter perf: 0.0119
  - Grain length: 0.6197 cm
- **Central ullage tube**
- **Electrical energy**
  - Ramped pulse over 1.9 ms
  - 41.167 kJ

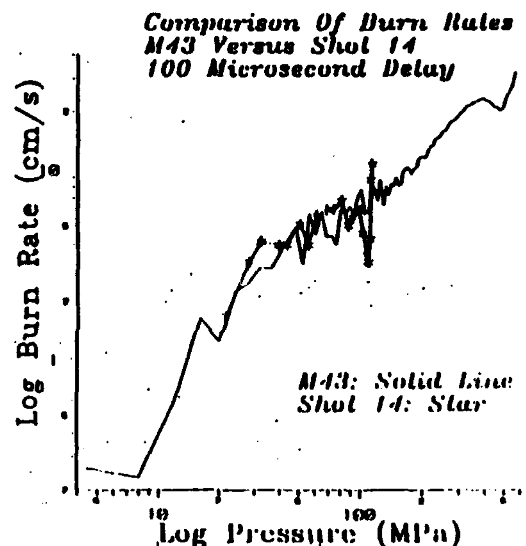




M43 Burn Rate with Plasma

- **Closed chamber data at ARL**
  - M43, lot IH91H-E00040
  - analyzed using BRLCB
- **Inverse code results**
  - use experimental data to obtain mass burned history
  - use m dot & grain geometry to deduce burn rate using modified BRLCB
- **Delay in plasma**
  - current & voltage measured at rear of capillary
  - assume 0.0 and 100 microsecond delay in energy release in combustion chamber





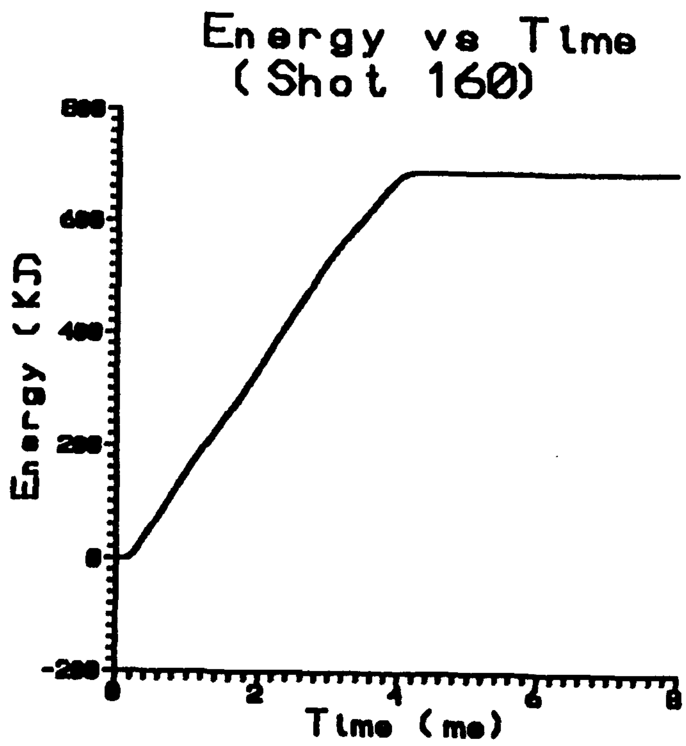
Wren & Oberle, 1993

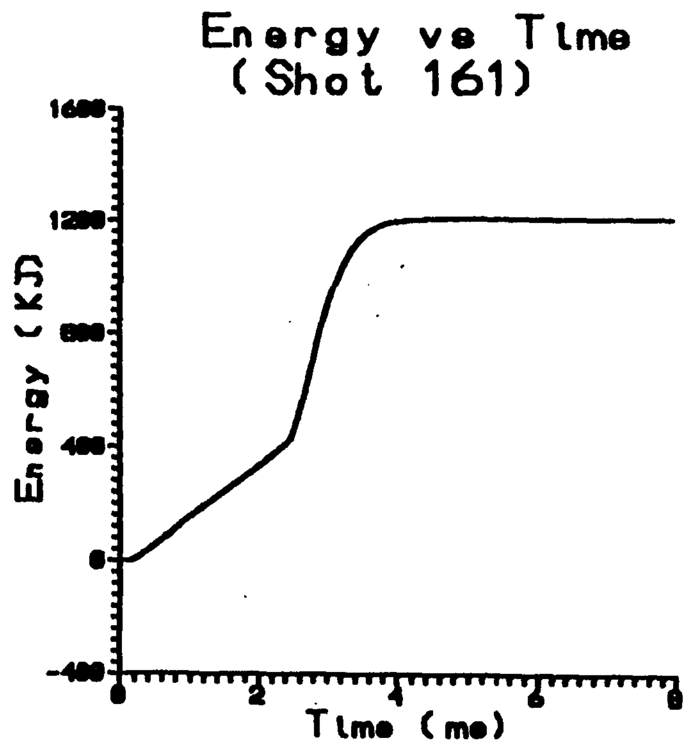
Shots 160 and 161 from Soreq

Input parameters:

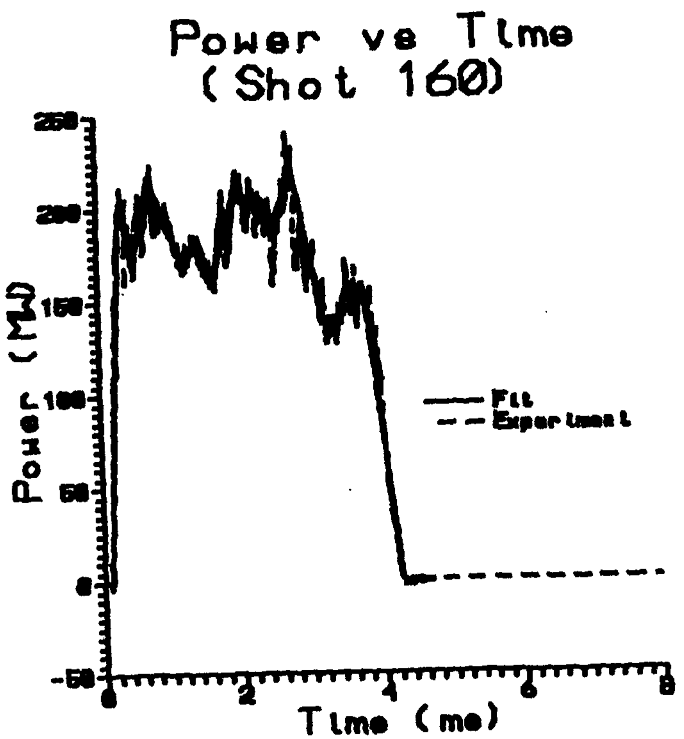
- Bore diameter: 60-mm
- Travel: 3.881 m
- Chamber volume: 2183 cc
- Charge weight: 1.73 Kg
- Propellant: M30, 7perf
- Projectile mass: 1.35 Kg

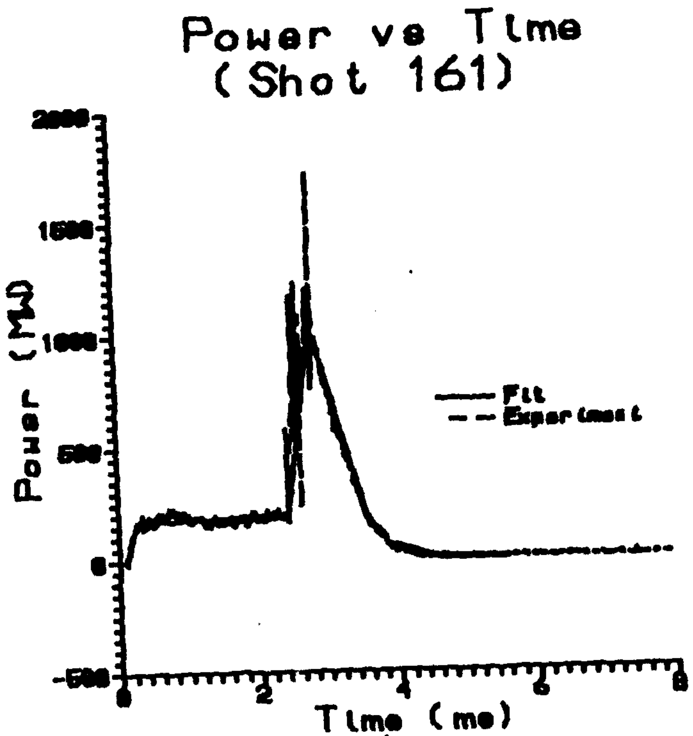
Energy vs Time



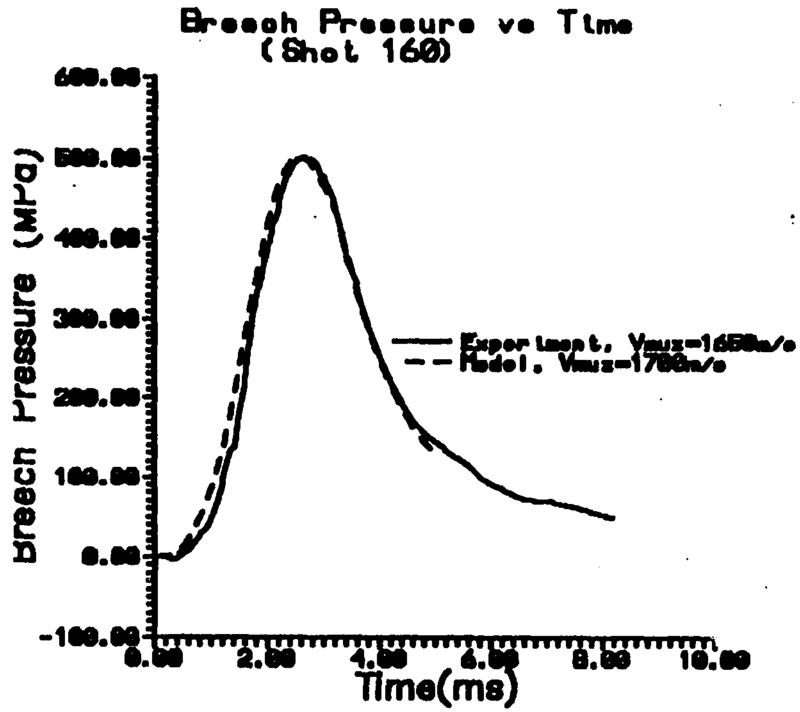


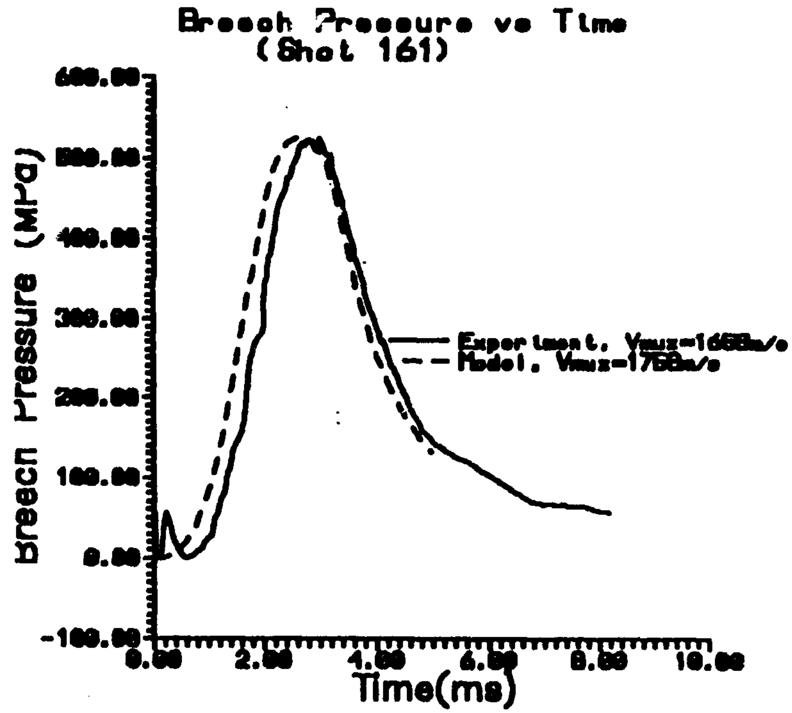
Power vs Time



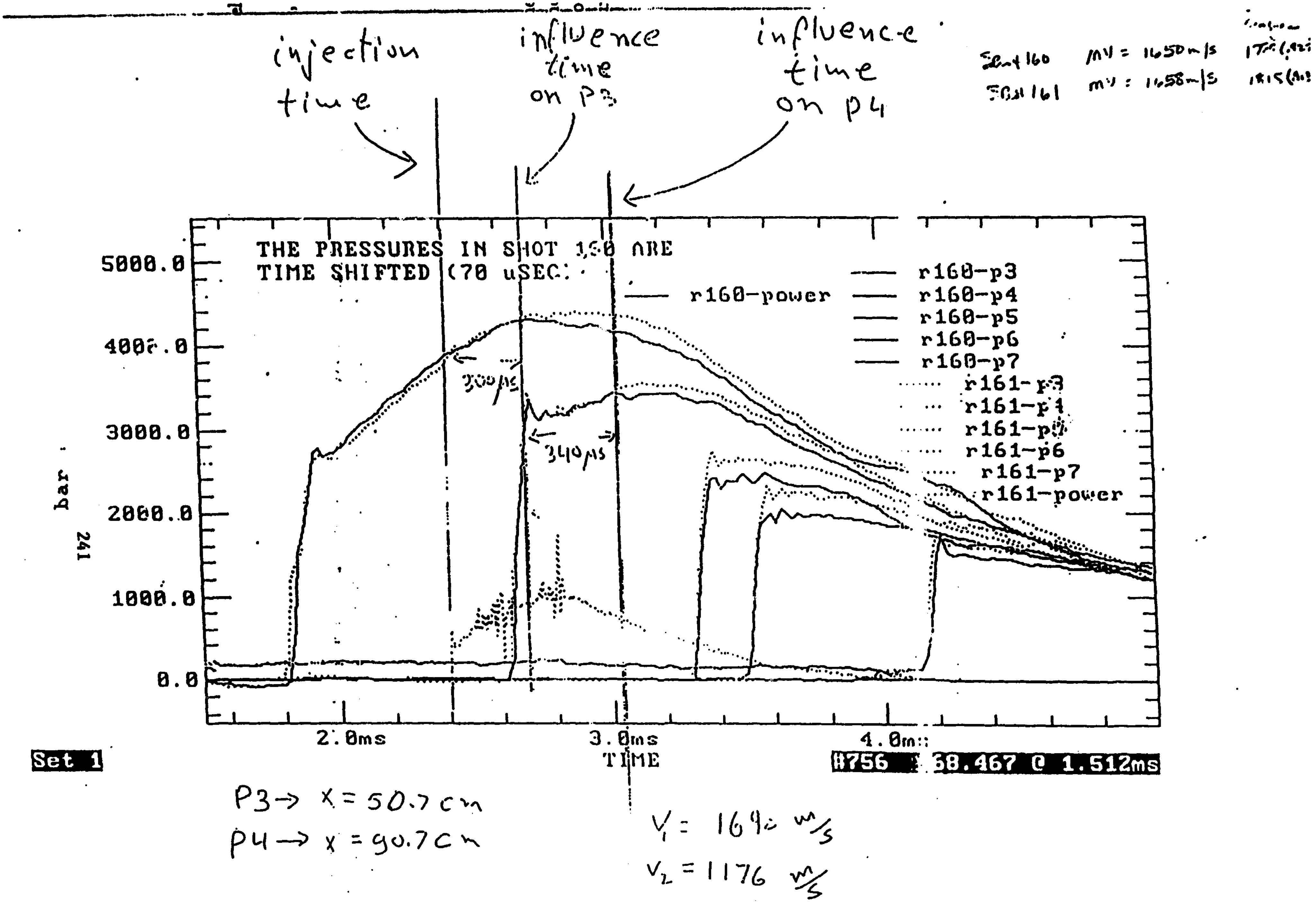


Pressure vs Time





#1- Propellant burning rate (cm/s): $r=.183796P^{.830226}$



injection time
influence time on P3
influence time on P4
MV = 1650 m/s
MV = 1658 m/s
THE PRESSURES IN SHOT 160 ARE
TIME SHIFTED (70 uSEC)
r160-power
r160-p3
r160-p4
r160-p5
r160-p6
r160-p7
r161-p3
r161-p4
r161-p5
r161-p6
r161-p7
r161-power
300μs
340μs
5000.0
4000.0
3000.0
2000.0
1000.0
0.0
bar
241
2.0ms
3.0ms
4.0ms
TIME
Set 1
#756
58.467 @ 1.512ms
P3 → x = 50.7 cm
P4 → x = 90.7 cm
V1 = 1692 m/s
V2 = 1176 m/s

Simulation of OCB14

- XNOVAKTC-ETC, 1D SP IB model (Gough)
  - uniform rupture of moderator tube at 0.3 ms based on pressure rise at combustion chamber gage
  - uniform ignition of propellant
  - plasma source term based on experiment
  - 100 microsecond delay in plasma energy

- Comparison

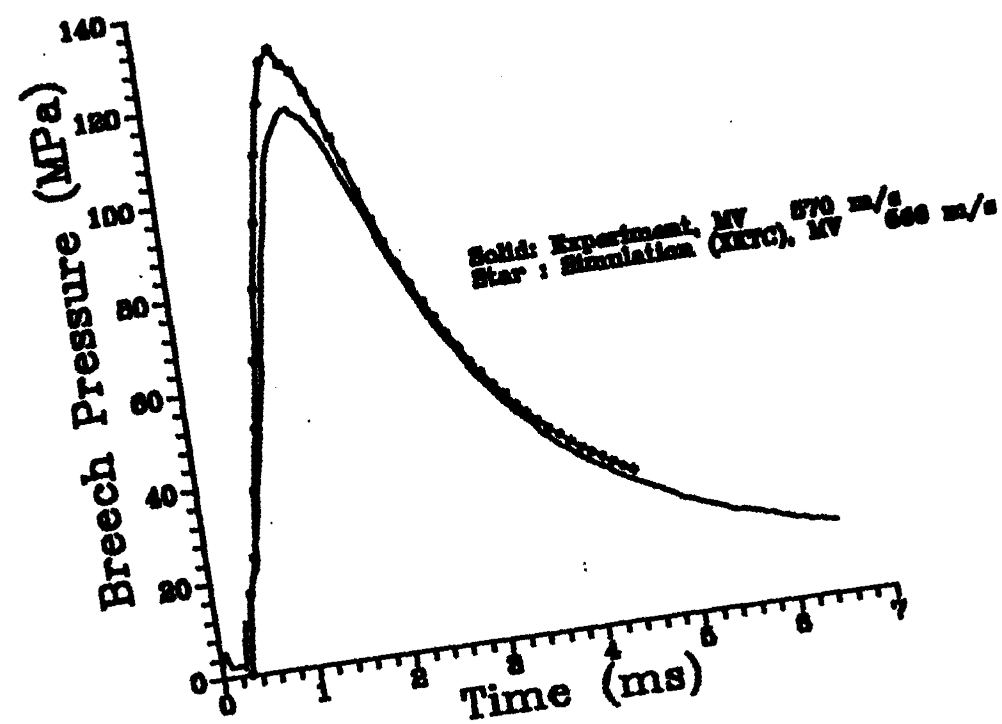
	Pmax	MV	Consumed mass
Experiment	117 MPa	570 m/s	35.36 g (inverse)
Simulation	131 MPa	569 m/s	33.93 g (XKTC)

(initial charge: 65.3 g M43 propellant)

ARL

Simulation of CCB14

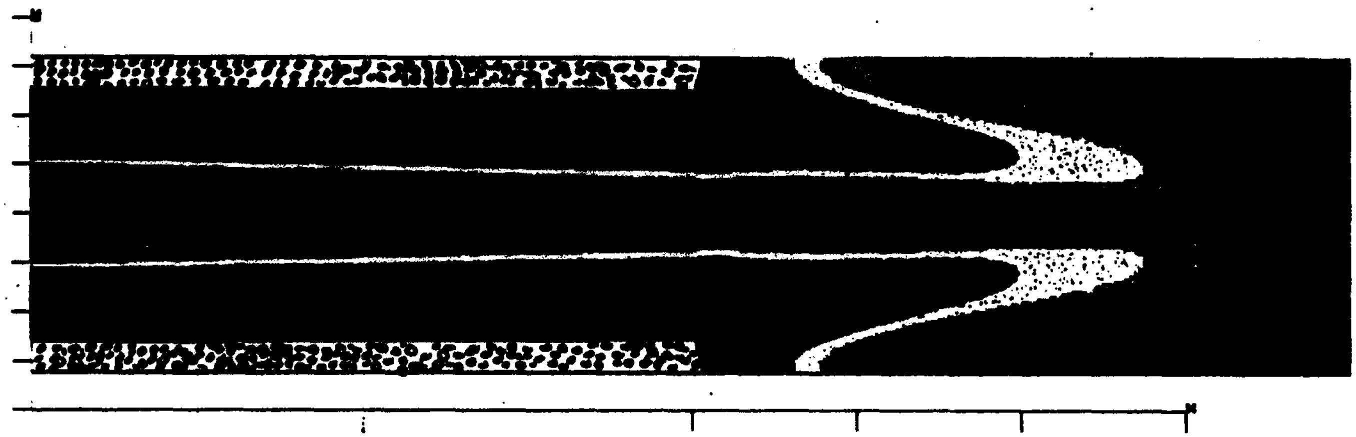
Olin Shot 14, M43, Plasma Delay (0.1 ms)



- **Unknowns**
  - M43 burn rate data at low pressure (< 20 MPa)
  - rupture of ullage tube & effect on bed rheology
  - effect of plasma on flamespreading
  - response of projectile to ullage tube pressurization

Radial Structure of Temperature

"LOG TEMPERATURE LEVELS AT 1.065 ms"
"SP ETC SHOT 45"



"LOG TEMPERATURE LEVELS AT 1.465 ms"
"SP ETC SHOT 45"

ARL

Summary

- ETC gun models integral to research efforts
- Goal: predictive end-to-end models (appropriate dimensionality)
  - dependent on physical process of interest
  - 0D, 1D, 2D, 3D models pertinent
- Burn rate of solid propellant does not appear changed under influence of plasma at electrical energy densities investigated (<1.0 kJ/g)
- Status of IB models
  - 0D models adequately capture macroscopic measurements & can be used for scoping studies
  - 1D models appear to be adequate if plasma components can be sufficiently modeled; useful for study of longitudinal phenomena such as pressure waves
  - 2D/3D models under active development; required to capture radial structure which is necessary for detailed cartridge design

INTENTIONALLY LEFT BLANK.

ARL ETC MODELING WORKSHOP

OLIN IRAD EFFORTS
RELATED TO ETC MODELING

H. McElroy, K. Linde

12 - 13 MAY, 1993

Olin ORDNANCE

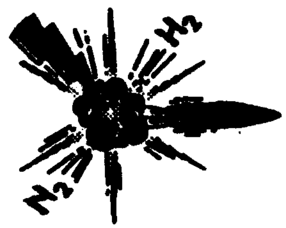
ACKNOWLEDGMENTS

Many Government, GT-Devices and other personnel have been of significant assistance in conducting the efforts described to date. We hope that the cooperative efforts outlined and planned for the future will also be supported as in the past.

In particular, G. Keller, P. Conroy, B. Oberle, G. Wren and N. Winsor contributed significantly to all phases and efforts.

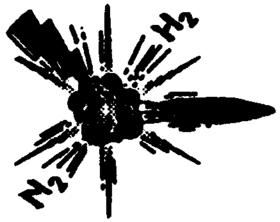
TOPICS

- Why Model - At Olin
- What we model now (routinely)
  - Equilibrium Thermochemistry
  - Simple Optimum Systems Upper Limit Bounds
  - Lumped Parameter or 0-D IB Models
- What we perceive as necessary for the future
- Challenges and Conclusions



WHY MODEL - AT OLIN

- Scoping new products/processes
- Quality Control
- Developing understanding of product capabilities & Limits
- Unraveling experimental data
- Preliminary safety & charge design
- Charge design verification studies
- Incident Analysis



WHAT WE MODEL ROUTINELY AT OLIN

- Equilibrium thermochemistry (Blake & MCVECP aka Hunter) with ET-C extensions

- CONPRESS - or constant chamber pressure model

*HUNT-CON - a combined equilibrium thermochem code with CONPRESS (hunter + conpress) and ET-C Extensions

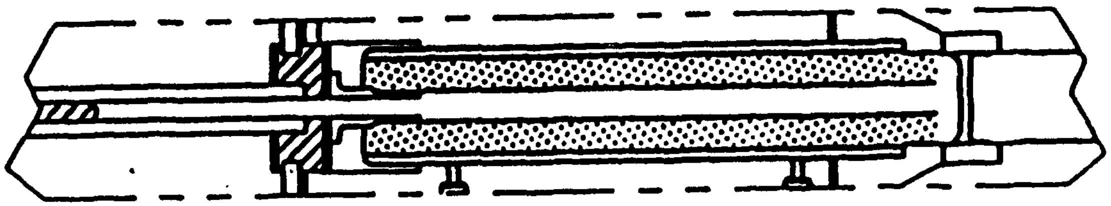
Olin ORDNANCE

LUMPED PARAMETER
Ø-D IB Code - IBHVG2.504G6

- Propellant Form Function Extensions
  - Inside Burner Single Perf Outside Inhib Grain
  - 15 point deterrant function/layer model
  - 10 propellant bins
  - Cased telescoped system
  - Cigarette burn - attached to chamber
- ET-C Functionality - added by GT-Devices
- English to metric and vice versa input/output capability - added by D. Chiu ARDEC - Preserves extensive .400 series data bases.

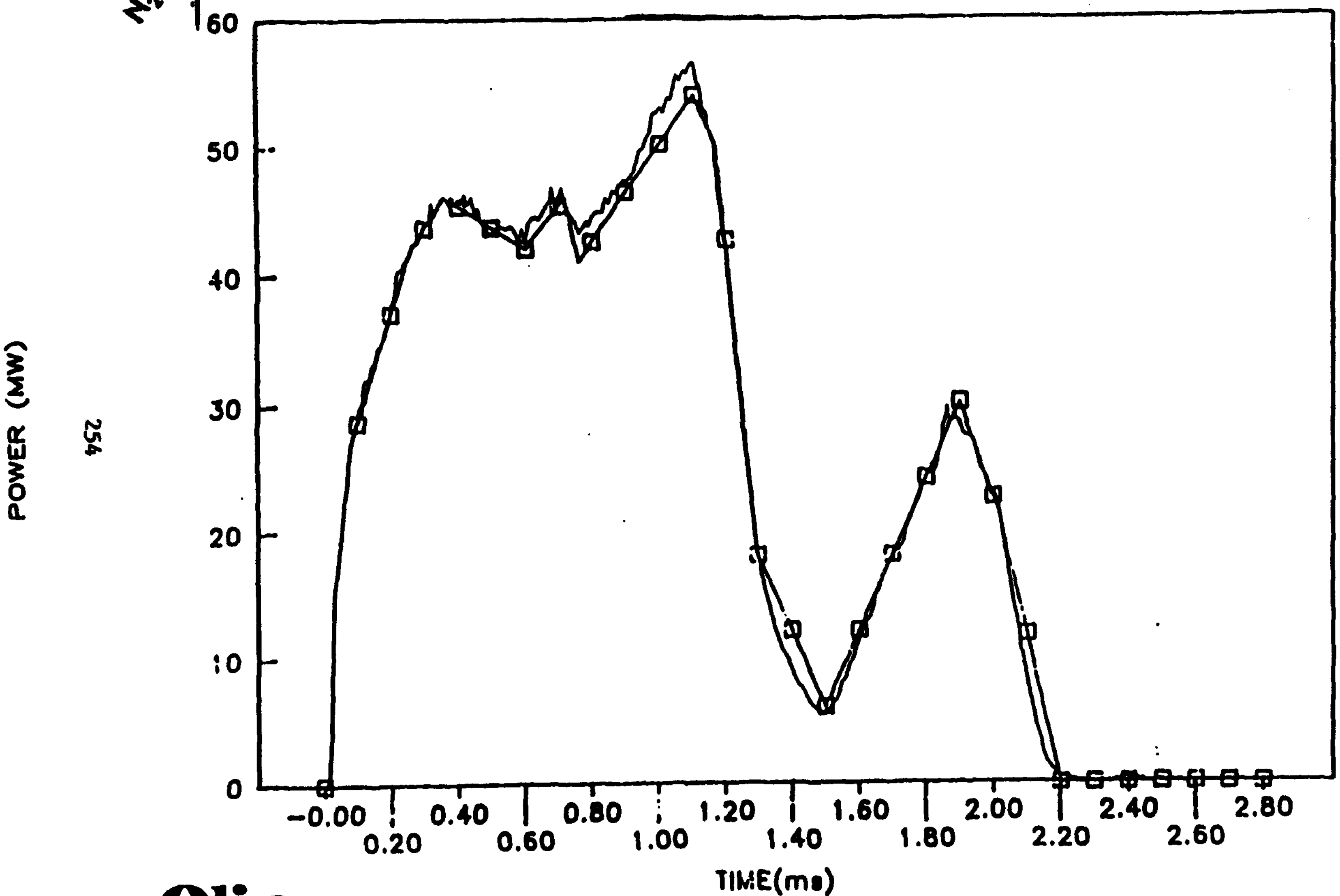
LOADING GEOMETRY

OC26



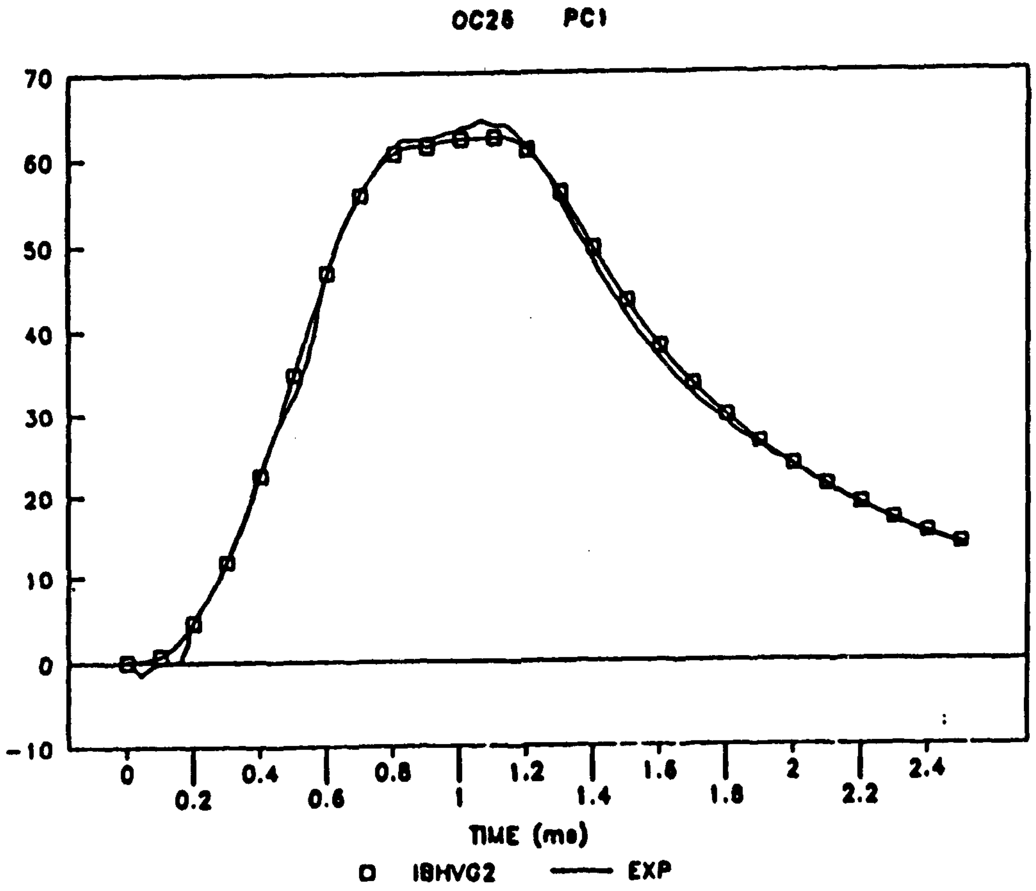
Olin ORDNANCE

30mm OLIN EXP DATA VS CODE RESULTS
OC 26–PCI



Olin ORDNANCE

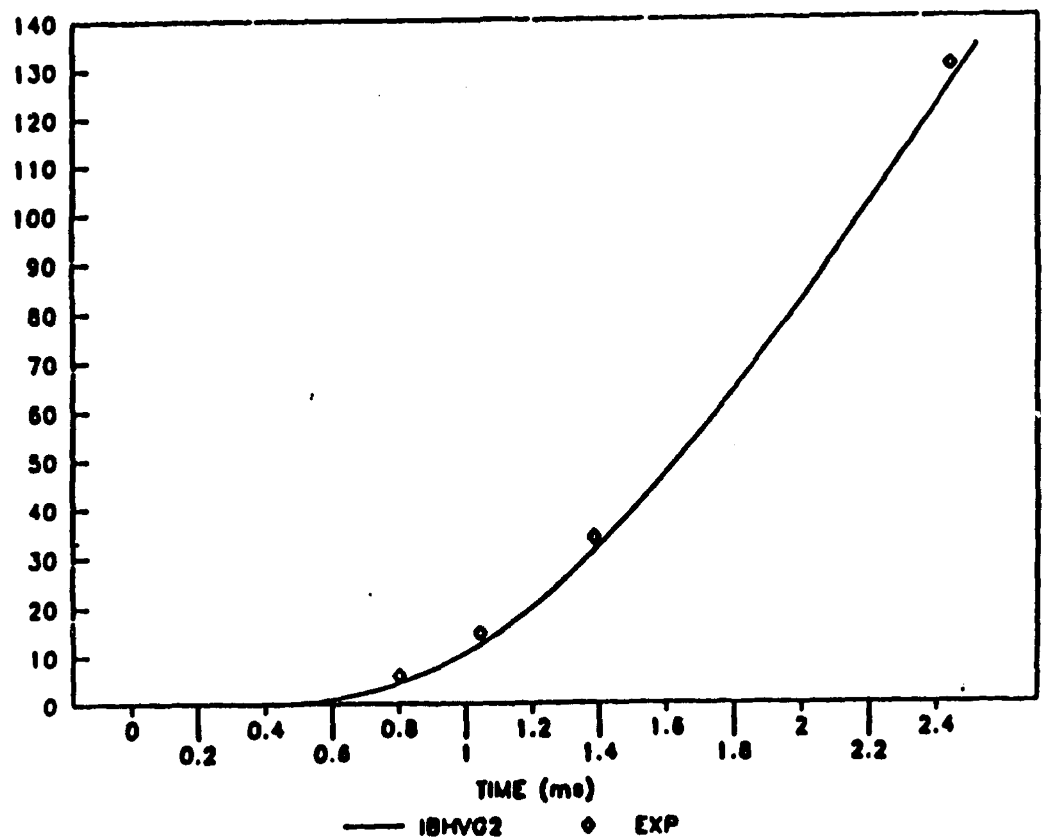
30mm OLIN EXP. DATA vs. CODE RESULTS

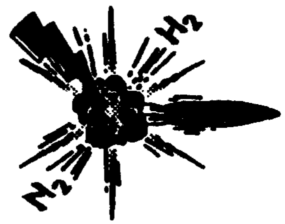


Olin ORDNANCE

CODE AND EXP. PROJECTILE TRAVEL

OC26

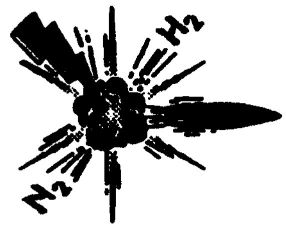




1-D XNOVAKTC (modified)

Beta Version
10426.+

- **Modified input routines to accept extended IBHVG2.504 input decks - or old style card image input if you don't want to change.**
- **Added thoes extensions which we added to IBHVG2.504G6 which were not already in XNOVAKTC. (e.g. Pan Cake Function).**
- **Corrected minor chemistry bug in layer properties - they defaulted to all being the same and increased points to 15.**
- **Release to GT-Devices for input of ET-C functionality - End of May.**



SAMPLE DUAL INPUT DECK

30mm Subscale Artillery for Shot EF044

Combined IBHVG2.504G6 & XNOVAKTC extensions

Olin ORDNANCE

```
$COMM    This run converted to XNOVAKTC 3/19/93 KRL
      NO885.IN  !! Commented out at stuff.
      30mm SUBSCALE ARTILLERY REVERSE ENGINEERING FOR EF044
       USING ADJUSTED 4TH LAYER TRANSITION
      ADJUSTING RATIO OF LARGE TO SMALL GRAIN SIZES TO DEMONSTRATE
       PROCESS CONTROL
$INFO
      RUN =  30mm ARTILLERY RESULTS

$XCONTROL     $M2 CONTROL DATA
          NPRINT = 1   NGRAPH   = 0
          NDISK  = 0   DSKRD    = 0
          IBTABL = 1   NFLAM    = 1
          NPTABL = 1   NEROS    = 0
          NDYN   = 0   NHTW     = 1
          NBC = 0,0
                       $ NRES(1)= 0   NRES(2) = 0   $not used
          LDBED   = 1  $ 0 = PROP BED INITIALLY UNCOMPACT, 1=COMPACTED
          JHTW    = 0  $1
          LYER    = 0  $IBRES = 1 moved to resi
          NTC     = 0
                       $   INHIB = 0,0,0   NO LONGER NEEDED
          NXCW    = 0
          NBLOWN  = 0
          NSWSOL  = 0
          KMODE   = 0
          MODET   = 0  $ 1 = TANK GUN allows modeling of center hole in prop
          NECHO   = 0
          INBCX   = 0

$XINTEGRA    $M3 INTEGRATION PARAMETERS
          NDIM    = 15 $40 $20 $ 10 $20
          DTPRT   = 0
          NSTEP   =    100   TSTOP  = 0.02  $0.0002  $.0200
          NDTST   =      0   ZSTOP  = 60.184
          NSTOP   =   3500   TINT   = 0.0002
          NUNIN   =      0   SAFE   = 1.1  $3    $1.1
          NUNOUT  =      0   CRIT   = 0.2
                             RZOLV  = 0.05  $0.1   $0.05
                             TABLIB = 0.0002
                             TABLP  = 0.0001

$XFILECNT    $M4 FILE COUNTERS
          $ NSTA    =  4   moved to GUN $NUMBER OF TUBE DIAMETER STATIONS
          NTEM    =  0     NEL    = 0
          NEPS    =  0,0,0
          $ NZPT    =  3 $ MOVED TO RESI DECK
          MORE    = 0,0,0
          NBL     =  0


$GUN
   NAME       = '30MM SMOOTHBORE'   $          CHAM     =  10.0384
     $ GRVE      =    1.1811                     LAND     =   1.1811
     $ G/L       =    1.0000                     TWST     =   99999.9
     $ TRAV      =   53.7008                     CLEN     =   7.8740
   NGAG      =  5  GLOC      =  -6.6929, -2.0079,  2.4016, 25.2362, 51.4173
   NSTA = 4    $NUM of Stations in tube profile
   ZA =     0.0,    7.55,     8.05.    60.184
   GUNDIA =1.26.  1.26.  1.1811.   1.1811      $ or use RA (radius)
   TWST = 99999 $ RIF = 6.0 or use TWST (TWST=360/RIF) Is this right????

$RESI     $C12 BORE RESISTANCE - BRD = DIST. BR = PRESSURE
```

```
 IBRES = 1 $LINEAR RESISTANCE , 2=BASED ON VELOCITY                          (2)
$ if TRAV or BRZ start with 0.0.the rest of the values are relative
$ to initial proj. location. if ` 0.0 all is relative to breech

   $ AIR        =  1
    NPTS        =  4
    TRAV        = 0.0,   0.5169,   0.6169, 53.7008
    PRES        = 0.0,    1200.0,   100.00, 50.0018

$PROJ           $M13 PROJECTILE AND RIFLING CHARACTERISTICS
           ZBPR    = 8.05 $7.85  $8.05  $9.856
           PRWT = 0.725 $ WTPR or PRWT or WT
           PRIN    = 0.14 $=POLAR MOM OF INERTIA --LBM-IN**2
             $RIF= 6.0 moved to $GUN

$XAMBGAS        $M5 AMB GAS PROPS
           TEMST   = 530            PST         = 14.7
           GMST    = 29             GAMST       = 1.4

$XPROPBED       $M6 PROPELLANT BED GENERAL PROPS
        $ can use either: TEMPR ,or TEMPF, or, TEMPC
      TEMPC = 21.0


$PRIM           $C8 IGNITER THERMOCHEMISTRY
      NAME       = 'LX CAPILLARY'                  $ CHWT       = .22046E-03
      GAMA       =   1.1100                        COV        =  22.9743
      TEMP       =   300.00                        FORC       =   33435.3
       $ EIG      = 6303000. or if FORC is used it will be used internally
       $         to calculate  EIG = (FORC*12.D0)/(GAMA-1.D0)
       GMIS      = 36.13
      $ NOTE: Following is a guess and may not match IBHVG
       JJ = 3 $NUMBER OF TIMES
       II = 3 $NUMBER OF POSITIONS (SEE M4)
       POSIIG =    0.0,     2.0,     4.00
       TIMEIG = 0.006,    0.008,    0.010
       RATEIG =   0.070,   0.070,   0.070,
                 0.040,   0.040,   0.040,
                 0.010,   0.010,   0.010     $ no comments above this allow

$PROP
      NAME       = 'LX CAPILLARY'                   GRAN       = '1PF  $2   $'1PF'
      CHWT       =   0.0231                         LEN        =   3.0000
      DIAM       =   0.5116                         DP         =   0.1875
     $ WEB        =   0.1621
      GAMA       =   1.1100
      COV        =  22.9743                         RHO        =   0.0434
      TEMP       =   300.00                         FORC       =   33455.3
      ALPH       = 0.0                              BETA       =   55.1181
       $ NTBL = 1
      $ Note: nova input needs follow for prop def
           ZGRLFT    = 0.0   $LEFT HAND LOC OF BAG OF PROP I
           ZGRRHT    = 3.0   $ is this right ??
           RGRI    = 0.09375 $INNER RAD OF PROP      note this is one dimensional
           RGRO    = 0.2558 $OUTER RADIUS note: NOT used in code

           SLW   = 0.0   $SLOT WIDTH
           NFIX = 0     $ 0=GRAIN FREE TO MOVE, 1 = ATTACH TO    E, 2= ATT PROJ
           BONDX   = 0.0  $ STRENGTH OF BOND

           GAP   = 17400.  $RHEOLOGY RATE OF PROPAGA OF STRESS OF SETTLED BED
           GEPO =0.8  $0.35    $ 0.820.28 $0.25 $0.301  $0.58387
           GCAP = 50000.   $RATE OF PROPAGA
           ANU   = 0          $POISSONS RATIO OF PROP
```

(3)

```
        TEMPIG    = 810.    $ IGNITION TEMPERATURE
        KP        = .0277   $ THERMAL CONDUCTIVITY
        ALPHAP =  .0001345  $ THERMAL DIFFUSIVITY
        EMMIS     = .6      $ EMMISIVITY FACTOR

$PROP
     NAME       = 'LX MOD TUBE'
     CHWT       = 0.003307
     LEN        =   7.2441
     GRAN       = '1PF '   $ 2 $ '1PF'
     DIAM       =   0.19625                     DPERF      =   0.1875
   $  WEB        = 0.008736
     GAMA       =   1.1100
     COV        =  22.9743                      RHO        =   0.0434
     TEMP       =   300.00                      FORC       =   33455.3
     ALPHA      = 0.0                            BETA      =   0.1969
      NTBL = 1
    $ Note: nova input needs follow for prop dek
        ZGRLFT    = 0.0   $LEFT HAND LOC OF BAG OF PROP I
        ZGRRHT    = 7.24412   $RIGHT HAN BOUND
        RGRI     = 0.1875 $INNER RAD OF PROP      note this is one dimensional
        RGRO     = 0.19625 $OUTER RADIUS note: NOT used in code

        SLW   = 0.0   $SLOT WIDTH
        NFIX = 0    $ 0=GRAIN FREE TO MOVE, 1 = ATTACH TO TUBE, 2= ATT PROJ
        BONDX   = 0.0   $ STRENGTH OF BOND

        GAP   = 17400.   $RHEOLOGY RATE OF PROPAGA OF STRESS OF SETTLED BED
        GEPO =0.8   $0.35 . $ 0.820.28 $0.25 $0.301   $0.58387
        GCAP = 50000.   $RATE OF PROPAGA
        ANU  = 0         $POISSONS RATIO OF PROP

        B1        = 0.0    $ BURN RATE CONSTANT
        TEMPIG    = 810.    $ IGNITION TEMPERATURE
        KP        = .0277   $ THERMAL CONDUCTIVITY
        ALPHAP =  .0001345  $ THERMAL DIFFUSIVITY
        EMMIS     = .6      $ EMMISIVITY FACTOR

$PROP
     NAME       = 'WC885'                      GRAN       =  BALL   $18
   $ IGNC       =  1                             THRC      = .50000E-03
     NTBL       = 1 $-1
     DIAM       =   0.0630
  $    DL/S      = 0.008570,   0.0315,   0.0851   ! NOVA does not like /'s
     DLS       = 0.008570,   0.0315,   0.0851
   $   DEPL = 0.0005399, 0.0019845, .0053613
     RHOL       =   0.0539,   0.0539,   0.0548,   0.0589
     GAML       =   1.2850,   1.2850,   1.2790,   1.2340
     FRCL       =  254259.9, 254259.9, 278213.9, 373962.8
     COVL       =  30.8077, 30.8077, 30.9184, 26.4897
     TMPL       =     1896.9.    1896.9.    2109.4,    3471.2
     COEL   = .62236E-03, .62236E-03, .75113E-3, 0.001788
     EXPL   =    0.8053,    .8053,        .8053,        .8053
     CHWT       =   0.3336
    $ Note: nova input needs follow for prop dek
        ZGRLFT    = 0.0   $LEFT HAND LOC OF BAG OF PROP I
        ZGRRHT    = 7.5   $guess   $RIGHT HAN BOUND
        RGRI     = 0.25 $guess$INNER RAD OF PROP   note this is one dimensional
        RGRO     = 0.63 $OUTER RADIUS note: NOT used in code

        SLW   = 0.0   $SLOT WIDTH
        NFIX = 0    $ 0=GRAIN FREE TO MOVE, 1 = ATTACH TO TUBE, 2= ATT PROJ
        BONDX   = 0.0   $ STRENGTH OF BOND

        GAP   = 17400.   $RHEOLOGY RATE OF PROPAGA OF STRESS OF SETTLED BED
```

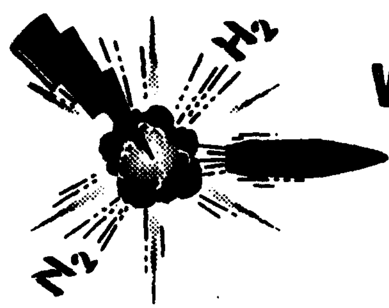
```
[illegible]
GCAP = 30000     $RATE OF PROPAGA
ANU  = 0         $POISSONS RATIC OF PROF

B1      = 0.0    $ BURN RATE CONSTANT
TEMPIG    = 810.    $ IGNITION TEMPERATURE
KP        = .0277   $ THERMAL CONDUCTIVITY
ALPHAP = .0001345 $ THERMAL DIFFUSIVITY
EMMIS     = .5      $ EMMISIVITY FACTOR
```

(4)

```
$COMM
   $ FOUR LAYER PROPELLANT MODEL (NOMINAL 1MM DIAM)
 $ warning this dek is metric because was comented out during convers
     NAME       =  'WC885'                            GRAN      =  BALL
     IGNC = 1           THRC = 0.0002
     DIAM       = 0.00100838
     NTBL       = -1
     DL/S       = 0.0136, 0.0500, 0.1350
     RHOL       = 1492.6, 1492.6, 1515.8, 1631.3
     GAML       = 1.285, 1.285, 1.279, 1.234
     FRCL       = 760000, 760000, 831600, 1117800
     COVL       = 0.001113, 0.001113, 0.001117, 0.000957
     TMPL       = 1896.9, 1896.9, 2109.4, 3471.2
     CF1L       = 0.00087          EX1L       = 0.8053
     CF2L       = 0.00087          EX2L       = 0.8053
     CF3L       = 0.00105          EX3L       = 0.8053
     CF4L       = 0.00250          EX4L       = 0.8053
     CHWT       =  0.1513

  $ETC
     $ WARNING This is metric et dek*********************************
          PFAC=1
          NPWR = 9
     TPWR = 0, 3E-5, 6E-5, 1.2E-4, 1E-3, 1.25E-3, 1.52E-3, 1.7E-3, 2E-3
     PWR = 0, 0, 4.4E6, 2.4E6, 4.6E6, 1.85E6, 0.45E6, 0.09E6, 0
$END
```



WHAT WE PERCEIVE AS NECESSARY FOR THE FUTURE • IRAD PLAN

CY 93 → BEYOND

- OLIN IRAD FUNDS
- COOPERATIVE PARTNER SHARE

CODE
- 0-D IB
- 1-D IB XKTC
- 1-1/2-D IB XKTC(M)
- 2D NG *
- 3D NG *

PHYSICS
- HIGH LD>1.3 g/cc
- BED RHEOLOGY
- BED POROSITY
- BED COMPACTION
- FLAME SPREAD ISSUES
- PLASMA / MODERATOR INTERACTIONS
- PLASMA / PROPELLANT INTERACTIONS
- CHEMICAL KINETICS / PATH MODIFICATION STUDIES
- VISUALIZATION STUDIES / X-RAY DIAGNOSTICS
- GUN FIRINGS / DIAGNOSTICS / SHORT TUBE / LONG TUBE

COOPERATIVE EXPERIMENTS WITH:

U.S. GOVT.	GT DEVICES
ARL / NAVY	GDLS
ARDEC	
SSDC / EGLIN AFB	
NAT LABS	

(* U.S. GOVT. DEVELOPED)

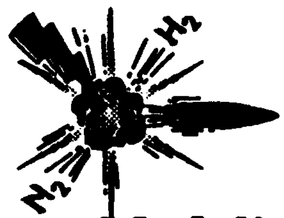
Olin ORDNANCE

VG 6/93 13373

THIS DOCUMENT CONTAINS OLIN ... COMPETITION-SENSITIVE MATERIAL

CHALLENGES FOR ETC MODELING

- Modeling technology must advance rapidly over next two years.
- Funds for 6.1/6.2 work appear scarce.
- For solids (ET-C) near to medium term technology (modeling) issues not as severe as liquids but significant technology challenges are present.
- Severe lack of high charge density/loading density experimental data with ET-C systems critical potential show stopper for modeling.
- US Government must articulate IM requirements more strongly as associated with ET-C.



CONCLUSIONS

- Modeling community must pull together - under <u>A R L</u> Guidance/Sponsorship/Leadership.
- Physics experiments must be jointly/cooperatively conducted to leverage scarce 6.1/6.2 resources all sources - Navy, Army, SDC, DNA, Air Force.
- We must be creative in our approaches.
- Olin will sell no propellant or cartridge systems before their time.

Our goal is to field ammunition/ctg systems. <u>NOT</u> Conduct long term R & D - Modeling is only one of the tools (but a necessary one)

INTENTIONALLY LEFT BLANK.

CALIFORNIA RESEARCH & TECHNOLOGY DIVISION
TITAN CORPORATION

Application of PDF Turbulent Combustion Model to Electrothermal-Chemical (ETC) Guns

Philip A. Hookham
Leonard Walitt

Presented at:

U.S. Army Research Laboratory
Aberdeen Proving Ground, Maryland 21005

12 May 1993

ETC Gun Modeling at CRT: Background

- Defense Nuclear Agency (DNA) sponsored ETC gun modeling under Turbulent Chemistry Modeling contract
- Work was performed over ~1 year period ending 12-92
- Contract emphasized turbulent mixing and combustion aspects of problem

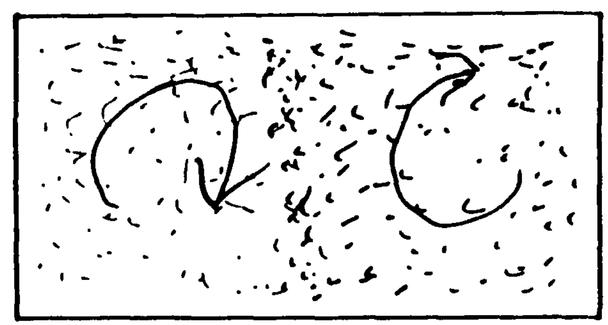
CRT0493-01PM

Unmixedness Modeling Using PDF Approach

Problem Definition

- Suppose we have a computational cell containing reactants α and β and product γ which is generated in an irreversible reaction (the assumption of irreversibility is not required): $\alpha + \beta \rightarrow \gamma$
- The mean mass fractions of α and β, $\overline{C_\alpha}$ and $\overline{C_\beta}$, are known
- The turbulent correlation $\overline{C'_\alpha C'_\beta}$ can be calculated from the second-order closure turbulence model (we have to model a source term in the evolution equation for this correlation, however)
- What is the rate of production of γ, i.e., $\overline{\dot{W}_\gamma}$?

$$\dot{w}_\gamma = K C_\alpha C_\beta$$

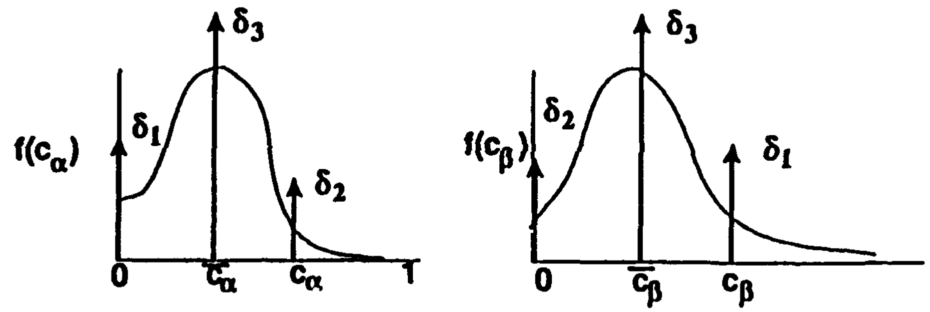


Computational cell

Unmixedness Modeling Using PDF Approach (continued)

Donaldson Unmixedness Approach

- Postulate the existence of N states within the cell, where each state is characterized by $C_{\alpha,i}$ and $C_{\beta,i}$ (and, in general, temperature T_i), i.e., approximate a continuous pdf with a finite number of Dirac delta functions δ_i with strengths ε_i.



- Calculate the probability ε_i of each state.
- Calculate the expectation of the rate of production of γ from the known states and ε_is:

$$\overline{\dot{W}_\gamma} = \sum_{i=1}^{N} \varepsilon_i \dot{W}_{\gamma,i}$$

Turbulent Unmixedness Modeling: Choice of States for a Two Species System

Suitable events should include states at the mean (i.e., when turbulence levels are low) as well as states where one or both concentrations disappear (intermittency).

If $\overline{c_1'c_2'} < 0$, we may choose

State 1: $c_{1,1} = 0, \quad c_{2,1} = 2\overline{C_2}$

State 2: $c_{1,2} = 2\overline{c_1}, \quad c_{2,2} = 0$

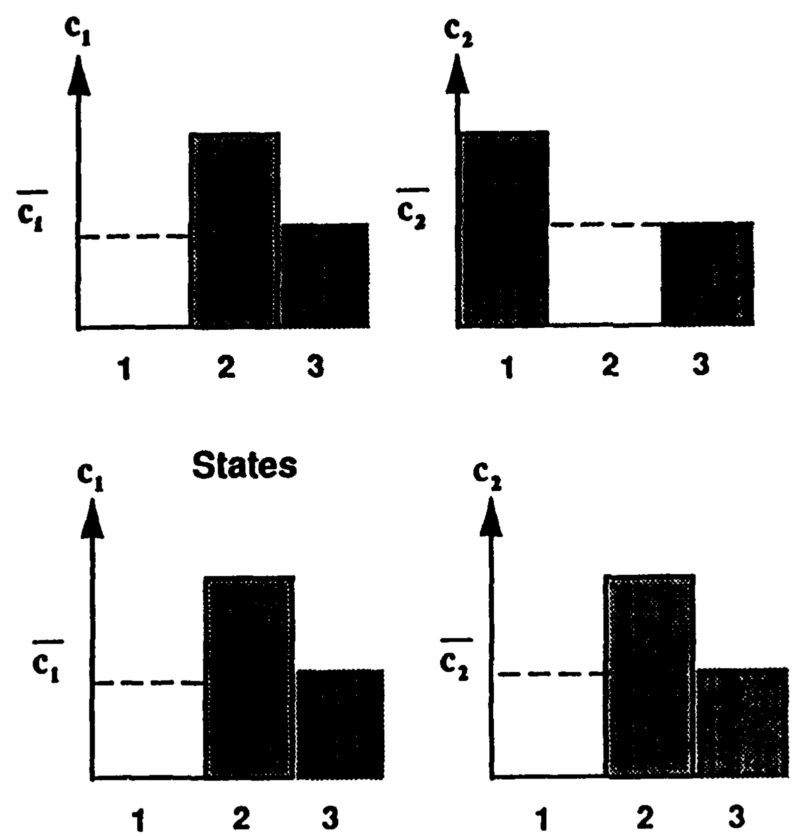
State 3: $c_{1,3} = \overline{c_1}, \quad c_{2,3} = \overline{c_2}$

Or if $\overline{c_1'c_2'} > 0$,

State 1: $c_{1,1} = 0, \quad c_{2,1} = 0$

State 2: $c_{1,2} = 2\overline{c_1}, \quad c_{2,2} = 2\overline{c_2}$

State 3: $c_{1,3} = \overline{c_1}, \quad c_{2,3} = \overline{c_2}$



Determination of PDF

Constraints

$$\sum_{i=1}^{N} \varepsilon_i C_{\alpha_{ji}} = \overline{C_\alpha}$$

$$\sum_{i=1}^{N} \varepsilon_i C_{\beta_{ji}} = \overline{C_\beta}$$

$$\sum_{i=1}^{N} \varepsilon_i C_{\alpha_{ji}} C_{\beta_{ji}} = \overline{C_\alpha C_\beta} = \overline{C_\alpha}\,\overline{C_\beta} + \overline{C_\alpha' C_\beta'}$$

$$\sum_{i=1}^{N} \varepsilon_i = 1$$

If number of states exceeds number of constraints, we need an additional criterion.

Maximize Entropy by minimizing

$$\sum_{i=1}^{N} \varepsilon_i \ln(\varepsilon_i)$$

Solution Procedure for Probabilities

Lagrange multiplier method

Define F =

$$\sum_{i=1}^{N} \varepsilon_i \ln \varepsilon_i \;+\; \lambda_{01}\left(\sum_{i=1}^{N} \varepsilon_i C_{\alpha,i} - \overline{C_\alpha}\right) \;+\; \lambda_{02}\left(\sum_{i=1}^{N} \varepsilon_i C_{\beta,i} - \overline{C_\beta}\right) \;+\; \lambda_{12}\left(\sum_{i=1}^{N} \varepsilon_i C_{\alpha,i} C_{\beta,i} - \overline{C_\alpha C_\beta}\right)$$

$$+\lambda_{00}\left(\sum_{i=1}^{N} \varepsilon_i - 1\right).$$

Then:

$$\varepsilon_i = \exp\left(-1 - \lambda_{01} C_{\alpha,i} - \lambda_{02} C_{\beta,i} - \lambda_{12} C_{\alpha,i} C_{\beta,i} - \lambda_{00}\right).$$

Solve for Lagrange multipliers using Newton's method, e.g.

Temperature Spottiness Modeling

Approach

- Determine the temperatures T_i associated with each state i (whose probabilities have already been calculated) by minimizing the function:

$$\sum_{i=1}^{N} \varepsilon_i T_i^2$$

subject to the constraints:

$$\sum_{i=1}^{N} \varepsilon_i C_{\alpha,i} T_i = \overline{C_\alpha T} \quad \text{and} \quad \sum_{i=1}^{N} \varepsilon_i C_{\beta,i} T_i = \overline{C_\beta T} \,.$$

i.e., maximize the entropy of mixing. Again, using Lagrange multipliers, solve for T_i

$$T_i = \lambda_1 C_{\alpha,i} + \lambda_2 C_{\beta,i}$$

Temperature Spottiness Modeling (continued)

- We must also satisfy a constraint on $\overline{T^2}$, however, and therefore an additional degree of freedom is needed (consider the case of only 1 species when there could be no unmixedness, but still there are temperature fluctuations). Introduce an additional parameter δ such that:

$$\varepsilon_{i1} = \varepsilon_i(1+\delta)/2, \quad \varepsilon_{i2} = \varepsilon_i(1-\delta)/2,$$
$$T_{i1} = T_i/(1+\delta), \quad T_{i2} = T_i/(1-\delta).$$

The constraint then becomes:

$$\overline{T^2} = \sum_{i=1}^{N}\left(\varepsilon_{i1}T_{i1}^2 + \varepsilon_{i2}T_{i2}^2\right) \quad ,$$

and delta is:

$$\delta = \sqrt{1 - \frac{1}{\overline{T^2}}\sum_{i=1}^{N}\varepsilon_i T_i^2} \quad .$$

ETC Gun Modeling Approach

- **Model from "first-principles":**
  - Fluid dynamics of plasma, liquid and vaporized working fluid components, reaction products
- **Use detailed parameterizations for:**
  - Mass, momentum, and heat transfer between gas and liquid (droplet) phases
  - Turbulence
  - Turbulent mixing and reaction of chemical species
  - Entrainment of droplets from working fluid

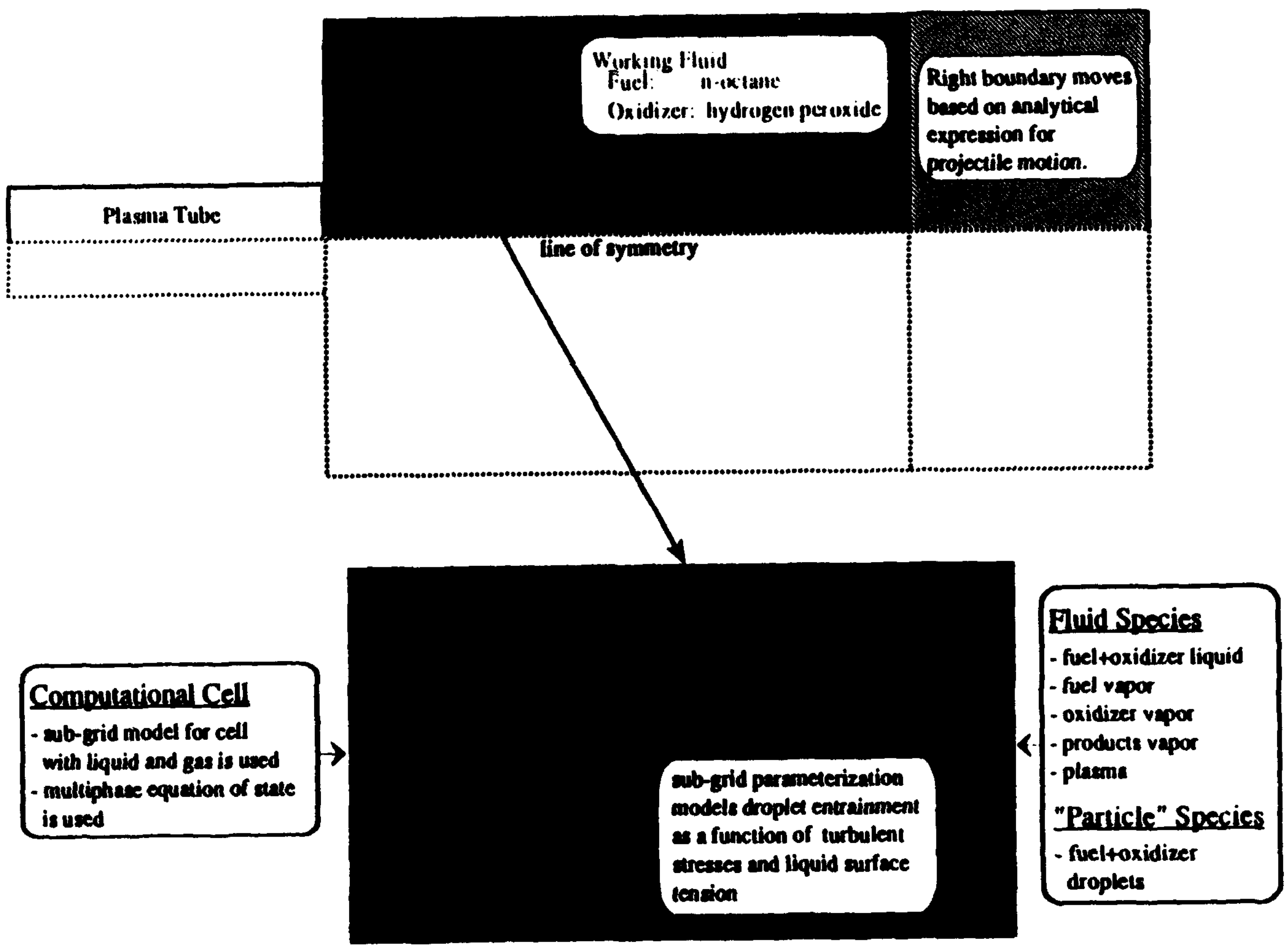
CRT0493-01PM

ETC Gun Modeling Approach (continued)

- **Model simply:**
  - Addition of electrical energy to plasma
  - Chemical kinetics
  - Projectile motion

CRT0493-01PM

ETC Gun Modeling Approach Schematic

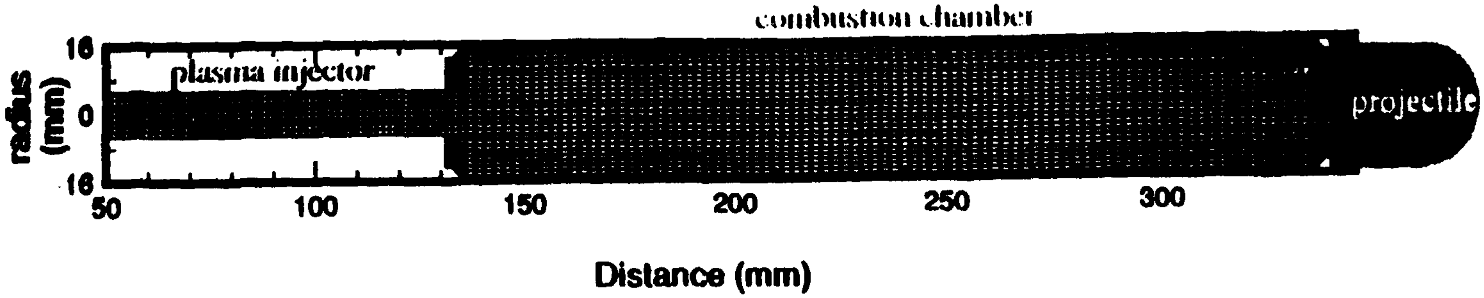


CRT0493-01PM

ETC Gun Calculation Description

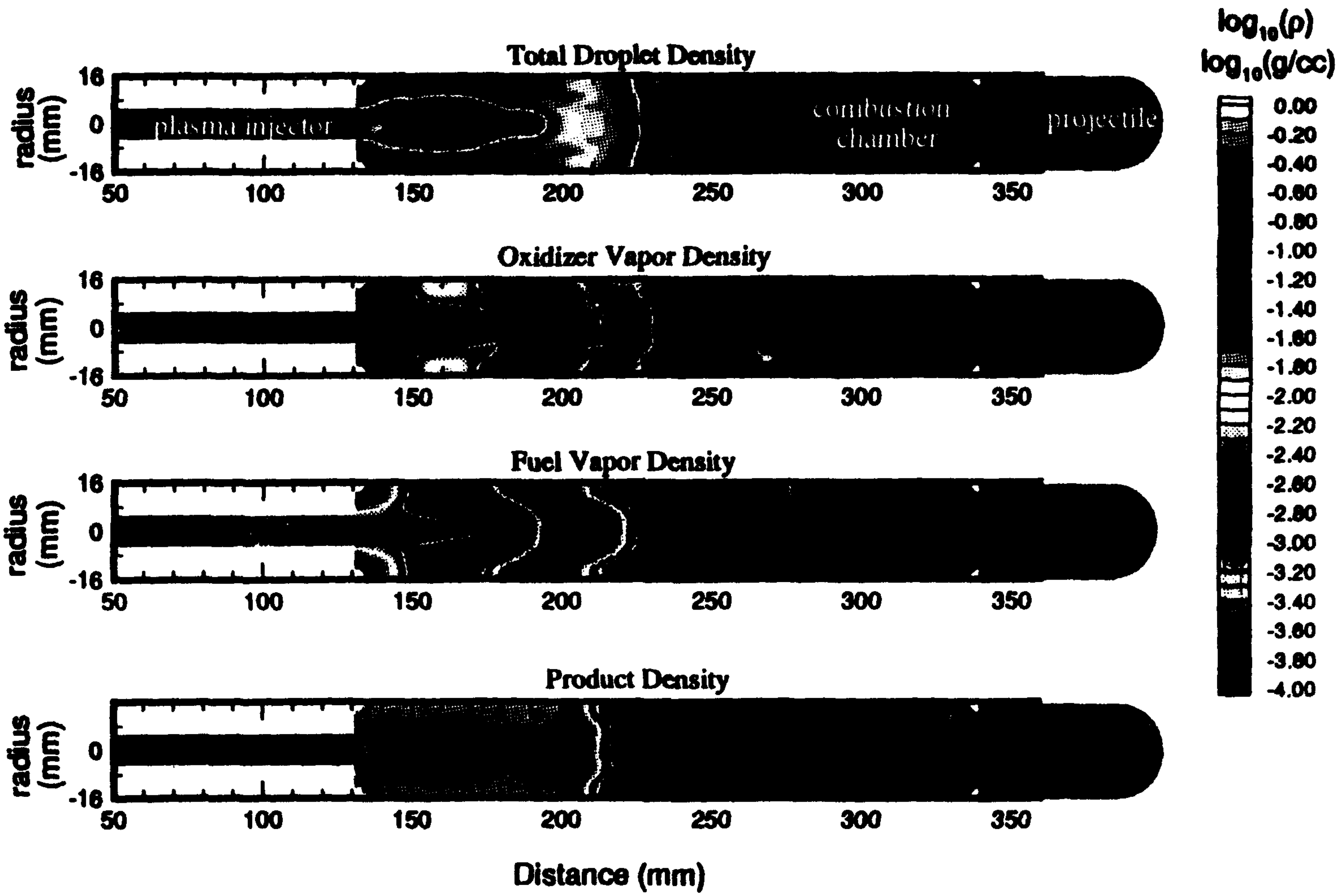
Features

- Simulation of DNA Shot #7
- 30mm nominal diameter, 57.4 caliber, projectile weight = 339 g
- Gun chamber is scaled version of 155mm gun chamber
- Propellant is 85% H_2O_2 by volume, 15% RJ4 (simulated by octane), 166 cc
- Total electrical energy input = 168 KJ, added over 1.1 msec
- 2-D MAZe code (axisymmetric)



CRT0493 01PM

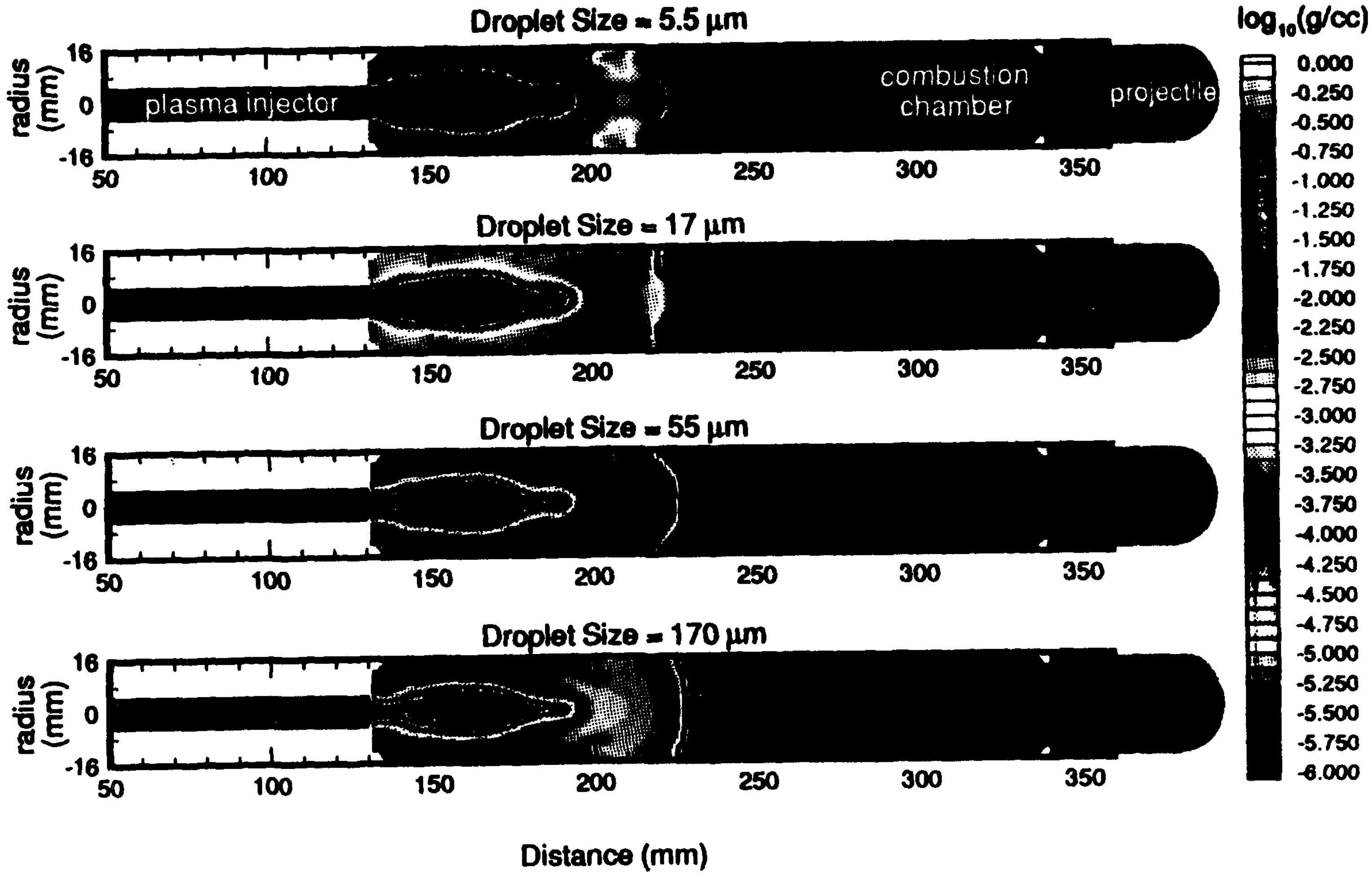
MAZe Code Simulation of 30mm ETC Gun Test
Selected Densities at 0.50 msec
Turbulent Unmixedness Case



MAZe Code Simulation of 30mm ETC Gun Test

Droplet Density   Time = 0.50 msec

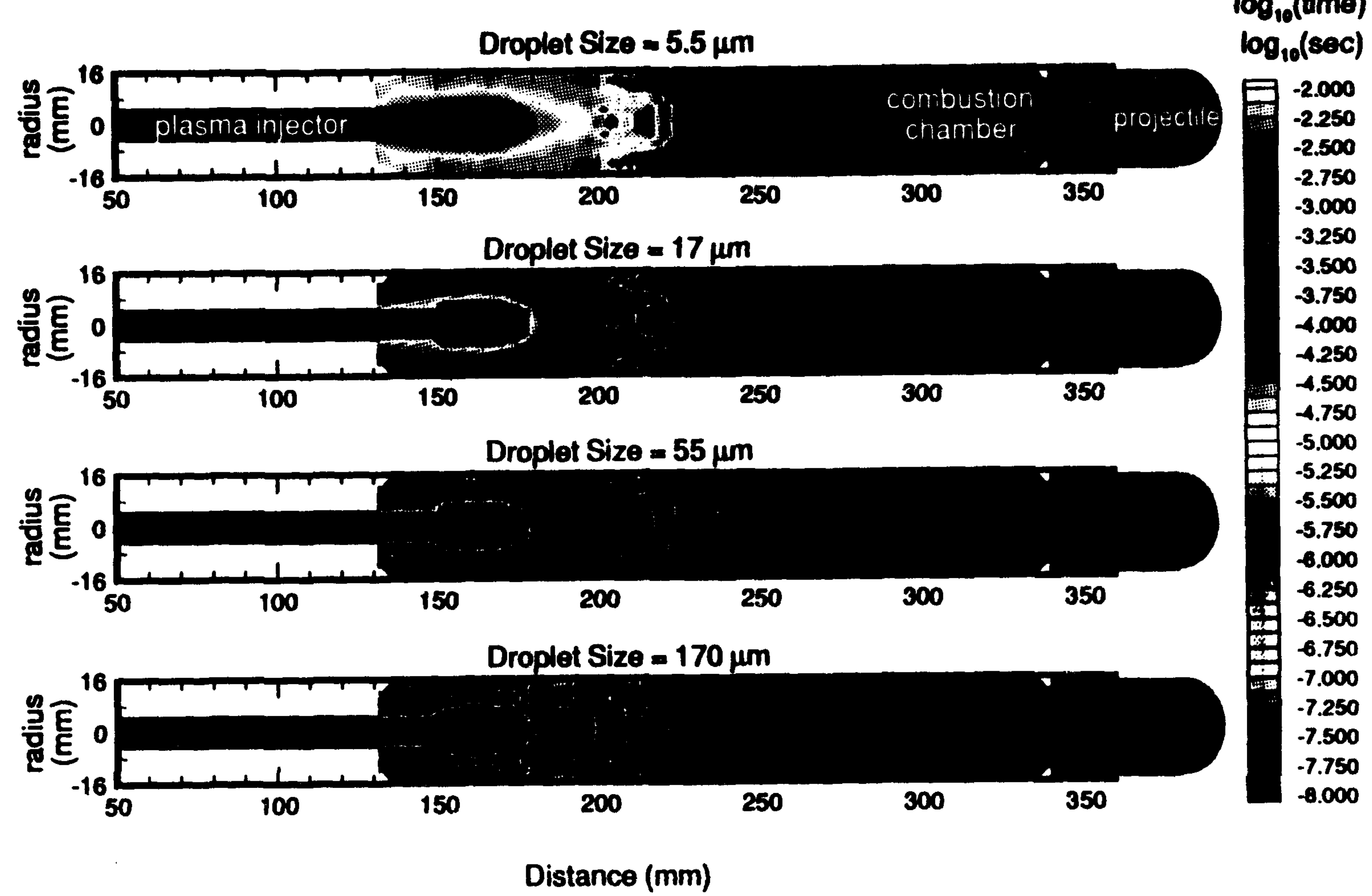
Turbulent Unmixedness Case



MAZe Code Simulation of 30mm ETC Gun Test

Droplet Extinction Time   Time = 0.50 msec

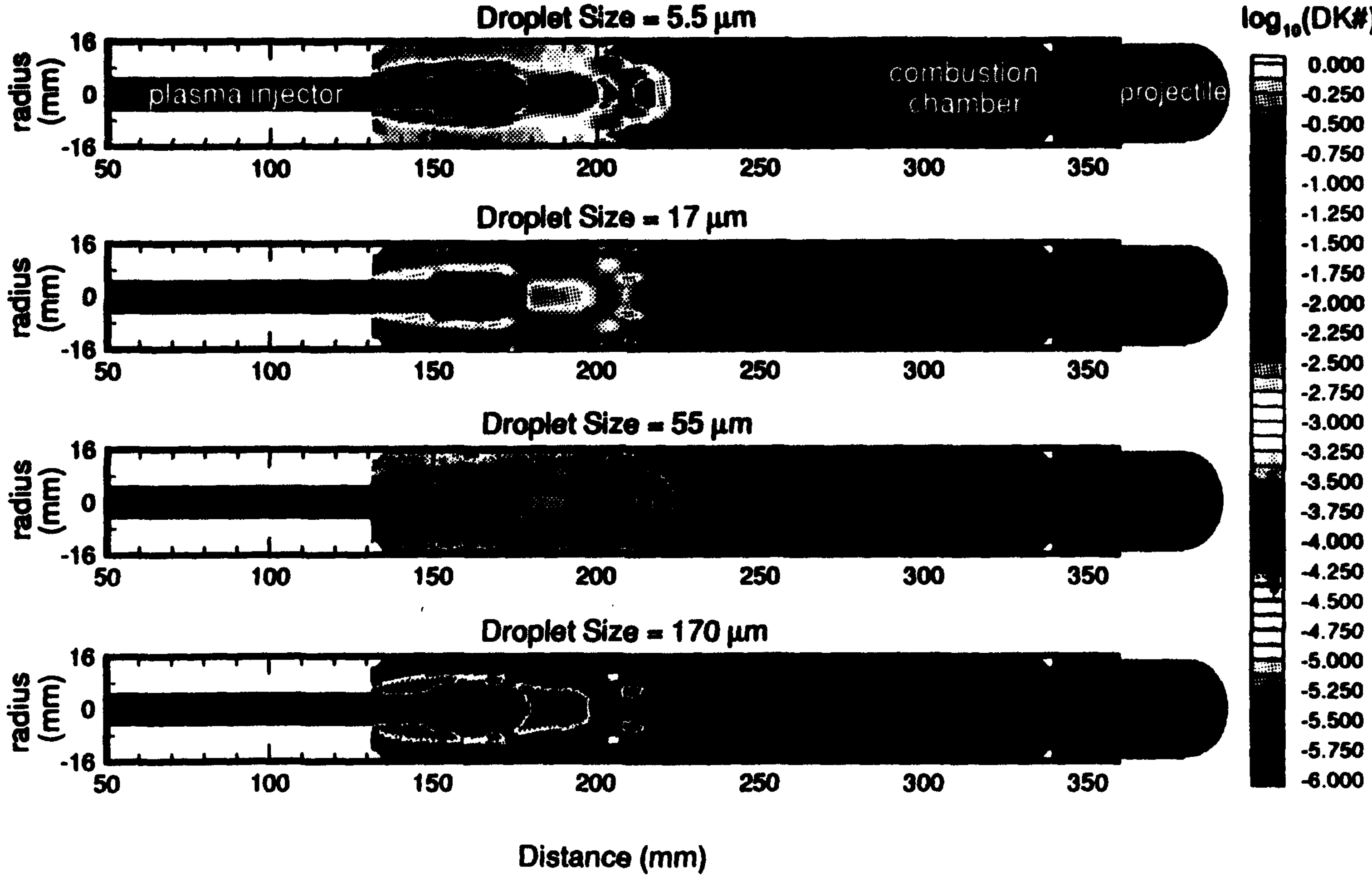
Turbulent Unmixedness Case



MAZe Code Simulation of 30mm ETC Gun Test

Turbulent Damköhler Number (t_{mix}/t_{evap}) Time = 0.50 msec

Turbulent Unmixedness Case



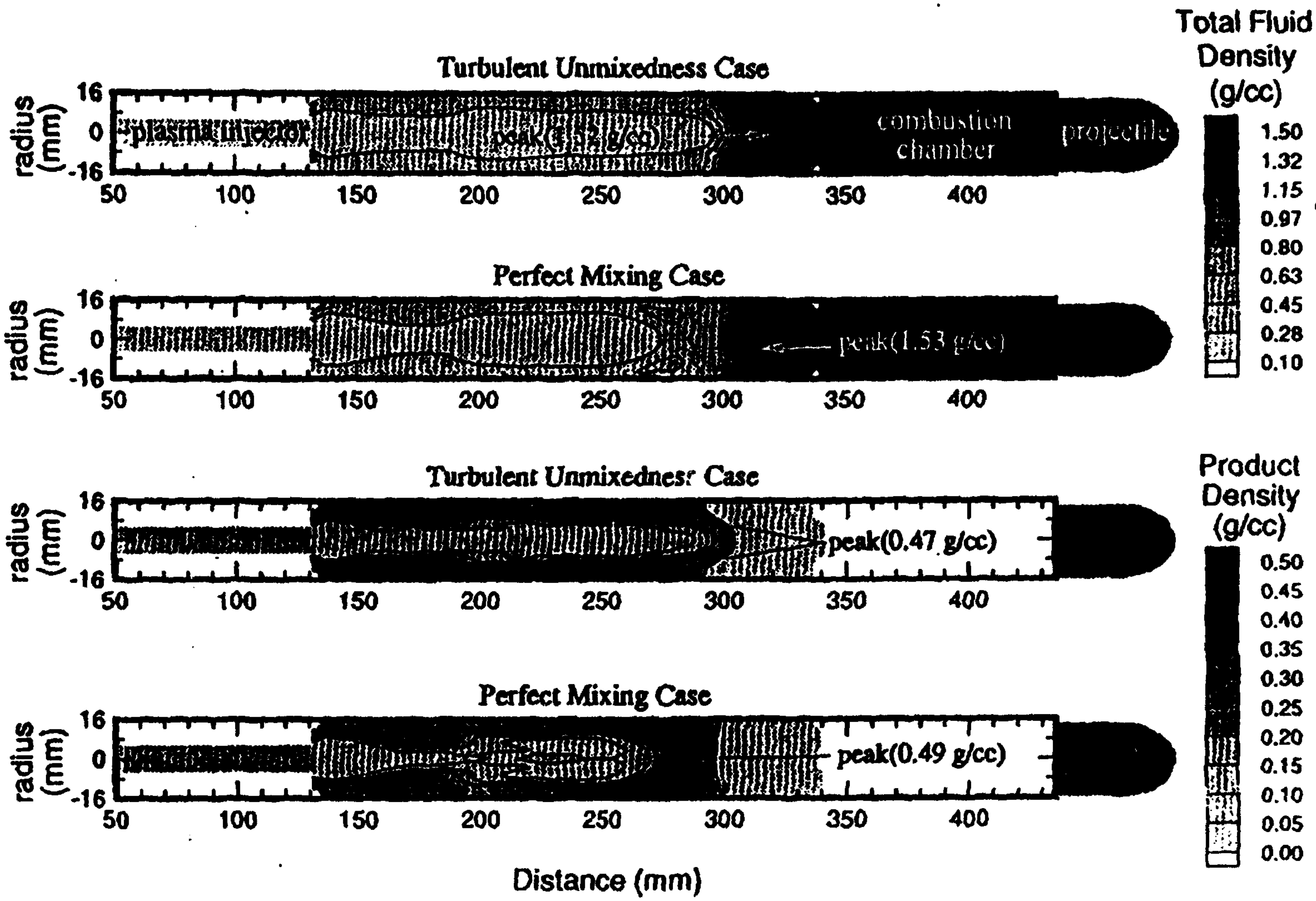


Figure 17. *Comparison of turbulent unmixedness and perfect mixing cases at 1.1 msec: total fluid density and product density contours.*

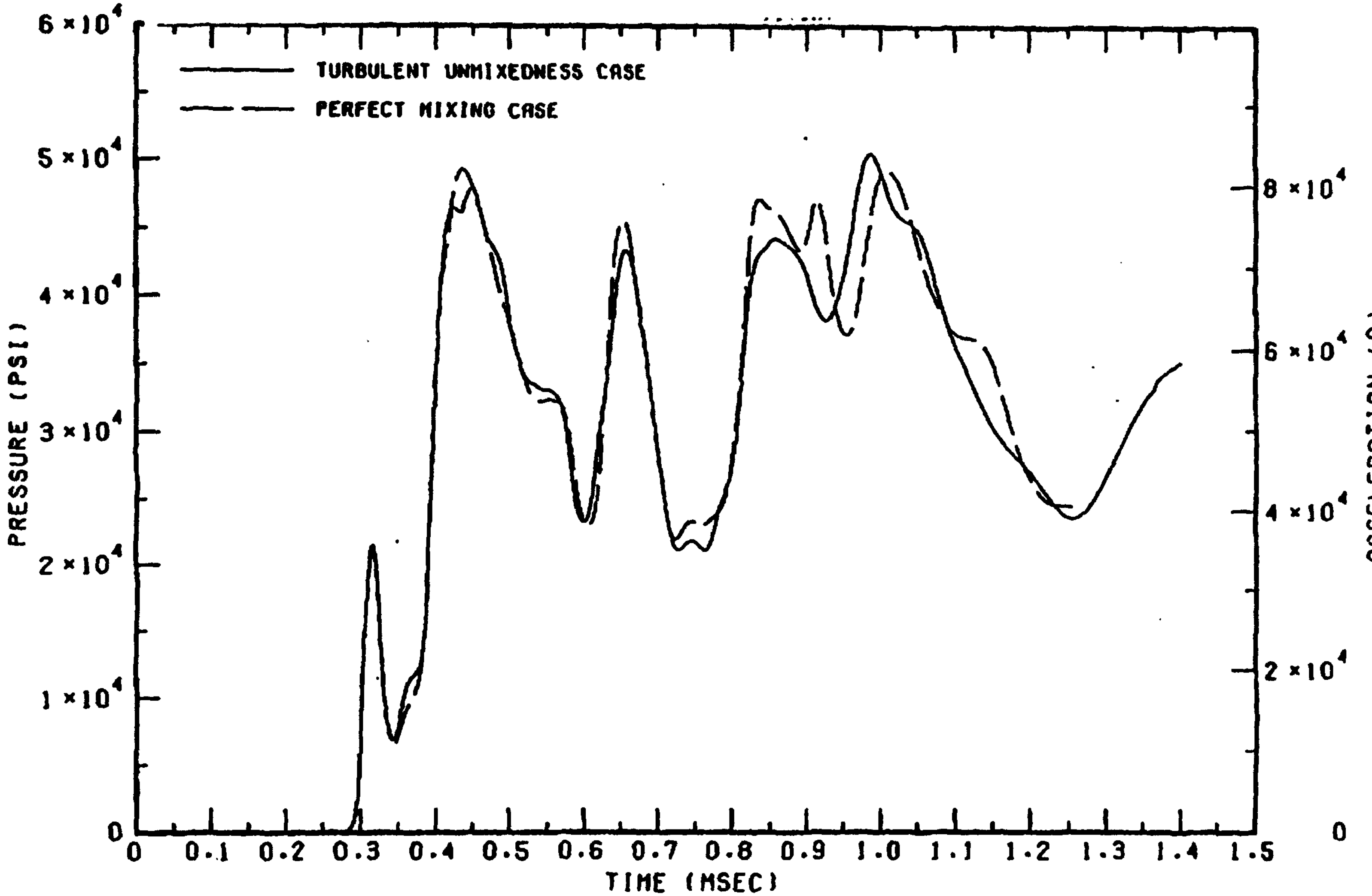
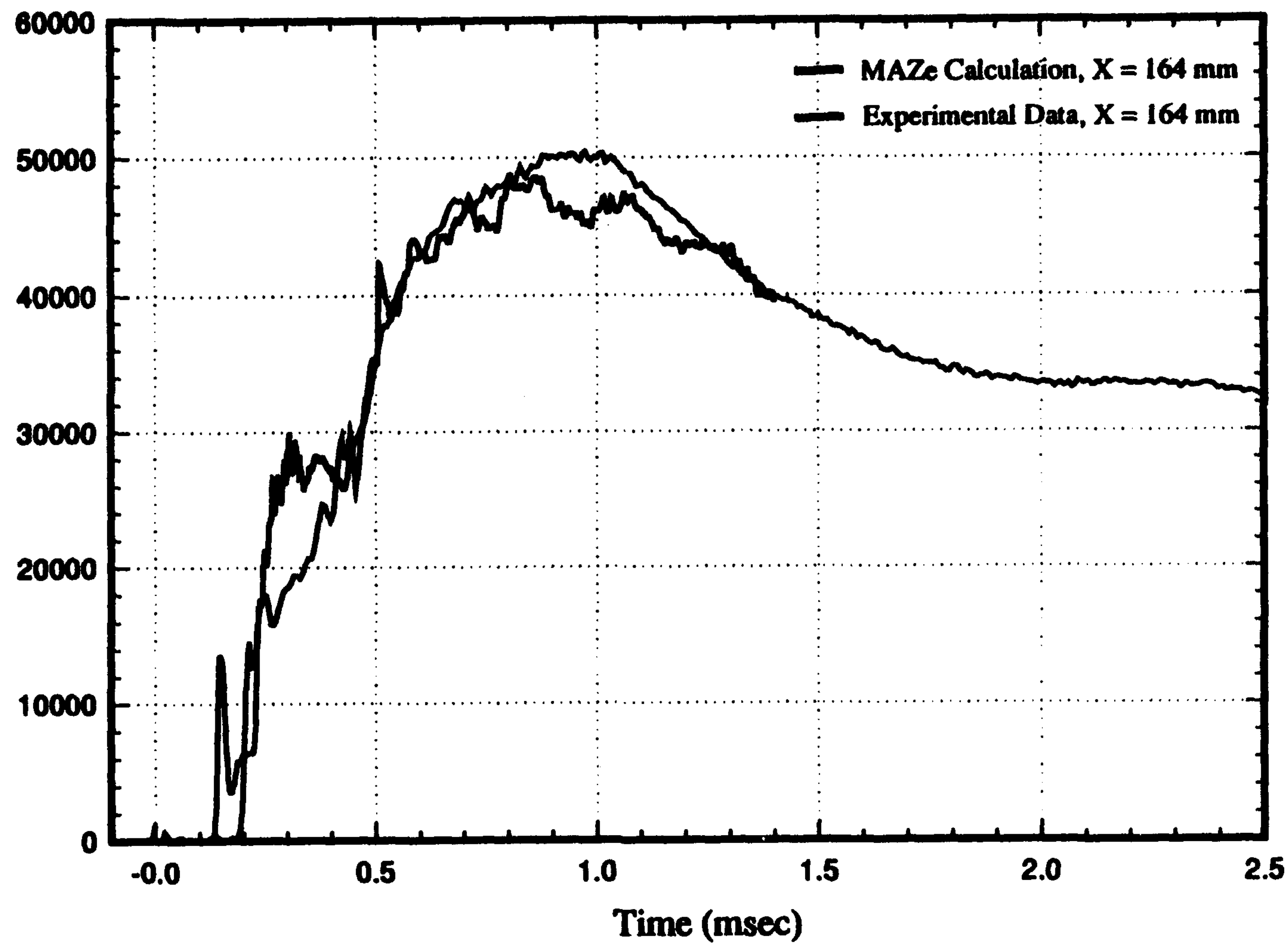
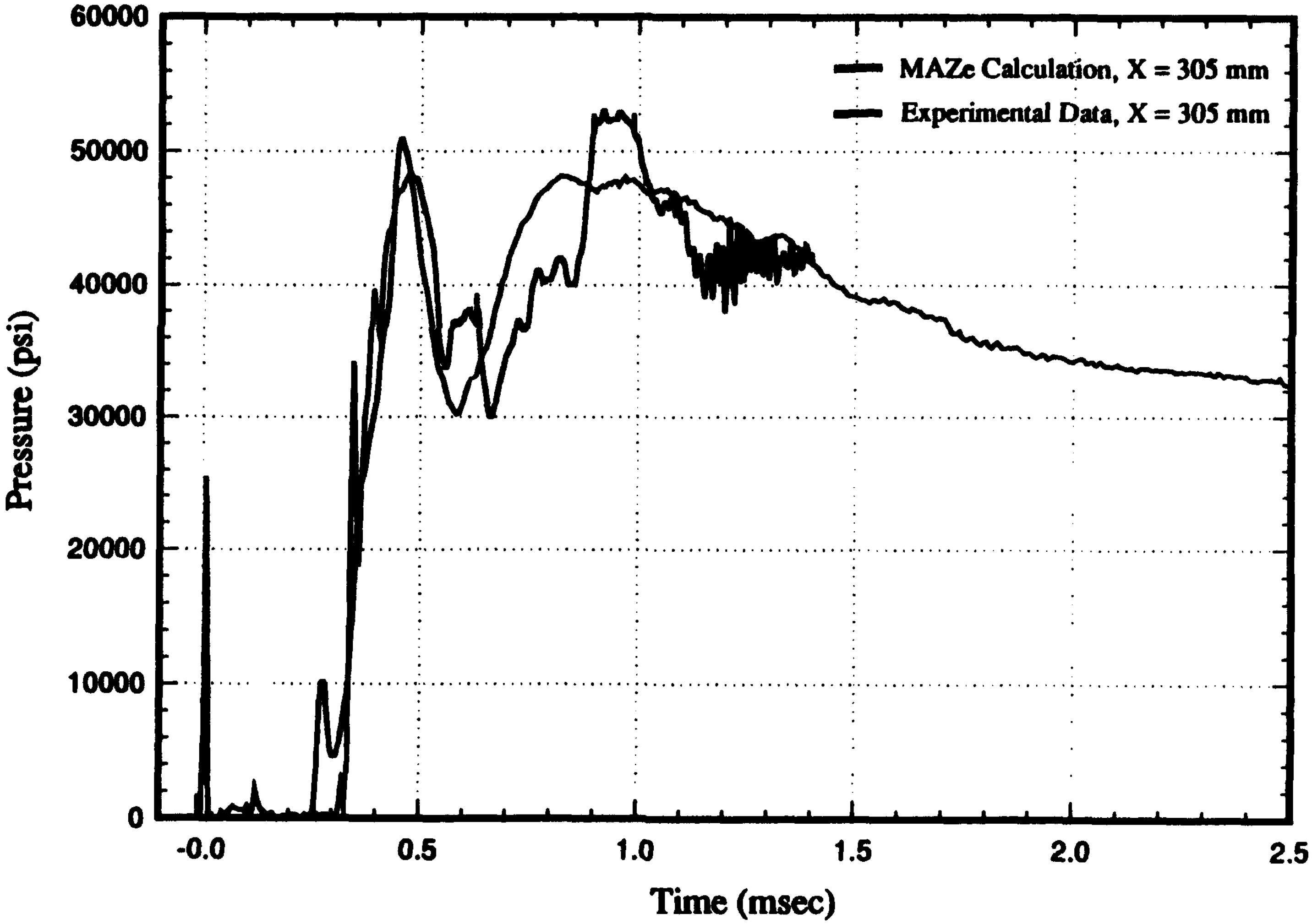


Figure 6. Projectile base pressure and acceleration time history.

MAZe Code Simulation of 30mm ETC Gun Test
Comparison with Experimental Overpressure Time-Histories



MAZe Code Simulation of 30mm ETC Gun Test
Comparison with Experimental Overpressure Time-Histories



INTENTIONALLY LEFT BLANK.

LIST OF PARTICIPANTS

Mr. Norberto Almeyda
Indian Head Division/NSWC
Code 6210D
100 Strauss Avenue
Indian Head, MD 20640
Phone: 301-743-6501
email: 6210D@smtphost.nosih.sea06.navy.mil

Dr. Jad Batteh
Science Applications Int'l Corp.
1519 Johnson Ferry Road, Suite 300
Marietta, GA 30068
Phone: 404-973-8935

Professor F. B. Cheung
The Pennsylvania State University
Prop Engr Rsch Ctr/Mech Engr Dept
140 Research Building "E"
University Park, PA 16802
Phone: 814-863-4261
FAX: 814-863-8682

Mr. Kwok L. Cheung
U.S. Army Armament Research, Development, and Engineering Center
ATTN: SMCAR-FSE
Picatinny Arsenal, NJ 07806-5000
Phone: 201-724-5455
email: klcheung@pica.army.mil

Mr. Donald Chiu
U.S. Army Armament Research, Development, and Engineering Center
ATTN: SMCAR-AEE
Picatinny Arsenal, NJ 07806-5000
Phone: 201-724-5759
email: dchiu@pica.army.mil

Dr. Terence Coffee
U.S. Army Research Laboratory
ATTN: AMSRL-WT-PA
Aberdeen Proving Ground, MD 21005-5066
Phone: 410-278-6169
FAX: 410-278-6159
email: tcoffee@brl.mil

Dr. Sanford Dash
Science Applications Int'l Corp.
501 Office Center Drive
Suite 420
Ft. Washington, PA 19034-3211
Phone: 215-542-1200
FAX: 215-542-8567

Mr. Jahn Dyvik
FMC Corporation
Naval Systems Division - M170
4800 E. River Road
Minneapolis, MN 55421-1498
Phone: 612-572-4756

Mr. Jon Earnhart
GT-Devices, Inc.
5705A General Washington Drive
Alexandria, VA 22312
Phone: 703-642-8150

Mr. Edward B. Fisher
Veritay Technology Inc.
4845 Millersport Highway
P.O. Box 305
East Amherst, NY 14051-0305
Phone: 716-689-0177
FAX: 716-689-0109

Dr. J. Robert Greig
GT-Devices, Inc.
5705A General Washington Drive
Alexandria, VA 22312
Phone: 703-642-8150

Dr. L. E. Harris
U.S. Army Armament Research, Development, and Engineering Center
ATTN: SMCAR-AEE-BR, Bldg. 382
Picatinny Arsenal, NJ 07806-5000
Phone: 201-724-4535
FAX: 201-724-2443

Dr. Philip A. Hookham
California Research and Technology Division
The TITAN Corporation
20943 Devonshire Street
Chatsworth, CA 91311-2376
Phone: 818-709-3705
FAX: 818-341-2663

Dr. Ashwin Hosangadi
Science Applications Int'l Corp.
501 Office Center Drive
Suite 420
Ft. Washington, PA 19034-3211
Phone: 215-542-1200

Dr. C. -C Hsiao
Science Applications Int'l Corp.
10210 Campus Point Drive
San Diego, CA 92121
Phone: 619-458-5058
FAX: 619-546-6584

Mr. Dave Hurlburt
GT-Devices, Inc.
5705A General Washington Drive
Alexandria, VA 22312
Phone: 703-642-8150
email: hurlburt@ra.nrl.navy.mil

Mr. Patrick Janke
FMC Corporation
Naval Systems Division - M170
4800 E. River Road
Minneapolis, MN 55421-1498
Phone: 612-572-6976
FAX: 612-572-4903

Dr. Steve Kempka
Advanced Projects V
Sandia National Laboratories
Albuquerque, NM 87185-5800
Phone: 505-844-8918
FAX: 505-844-7020

Mr. Karl R. Linde
Olin Ordnance
200 E. High Street
Red Lion, PA 17356
Phone: 717-244-4551
FAX: 717-244-5006

Mr. Hugh A. McElroy
Olin Ordnance
10101 9th Street North
St. Petersburg, FL 33716
Phone: 813-578-8239
FAX: 813-578-8119

Mr. Michael Nusca
U.S. Army Research Laboratory
ATTN: AMSRL-WT-PE
Aberdeen Proving Ground, MD 21005-5066
Phone: 410-278-2057
FAX: 410-278-6094
email: nusca@brl.mil

Mr. William Oberle
U.S. Army Research Laboratory
ATTN: AMSRL-WT-PA
Aberdeen Proving Ground, MD 21005-5066
Phone: 410-278-6200
FAX: 410-278-6159
email: oberle@brl.mil

Ms. Susan Peters
Indian Head Division/NSWC
Code 6210D
100 Strauss Avenue
Indian Head, MD 20640
email: 6210c@smtphost.nosih.sea06.navy.mil

Dr. John Powell
U.S. Army Research Laboratory
ATTN: AMSRL-WT-WD
Aberdeen Proving Ground, MD 21005-5066
Phone: 410-278-5783
email: powell@brl.mil

Ms. Sharon Richardson
U.S. Army Research Laboratory
ATTN: AMSRL-WT-PA
Aberdeen Proving Ground, MD 21005-5066
Phone: 410-278-6188
FAX: 410-278-6159
email: slrich@brl.mil

Dr. W. J. Sarjeant
Professor, State U. of NY at Buffalo
Department of Electrical Engineering
312 Bonner ECE-SUNY/AB
Buffalo, NY 14260
Phone: 716-645-3117

Mr. Neeraj Sinha
Science Applications Int'l Corp.
501 Office Center Drive
Suite 420
Ft. Washington, PA 19034-3211

Dr. Fred Su
Science Applications Int'l Corp.
10210 Campus Point Drive
San Diego, CA 92121

Ms. Phuong Tran
U.S. Army Research Laboratory
ATTN: AMSRL-WT-PA
Aberdeen Proving Ground, MD 21005-5066
Phone: 410-278-6160
FAX: 410-278-6159
email: ptran@brl.mil

Dr. Mel Widner
General Dynamics
Land Systems Division
P.O. Box 2074
Warren, MI 48090-2074
Phone: 313-825-5072
FAX: 313-825-5075

Dr. Niels K. Winsor
GT-Devices, Inc.
5705A General Washington Drive
Alexandria, VA 22312
Phone: 703-642-8150
FAX: 703-642-9146
email: winsor@ccf.nrl.navy.mil

Ms. Gloria P. Wren
U.S. Army Research Laboratory
ATTN: AMSRL-WT-PA
Aberdeen Proving Ground, MD 21005-5066
Phone: 410-278-6199
FAX: 410-278-6159
email: wren@brl.mil

INTENTIONALLY LEFT BLANK.

No. of Copies	Organization
2	Administrator Defense Technical Info Center ATTN: DTIC-DDA Cameron Station Alexandria, VA 22304-6145
1	Commander U.S. Army Materiel Command ATTN: AMCAM 5001 Eisenhower Ave. Alexandria, VA 22333-0001
1	Director U.S. Army Research Laboratory ATTN: AMSRL-OP-CI-AD, Tech Publishing 2800 Powder Mill Rd. Adelphi, MD 20783-1145
1	Director U.S. Army Research Laboratory ATTN: AMSRL-OP-CI-AD, Records Management 2800 Powder Mill Rd. Adelphi, MD 20783-1145
2	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-TDC Picatinny Arsenal, NJ 07806-5000
1	Director Benet Weapons Laboratory U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-CCB-TL Watervliet, NY 12189-4050
1	Director U.S. Army Advanced Systems Research and Analysis Office (ATCOM) ATTN: AMSAT-R-NR, M/S 219-1 Ames Research Center Moffett Field, CA 94035-1000

No. of Copies	Organization
1	Commander U.S. Army Missile Command ATTN: AMSMI-RD-CS-R (DOC) Redstone Arsenal, AL 35898-5010
1	Commander U.S. Army Tank-Automotive Command ATTN: AMSTA-JSK (Armor Eng. Br.) Warren, MI 48397-5000
1	Director U.S. Army TRADOC Analysis Command ATTN: ATRC-WSR White Sands Missile Range, NM 88002-5502
(Class. only) 1	Commandant U.S. Army Infantry School ATTN: ATSH-CD (Security Mgr.) Fort Benning, GA 31905-5660
(Unclass. only) 1	Commandant U.S. Army Infantry School ATTN: ATSH-WCB-O Fort Benning, GA 31905-5000
1	WL/MNOI Eglin AFB, FL 32542-5000
	Aberdeen Proving Ground
2	Dir, USAMSAA ATTN: AMXSY-D AMXSY-MP, H. Cohen
1	Cdr, USATECOM ATTN: AMSTE-TC
1	Dir, USAERDEC ATTN: SCBRD-RT
1	Cdr, USACBDCOM ATTN: AMSCB-CII
1	Dir, USARL ATTN: AMSRL-SL-I
5	Dir, USARL ATTN: AMSRL-OP-AP-L

No. of Copies	Organization
1	ODDR&E(AT) The Pentagon ATTN: Mr. R. Menz Room 3D1089 WASH DC 20310
1	HQ, Department of the Army The Pentagon Deputy Assistant Secretary of the Army for Research, Development & Acquisition ATTN: SARD-TT, Dr. Fenner Milton Room 3E479 WASH DC 20310-0103
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-AEE, Mr. Donald Chiu Picatinny Arsenal, NJ 07806-5000
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-FSE, Mr. Kwok L. Cheung Picatinny Arsenal, NJ 07806-5000
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-AEE-B, Bldg. 382, Dr. David S. Downs Picatinny Arsenal, NJ 07806-5000
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-AEE-BR, Bldg. 382, Dr. L. E. Harris Picatinny Arsenal, NJ 07806-5000
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-FSC, Ms. Hildi Libby Picatinny Arsenal, NJ 07806-5000

No. of Copies	Organization
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-TDC, Bldg. 1, Renata Price Picatinny Arsenal, NJ 07806-5000
1	Commander U.S. Army Armament Research, Development, and Engineering Center ATTN: SMCAR-FSC, Mr. Roger Zimmany Picatinny Arsenal, NJ 07806-5000
1	Commander Strategic Defense Command ATTN: SSFAE-SD-HVA, Mr. Tim Aden P.O. Box 1500 Huntsville, AL 35887-3801
1	Indian Head Division/NSWC Code 6210D ATTN: Ms. Susan Peters 100 Strauss Ave. Indian Head, MD 20640
1	Indian Head Division/NSWC Code 6210D ATTN: Mr. Norberto Almeyda 100 Strauss Ave. Indian Head, MD 20640
1	Commander Naval Sea Systems Command Department of the Navy CSEA 06 KR12 ATTN: Craig Dampier Washington, DC 20362-5101
1	Commander Naval Surface Warfare Center Code G33 ATTN: Mr. Thomas E. Doran Dahlgren, VA 22448-5000
1	Commander Naval Surface Warfare Center Indian Head Division, Code 6110J ATTN: Mr. Kirk Rice 20 Strauss Ave. Indian Head, MD 20640-5035

No. of Copies	Organization
1	Director Sandia National Laboratories Advanced Projects Division, Org. 9123 ATTN: Dr. David Benson Albuquerque, NM 87185-5800
1	Defense Nuclear Agency ATTN: COL Downie 6801 Telegraph Rd. Alexandria, VA 22310
1	Director Sandia National Laboratories Computational Fluid Dynamics Div, 1511 ATTN: Dr. Gregory F. Homicz Albuquerque, NM 87185
1	Director Sandia National Laboratories Advanced Projects V ATTN: Dr. Steve Kempka Albuquerque, NM 87185-5800
1	Defense Nuclear Agency ATTN: Dr. R. Rohr 6801 Telegraph Rd. Alexandria, VA 22310
1	The Pennsylvania State University ATTN: Professor F. B. Cheung Prop Engr Rsch Ctr/Mech Engr Dept 140 Research Building "E" University Park, PA 16802
1	University of Tennessee Space Institute Center for Laser Applications, MS-14 ATTN: Dr. Dennis Keefer Tullahoma, TN 37388-8897
1	The Pennsylvania State University Prop Engr Rsch Ctr/Mech Engr Dept ATTN: Professor Kenneth K. Kuo 140 Research Building "E" University Park, PA 16802

No. of Copies	Organization
1	Princeton Combustion Rsch Lab Princeton Corporate Plaza ATTN: Dr. Neale A. Messina 11 Deerpark Dr., Bldg. IV, Suite 119 Monmouth Junction, NJ 08852
1	Science Applications Int'l Corp. ATTN: Dr. Gary Phillips 10210 Campus Point Dr. San Diego, CA 92121
1	Science Applications Int'l Corp. ATTN: Dr. C.-C. Hsiao 10210 Campus Point Dr. San Diego, CA 92121
1	Science Applications Int'l Corp. ATTN: Dr. Fred Su 10210 Campus Point Dr. San Diego, CA 92121
1	Science Applications Int'l Corp. ATTN: Dr. Jad Batteh 1519 Johnson Ferry Rd., Suite 300 Marietta, GA 30068
1	Science Applications Int'l Corp. ATTN: Dr. Sanford Dash 501 Office Center Dr. Suite 420 Fort Washington, PA 19034-3211
1	Science Applications Int'l Corp. ATTN: Mr. Neeraj Sinha 501 Office Center Dr., Suite 420 Fort Washington, PA 19034-3211
1	Science Applications Int'l Corp. ATTN: Dr. Ashwin Hosangadi 501 Office Center Dr. Suite 420 Fort Washington, PA 19034-3211
1	FMC Corporation Naval Systems Division - M170 ATTN: Mr. Patrick Janke 4800 E. River Rd. Minneapolis, MN 55421-1498

No. of Copies	Organization
1	FMC Corporation Naval Systems Division - M170 ATTN: Mr. Jahn Dyvik 4800 E. River Rd. Minneapolis, MN 55421-1498
1	Technology Gateways Incorporated ATTN: Mr. Jere Brown 600 East John Sims Parkway, Suite 118 Niceville, FL 32578
1	Veritay Technology Inc. ATTN: Mr. Edward B. Fisher 4845 Millersport Highway P.O. Box 305 East Amherst, NY 14051-0305
1	GT-Devices, Inc. ATTN: Dr. Niels K. Winsor 5705A General Washington Dr. Alexandria, VA 22312
1	GT-Devices, Inc. ATTN: Mr. Dave Hurlburt 5057A General Washington Dr. Alexandria, VA 22312
1	GT-Devices, Inc. ATTN: Jon Earnhart 5705A General Washington Dr. Alexandria, VA 22312
1	GT-Devices, Inc. ATTN: Dr. J. Robert Greig 5705A General Washington Dr. Alexandria, VA 22312
1	Eli Freedman & Associates ATTN: Dr. Eli Freedman 2411 Diana Rd. Baltimore, MD 21209-1525
1	Paul Gough Associates, Inc. ATTN: Dr. Paul S. Gough 1048 South St. Portsmouth, NH 03801

No. of Copies	Organization
1	California Research & Technology Division The TITAN Corporation ATTN: Dr. Philip A. Hookham 20943 Devonshire St. Chatsworth, CA 91311-2376
1	Olin Ordnance ATTN: Mr. Karl R. Linde 200 E. High St. Red Lion, PA 17356
1	Olin Ordnance ATTN: Mr. Hugh A. McElroy 10101 9th St. North St. Petersburg, FL 33716
1	State University of New York at Buffalo Department of Electrical Engineering ATTN: Professor, Dr. W. J. Sarjeant 312 Bonner ECE-SUNY/AB Buffalo, NY 14260
1	General Dynamics Land Systems Division ATTN: Dr. Mel Widner P.O. Box 2074 Warren, MI 48090-2074

No. of Copies	Organization
	Aberdeen Proving Ground
37	Dir, USARL ATTN: AMSRL-WT-P, I. May AMSRL-WT-PA, T. Coffee G. Wren (15 cps) P. Tran S. Richardson W. Oberle K. White A. Juhasz AMSRL-WT-PB, E. Schmidt C. Nietubicz AMSRL-WT-PC, R. Fifer AMRSL-WT-PD, B. Burns AMSRL-WT-PE, M. Nusca F. Robbins P. Conroy T. Minor D. Kooker G. Keller A. Horst AMSRL-WT, D. Eccleshall AMSRL-WT-T, W. Morrison AMSRL-WT-WD, J. Powell A. Niiler

INTENTIONALLY LEFT BLANK.

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. ARL Report Number ARL-SR-10 Date of Report May 1994

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. Specifically, how 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

Organization ______

Name ______

Street or P.O. Box No. ______

City, State, Zip Code ______

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

OLD ADDRESS

Organization ______

Name ______

Street or P.O. Box No. ______

City, State, Zip Code ______

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

(DO NOT STAPLE)

DEPARTMENT OF THE ARMY

OFFICIAL BUSINESS

BUSINESS REPLY MAIL

FIRST CLASS PERMIT No 0001, APG, MD

Postage will be paid by addressee.

NO POSTAGE NECESSARY IF MAILED IN THE UNITED STATES

Director
U.S. Army Research Laboratory
ATTN: AMSRL-OP-CI-B (Tech Lib)
Aberdeen Proving Ground, MD 21005-5066