

SPECIAL PUBLICATIONS BRL-SP-92

# BRL

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ELECTROTHERMAL-CHEMICAL MODELING  
AND DIAGNOSTICS WORKSHOP,  
VOLUME 2

GLORIA P. WREN  
SHARON L. RICHARDSON

OCTOBER 1991

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## **ACKNOWLEDGMENTS**

I would like to take this public opportunity to thank each of the workshop participants for their excellent presentations. The support of government, university, contractors, and industry is gratefully acknowledged. Sincere appreciation is expressed to Mrs. Sharon Richardson, Workshop Coordinator, and Ms. Jennifer Hughey, student contractor, for their invaluable assistance.

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## 1. INTRODUCTION

Currently, a number of diverse efforts are underway toward modeling and diagnostics of the electrothermal-chemical (ETC) gun. These efforts have been initiated primarily in the past two years, include Government (Army, Navy, DNA, and DOE), university, and industry, and are funded by both private and Government sectors.

The three (Army, Navy, and DNA) major Government programs associated with development of ETC technology have target dates of FY92 for assessment. Thus, a need exists to increase and encourage progress toward understanding the dominant physical mechanisms in the ETC gun, which hopefully, will result in improved control of the interior ballistic process.

As a means of addressing the above concerns, a JANNAF workshop on Electrothermal-Chemical Modeling and Diagnostics was held July 9-11, 1991, at the U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD. The objectives of the workshop were to assemble experts, drawn from gun, plasma physics, engineering, and related disciplines from Government, industry, and academia to examine theoretical methodologies and experimental approaches and data, and to review and evaluate the present state-of-knowledge in the ETC gun. Specifically, the workshop objectives were to:

- Survey methods of modeling interior ballistic process, particularly the interaction of the plasma and the work fluid.
- Summarize the areas of agreement and determine diagnostic experiments needed to validate hypotheses and provide input for models.
- Identify diagnostic experiments which may impact modeling.
- Assess the state of plasma modeling and diagnostics for ETC guns.
- Identify gaps in experimental and theoretical investigations.
- Recommend future ETC gun research areas.

Workshop participants jointly summarized current modeling and diagnostic efforts in the U.S. and experimental measurements needed to improve ETC models. Their summary is in the form of the following charts (see vol. 1):

- a. Current ETC Modeling Activities in the U.S.
- b. Diagnostic Measurements Desired by ETC Modelers
- c. Current ETC Diagnostic Activities in the U.S.
- d. Use of Diagnostic Measurements Desired by ETC Modelers

The dialogue between modelers and experimentalists will, hopefully, provide a common focus for future work.

## **ELECTROTHERMAL-CHEMICAL GUN PROGRAM**

D. A. Benson, P. Cahill, S. N. Kempka, and R. L. Woodfin  
Sandia National Laboratories  
Albuquerque, NM 87185-5800

### **ABSTRACT**

The Sandia National Laboratories ETC Gun Program seeks to achieve a better understanding of the fundamental processes at work in such a device. An experimental apparatus resembling a gun chamber with an external "capillary" for the generation of a plasma which mixes with a working fluid in the chamber has been constructed. A series of detailed models of the process is being developed. Several diagnostics techniques are being developed to better measure the parameters of the process. Several possible fuel materials, are being investigated. Future plans include a more "gun-like" apparatus with variable geometries.



Sandia National Laboratories

**ETC Gun**

RLW 5/4/91

# **Electrothermal-Chemical Gun Program**

**Dr. Ronald L. Woodfin  
Advanced Projects Division V  
(505) 844-3111 AV 244-3111**



## Project Organization

### Sponsors:

DoE

Office of Munitions

ARDEC

- Electric Armaments Division

### Technical Coordinator:

BRL

- Advanced Ballistic Concepts

### Sandia:

Albuquerque, NM

- Plasma/Accumulator Exp's & Models  
Materials Studies, Project Management

Livermore, CA

- Shock Tube Ablation Exp's & Models  
Mixing & Combustion Diagnostics Dev



## Critical Needs & Major Unknowns (BRL 1989)

### Critical needs:

- \*New working fluids
- \*Well instrumented firings
- \*Plasma / working fluid diagnostics
- Bore temperature and erosion studies
- Projections of growth of power supplies

### Major unknowns:

- \*Physics & chemistry of mixing
- \*Gas generation rate vs electrical input
- \*Gun thermal environment
- Heat transfer & erosion
- Muzzle reactions & weapon effluents
- Ballistic temperature coefficient
- \*Reproducibility



## Scope & Target

**Physics of plasma arc sources**

**Physics & chemistry of mixing processes**

**Modeling of the electric / thermal / chemical process**

**Properties of propellant materials**

**Gun chamber diagnostics**

**Improvements in plasma density / mixing**



## Project Character

**Integrated experimental & analytical effort**

**Produces & verifies detailed physical models**

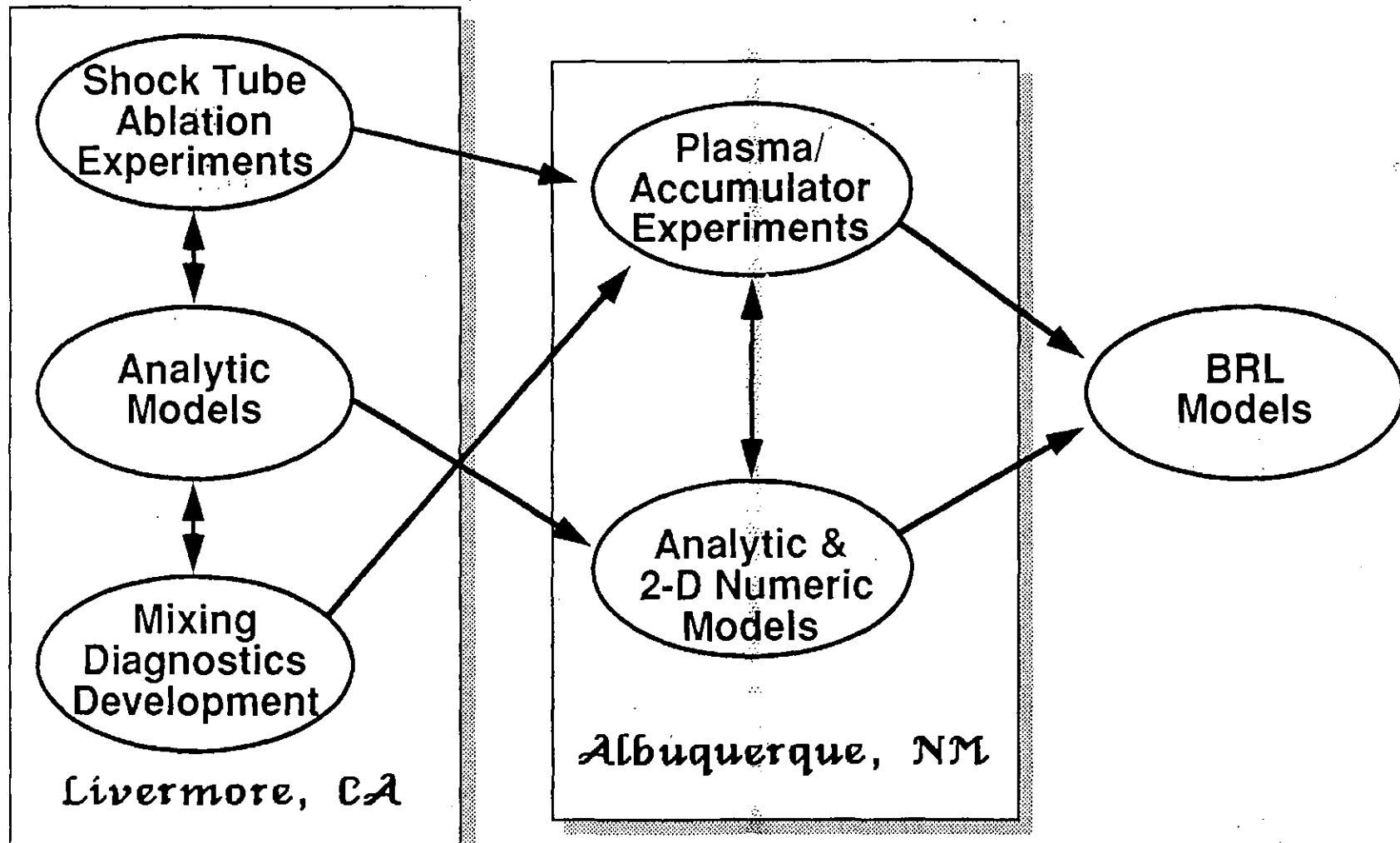
**Supports Army modeling of interior ballistics**

**Develops new diagnostics for mixing & combustion**





## Program Structure





## Required Diagnostic Capability

**Goal** is to be able to identify:

plasma penetration depth & volume

&

location of species

under gun conditions

as a function of time.

**Diagnostics** will measure:

Plasma development

Temperature

Species



## Physics of Plasma Arc Sources

### **Experimental chamber**

**To 100,000 psi**

**40KJ**

**Heavily instrumented**

**Contained products**

**Ablative capillary liner**

### **Analytical model**

**2-D, axisymmetric, compressible flow**

**Dissociated & ionized species**

**Electrical conductivity**

**Gas equation of state**

**Radiative energy transport by diffusion approximation**



# Physics & Chemistry of the Mixing Process

## **Plasma / working fluid interaction**

Flow

Mixing

Areas of reactivity

Entrainment processes

## **Ablation of capillary material**

Mass / momentum addition to plasma

Reactivity alteration in accumulator

## **Constitution of plasma**

Mixture of ablative material & working fluid

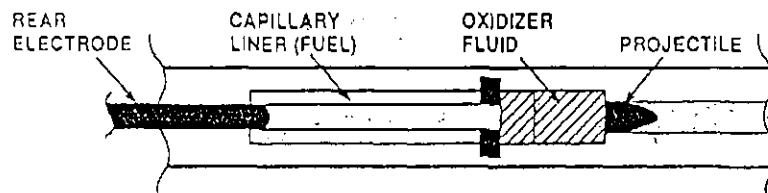


## Electrothermal Injector Studies

Develop ETC technology base for future system assessment

- Fundamental electrothermal chemical measurements
- Materials development
- Modeling
- Coordinate with DoD and industry efforts

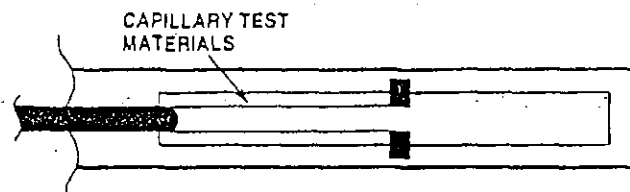
SIMPLIFIED GUN DESIGN



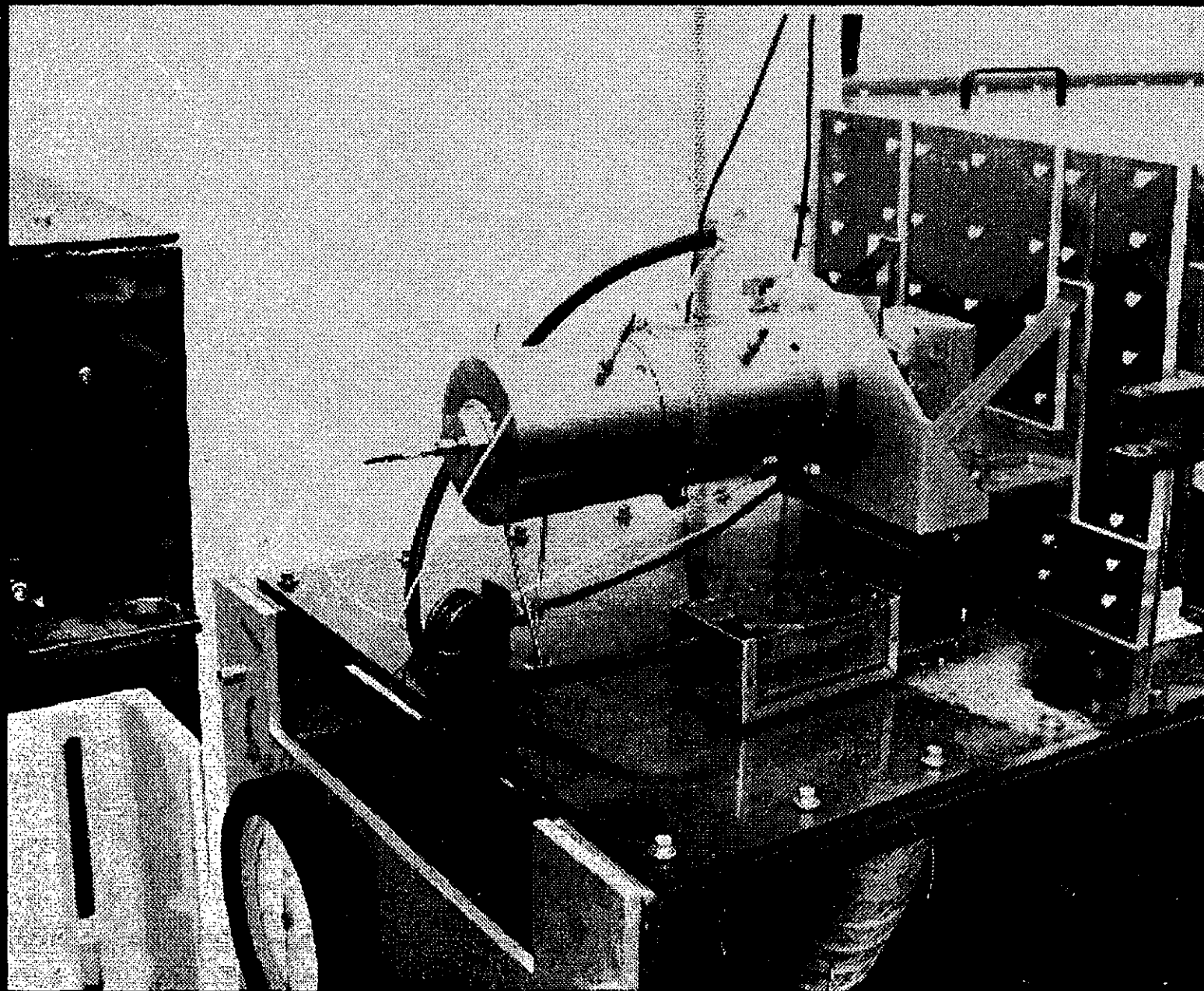
### Objectives

- Develop closed vessel electrothermal test
- Acquire data for capillary model development
- Improve efficiency and controllability of ETC devices
- Enhance capillary mass transfer
- Evaluate reactive materials for use in capillary
- Study capillary turbulence, heat transfer, erosion

ELECTROTHERMAL INJECTOR TEST



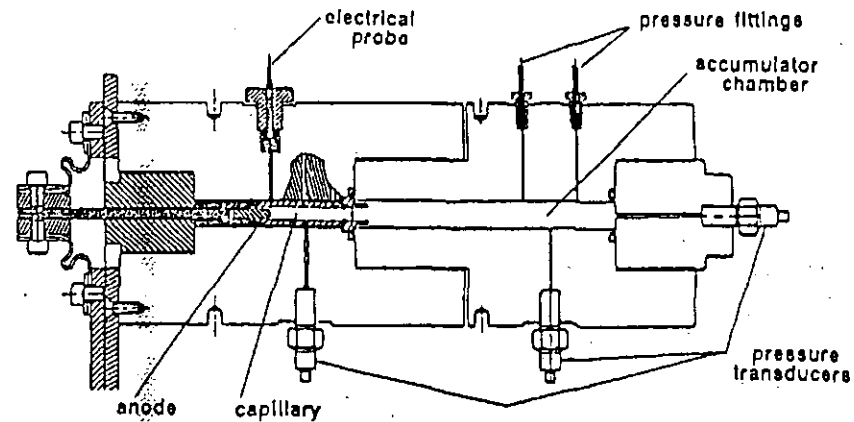
# Electrothermal Injector Mounted on Capacitor Bank





## Electrothermal Injector Experimental Apparatus

- Capacitor Discharge System  
40 kJ, 250 kA, 10 kV
- Liner Materials  
Polyethylene  
Delrin  
Nitrated Polyethylene
- Diagnostics  
Arc Impedance  
Electrical Power Input  
Accumulator Chamber Pressure  
Capillary Pressure vs Time  
Total Mass Removal from Capillary Liner
- Post-Test Particulate Analysis  
Scanning Electron Microscopy  
Energy Dispersive X-Ray Analysis



Electrothermal Injector Cross-Section View

- Experimental Setup  
Accumulator Volume  $14 \text{ cm}^3$   
Arc Length 4.3 cm  
Capillary Inside Dia. 0.58 cm  
Max. Pressure 100 kpsi

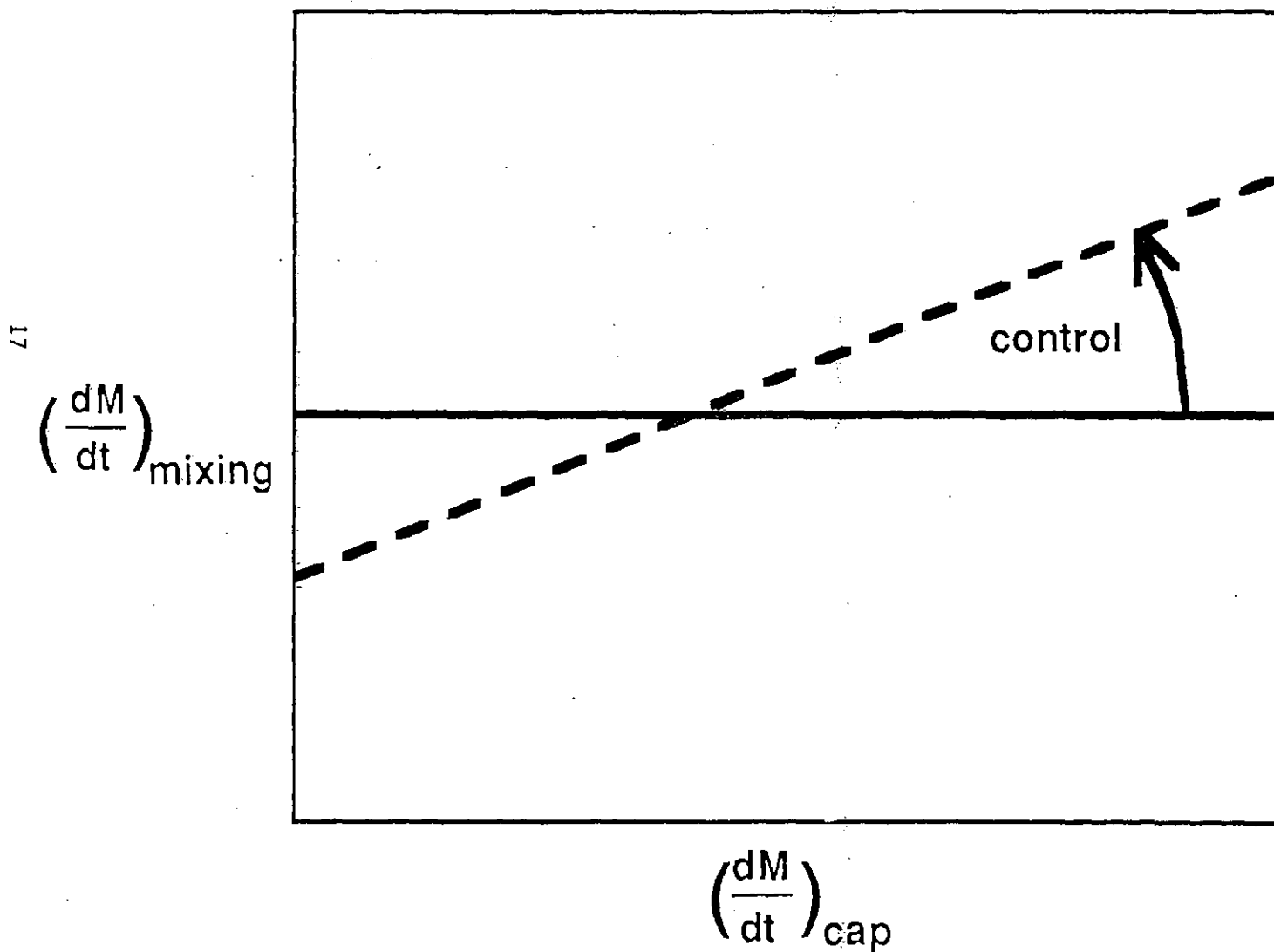
# Photographs of Burning Gas

Burning Gas





## Effect of Capillary Efflux on Accumulator Mixing

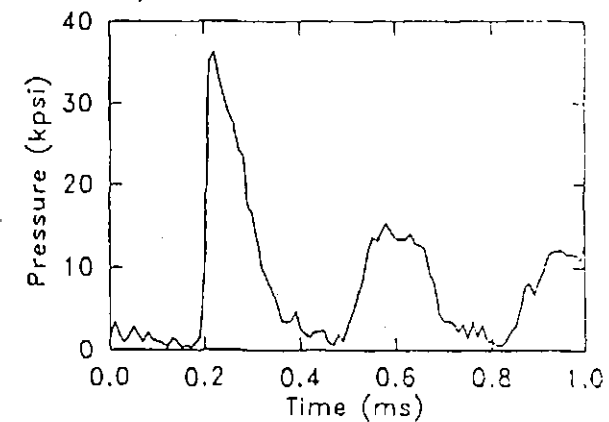
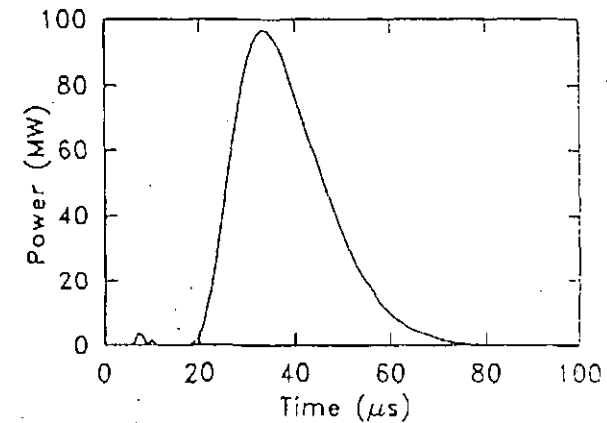




## Accomplishments on Electrothermal Injector Project

- Developed closed vessel test system for the Dynamic Heating Facility
- Conducted initial tests with polyethylene (10 to 80 mg ablated)
- Calculated optical absorption to predict radiative paths under ET conditions
- Performed hydrodynamic calculations to show characteristic times for capillary
- Prepared and characterized nitrated polyethylene materials (PEVN) for liners
- Demonstrated enhanced arc induced ablation with PEVN liners

arc power dissipated



accumulator chamber pressure



## Modeling of Thermal / Electric / Chemical Process

### **Model of injector / accumulator**

Electric discharge

Plasma generation

2-D fluid flow

Adaptation of existing codes

Mixing, combustion, heat transfer

Geometric sensitivity studies

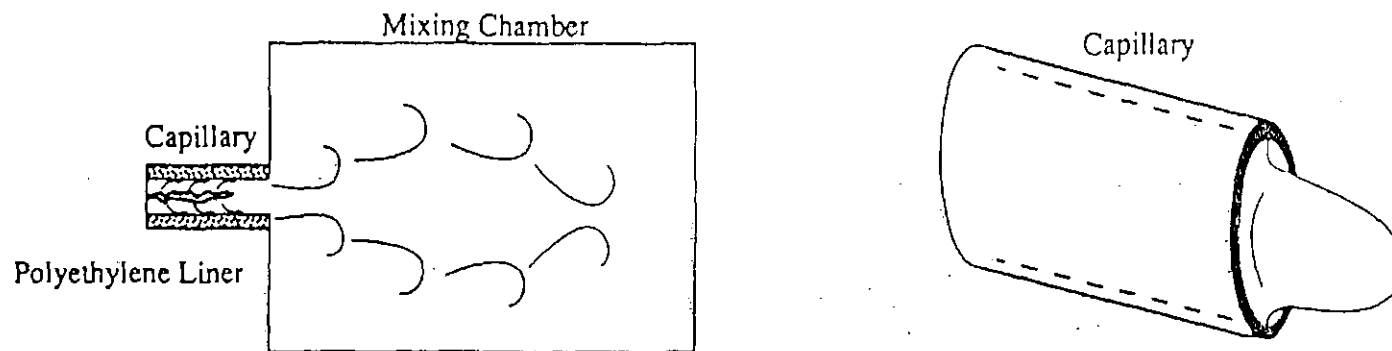
### **Model of ablation process**

Code models measurements

Input to 2-D model



## 1-D Radial Model of an ETC Capillary

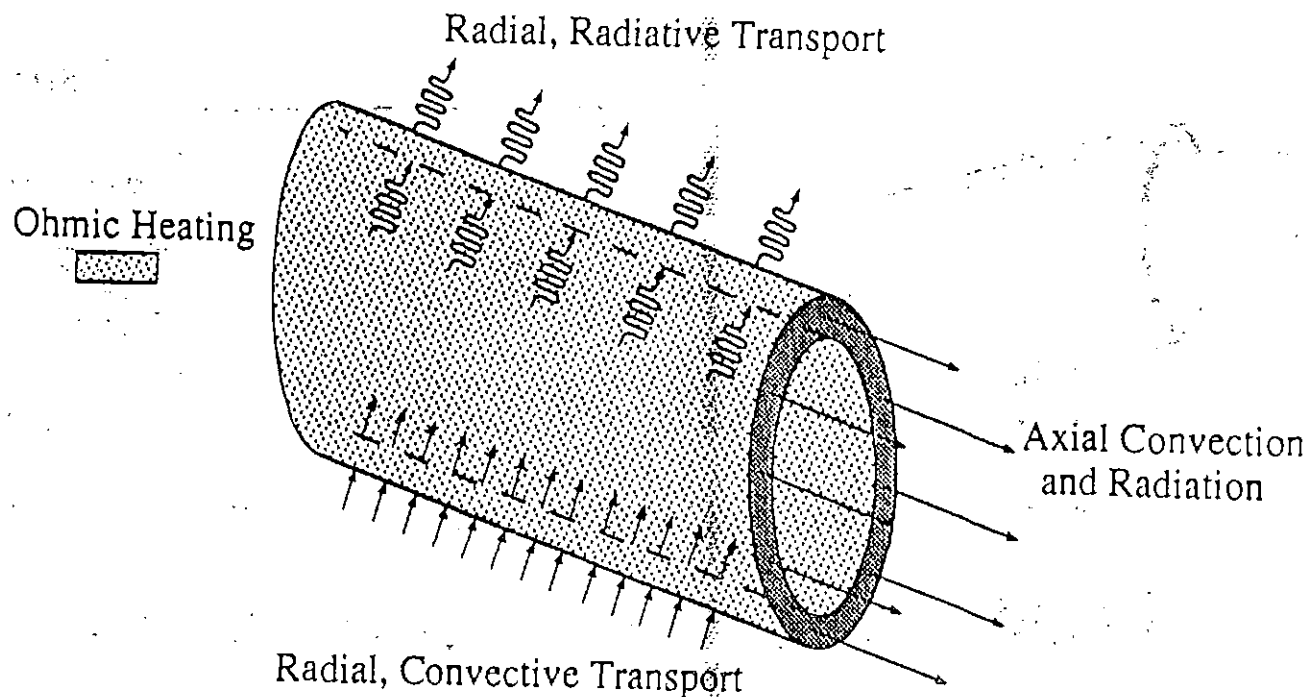


- Objectives

1. Examine extent of radial variations in plasma
  - radial variations influence mixing instabilities
2. Validate plasma transport properties for use in 2-D hydro model
  - diffusive radiation transport (Rosseland mean free path)
  - electrical conductivity (electron-ion, electron-neutral collisions)



## Energy Balance on Differential Annulus





## Assumptions in 1-D Radial Model

---

- Steady-State, LTE,  $(\text{collision rate})^{-1} \ll \tau_{\text{sonic}}$
- Axially uniform velocity and temperature
- Axial flow: Exit capillary at local sonic velocity
- Radial flow: obtained from conservation of mass
- Radial pressure gradient from radial momentum equation (mhd included)

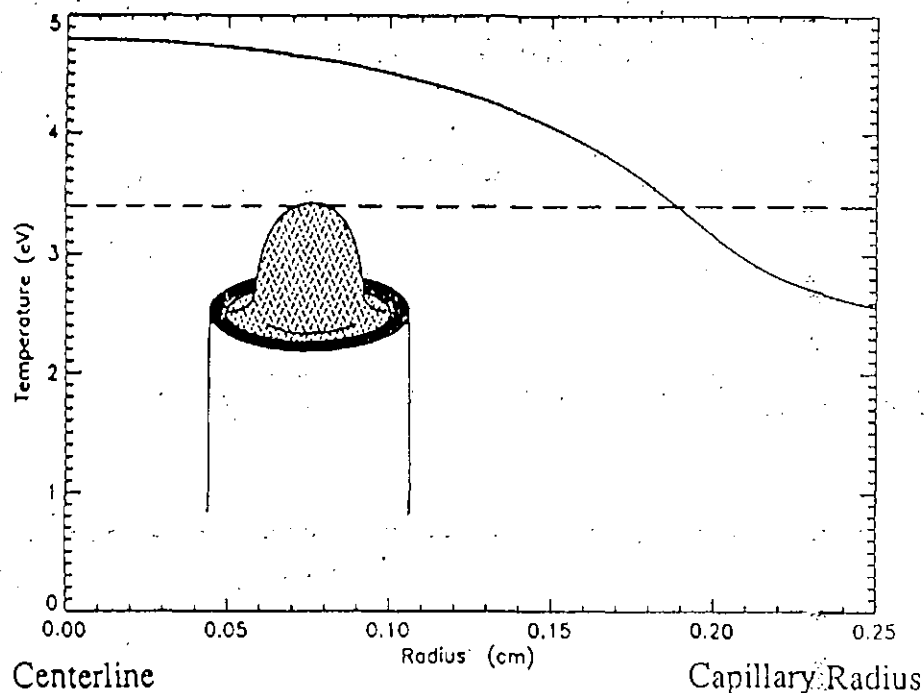
$$\rho v_r \frac{d}{dr} (v_r) = -\frac{dP}{dr}$$

- Uniform Electrical field
- Saha equations: C, C<sup>+</sup>, C<sup>++</sup>, H, H<sup>+</sup>



## Computed Radial Distributions

- Find solution that matches SNL experimental data
  - Peak values: 40 kAmps, 100 MW, 600 V/cm
- Temperature varies from 4.8 eV to 2.5 eV across capillary radius (0.25 cm)



- Species also vary significantly with radius

- Uniform temperature:

$$\text{Power} = \sigma T^4 \cdot 2\pi RL$$



## 1-D Radial Model Conclusions

---

- Radial model provides insight into capillary physics:
  - Radial variations in plasma temperature, species are large
  - Radial variations effect mixing instabilities, control issue
- Modeling issues to be resolved:
  - Ionization energy depends on density (constant value used)
  - Electrical conductivity of plasma for high densities





## 2-D Hydrodynamic Model

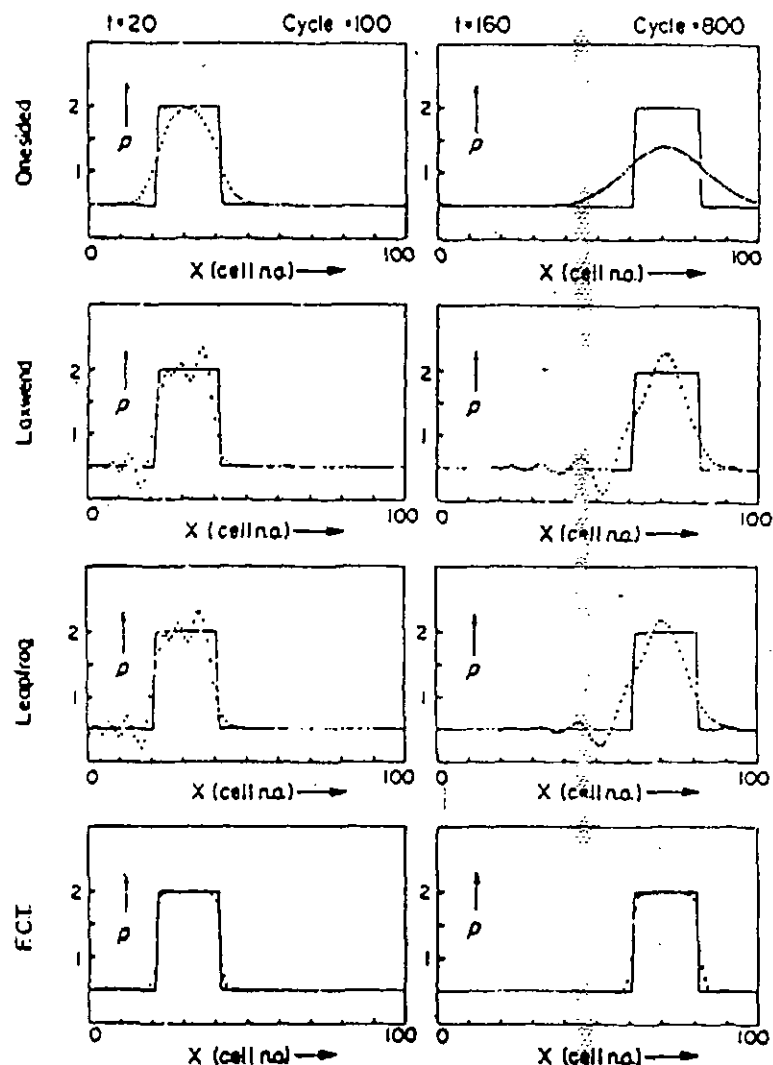
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- Include capillary model in 2-D hydro model to examine scaling, mixing
- Time-step issue
  - Explicit: expensive, accurate
  - Implicit: cheaper, large numerical diffusion, dispersion
- Explicit: time-split diffusive and convective transport: different time scales
- Flux Corrected Transport for convective transport
- Test: Numerical Simulation of Convection: Propagating Wave

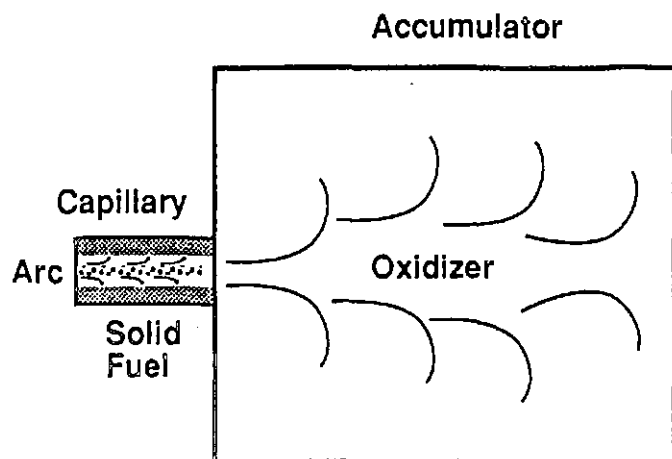
$$\frac{\partial f}{\partial t} + u \frac{\partial f}{\partial x} = 0$$



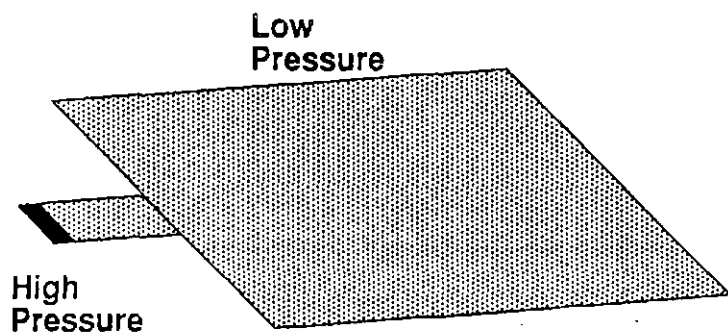
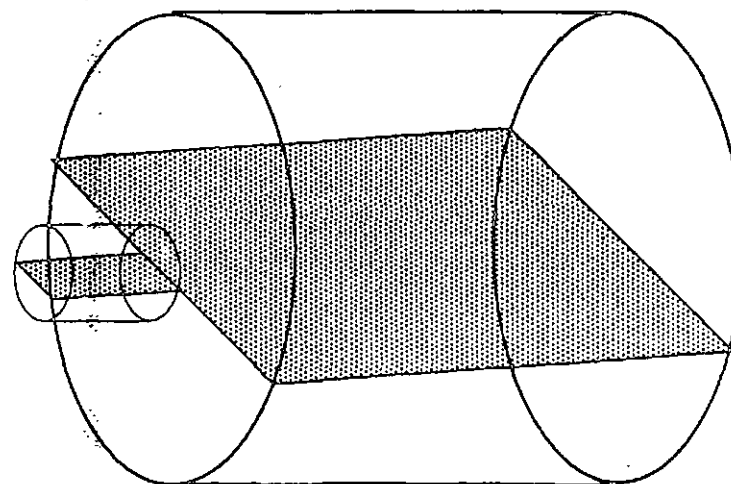
## Propagating Square Wave



• Ref.: Oran, E. S. and J. P. Boris, "Detailed Modeling of Combustion Systems," Prog. Energy Combust. Sci., 1981

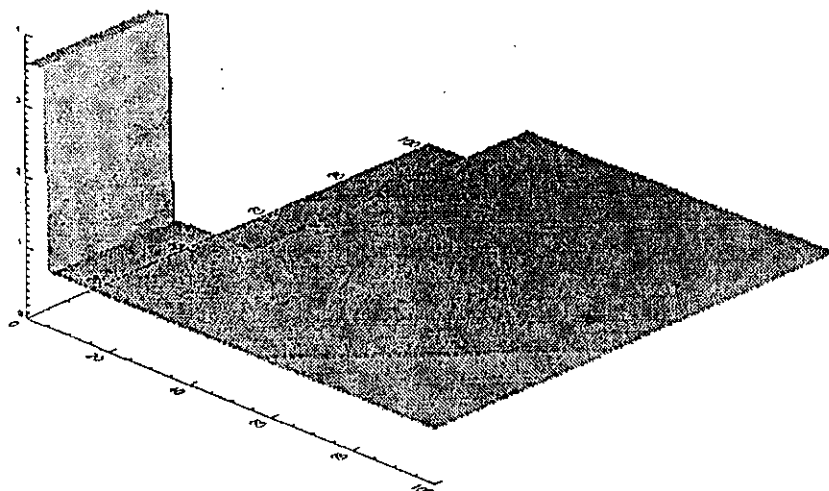


## Modeling Diagram

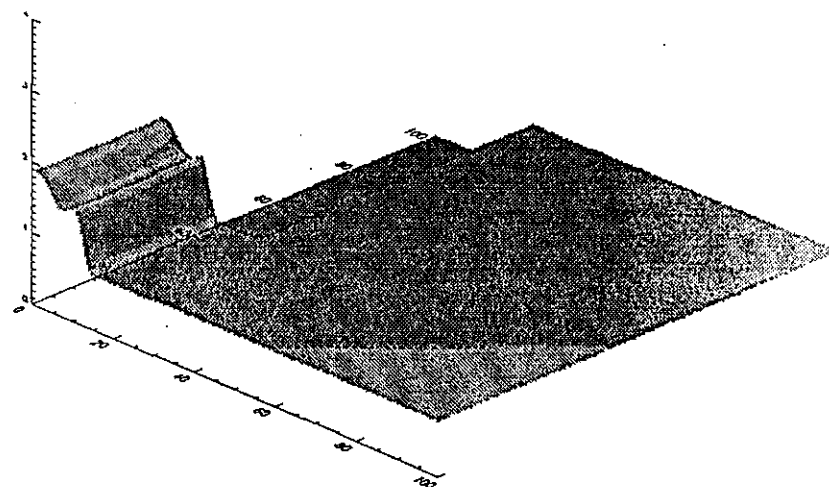




## Example Results Pressure Ratio = 5



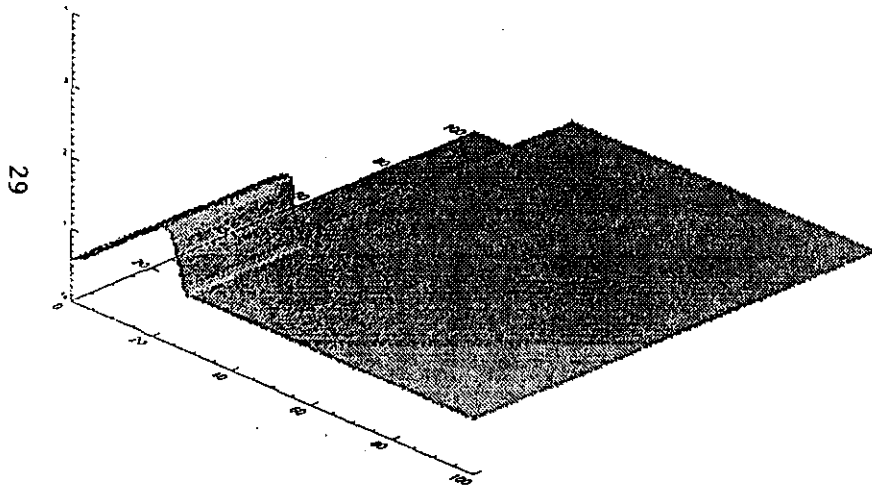
$t^* = 0$



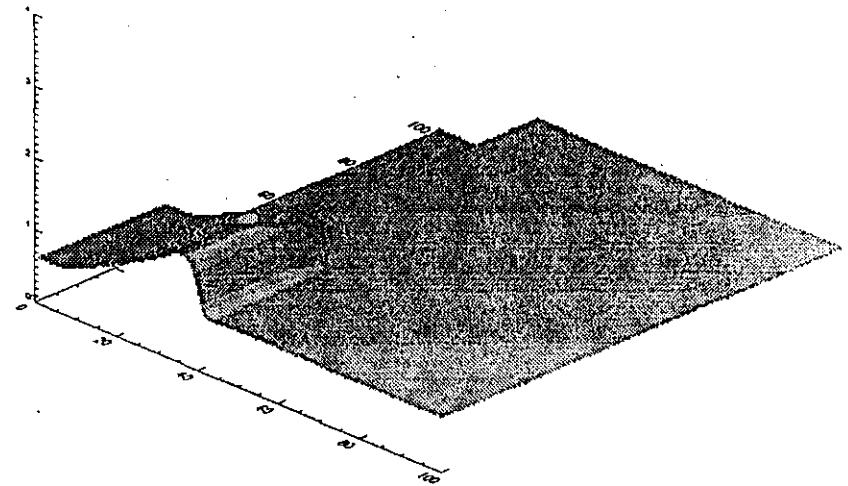
$t^* = 0.054$



## Example Results Pressure Ratio = 5



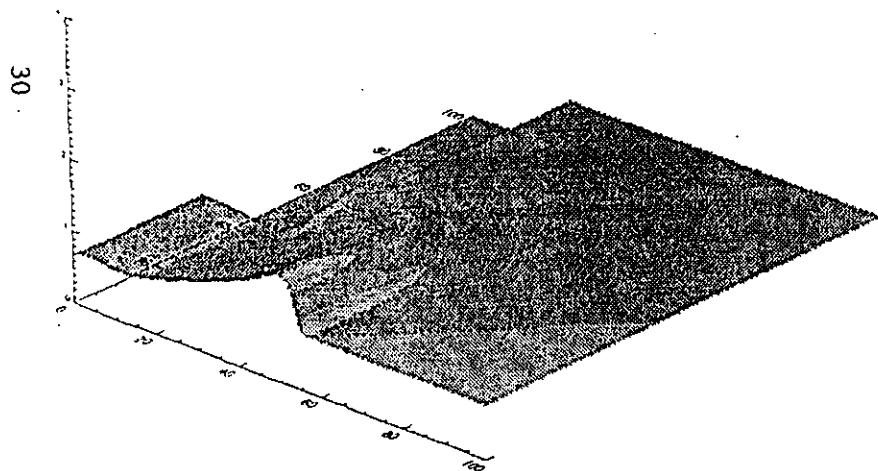
$t^* = 0.151$



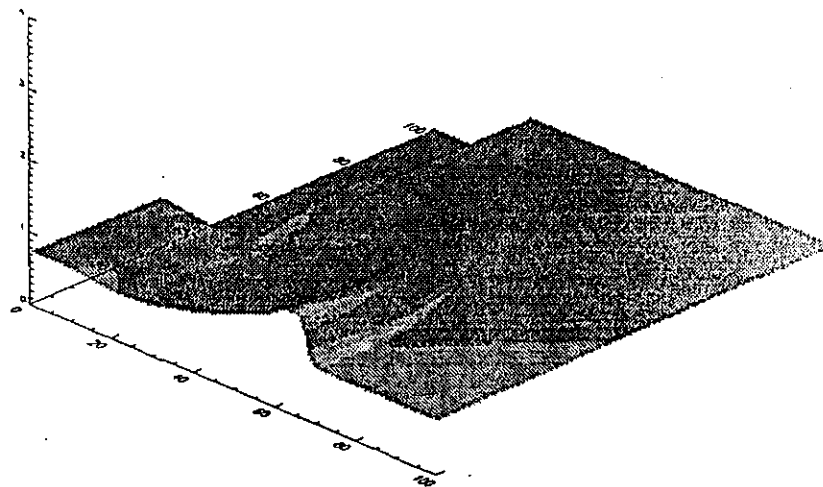
$t^* = 0.247$



## Example Results Pressure Ratio = 5



$t^* = 0.349$



$t^* = 0.451$



## Improvements in Plasma Density & Mixing

**Reactive injector liners**

**Graded liners / current profiling**

**Ablation rate measurements**

**Modeling of ablation**

**Observations of density vs mixing**



## Properties of Propellant Materials

### **Developing copolymer reactive liners**

- Nitrated ethylene / PVA copolymer

- For increasing plasma density

- For use with HAN

### **Ablation rate calibration**

- From shock tube experiments

### **Gun simulator testing of above materials**

- For plasma density effects

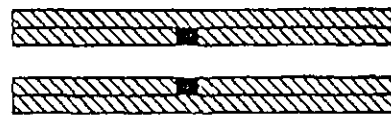
- For mixing improvements

- For energetics / kinetics





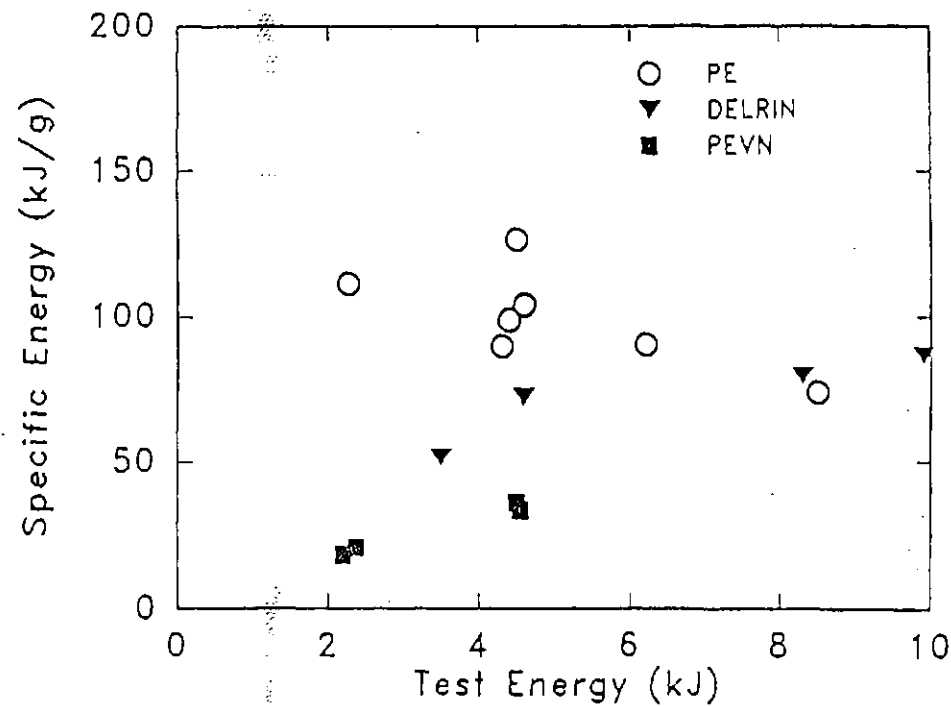
## Ablation Data from Electrothermal Injector Tests for Three Materials



washer tests



full liner tests



■ Washer tests (PEVN), preliminary safety testing

■ Full liner tests, normal testing configuration

■ Specific Energy --- Elec. Energy to arc / Total liner mass removed  
(Small value ---> Large mass removed)



## Summary

**Studying fundamental processes**

**Provide inputs to higher level models**

**Supports BRL efforts**

**Will answer some scaling issues**

**Methodical, low risk approach**

## DIAGNOSTICS DEVELOPMENT FOR THE ETC PROGRAM

Donald W. Sweeney, Steven Vosen, Jeffrey Gray, and Robert Armstrong  
Sandia National Laboratories  
Livermore, CA 94551-0969

### ABSTRACT

Control of the ET process is governed by the proper coupling of plasma energy to chemical energy. Optimization requires that the mixing and combustion process be understood. The physics and chemistry of the mixing of a plasma injected into a confined liquid will be studied by combining the techniques of high-speed cinematography and emission spectroscopy. Variation of the mixing chamber geometry and of the liquid, with increasing energetic content (e.g., from water to methanol to hydroxyl ammonium nitrate), will allow the effects of chemistry on plume development and mixing to be studied.

---

# ***DIAGNOSTIC DEVELOPMENT FOR THE ETC PROGRAM***

JANNAF Workshop  
ETC Modeling & Diagnostics

July 9-11, 1991

Donald Sweeney, Steve Vosen,  
Jeff Gray and Rob Armstrong



## *We Will Review Three Components of the CRF Program*

---

1. Diagnostics of plasma generation and fluid mixing
2. Chemical and thermal ablation studies
3. Laser-induced plasmas for ETC development



***Diagnostics for measuring gas generation and plasma behavior will be developed for gun conditions***

---

**Development of diagnostics for use at gun conditions is underway to quantify:**

- 1) plasma behavior, and**
- 2) gas generation rates.**

**Development will progress through three pressure regimes:**

- 1) Low Pressure :  $P < 1$  kpsi (FY 91),**
- 2) Medium Pressure:  $P = 1 - 15$  kpsi (FY 92), and**
- 3) High Pressure:  $P = 10 - 100$  kpsi (FY 93).**



***At low pressures we will observe fluid mixing  
over a range of pressures***

---

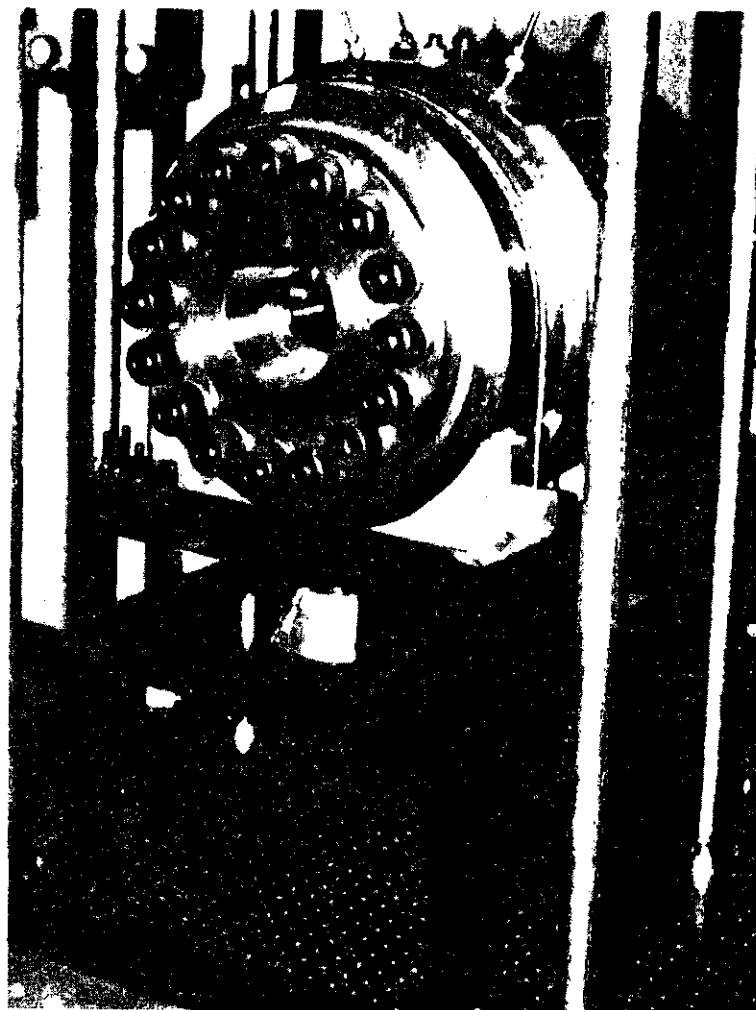
**Pressures: 15-1000 psi**

| <b>Process/Location</b>                       | <b>Diagnostic Technique</b> <ul style="list-style-type: none"><li>• <b>Measurement</b></li></ul>                                                                                                                                                                                                                                                                                                        |
|-----------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Gas Generation/<br/>Mixing Chamber</b>     | <b>Photography and image processing</b> <ul style="list-style-type: none"><li>• <b>Develop image processing techniques, similar to those developed for liquid propellants, to quantify images of full flow-field mixing</b></li></ul> <b>Vary energy and mixing fluid.</b> <ul style="list-style-type: none"><li>• <b>Determine effect of energy and fluid on evolution of mixing region.</b></li></ul> |
| <b>Plasma Formation/<br/>Plasma Cartridge</b> | <b>n.a.</b><br><b>(explosive charge)</b>                                                                                                                                                                                                                                                                                                                                                                |



## **Pressure vessel**

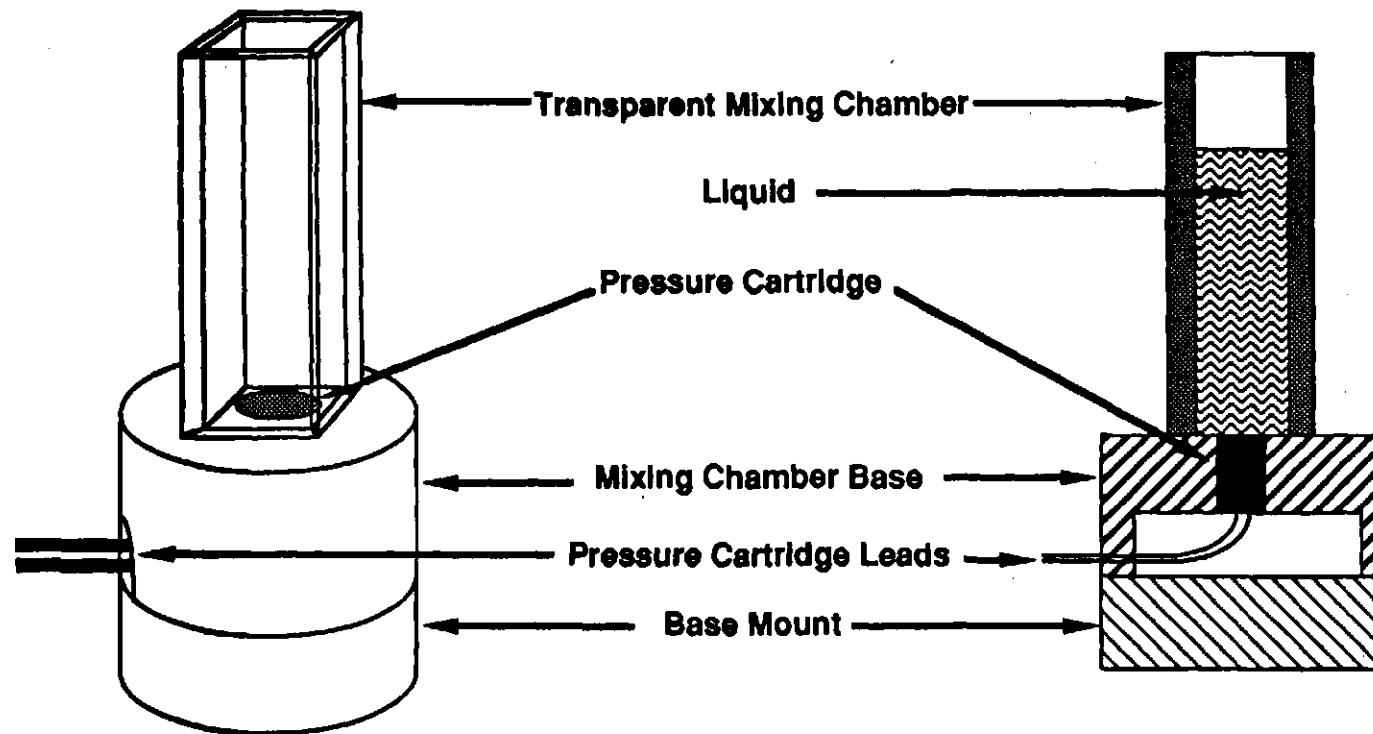
**Pressure: 0 - 5000 psig**  
**Volume: 13 liters**  
**Windows: 4, 100 mm dia.**





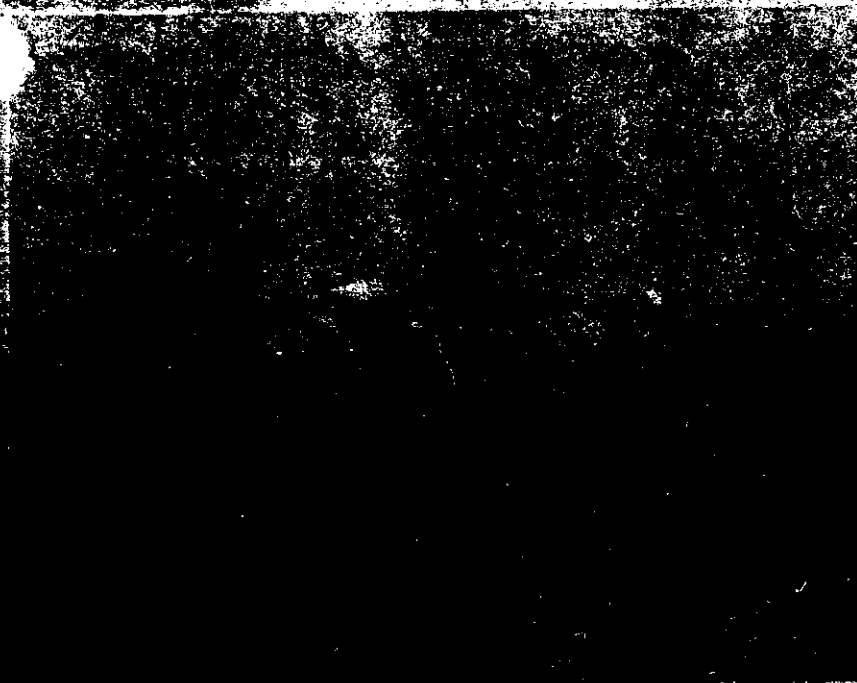
***Mixing/image processing experiments will  
be done in a low pressure apparatus***

---



## *Pressure cartridge deliver energy to low pressure mixing chamber*

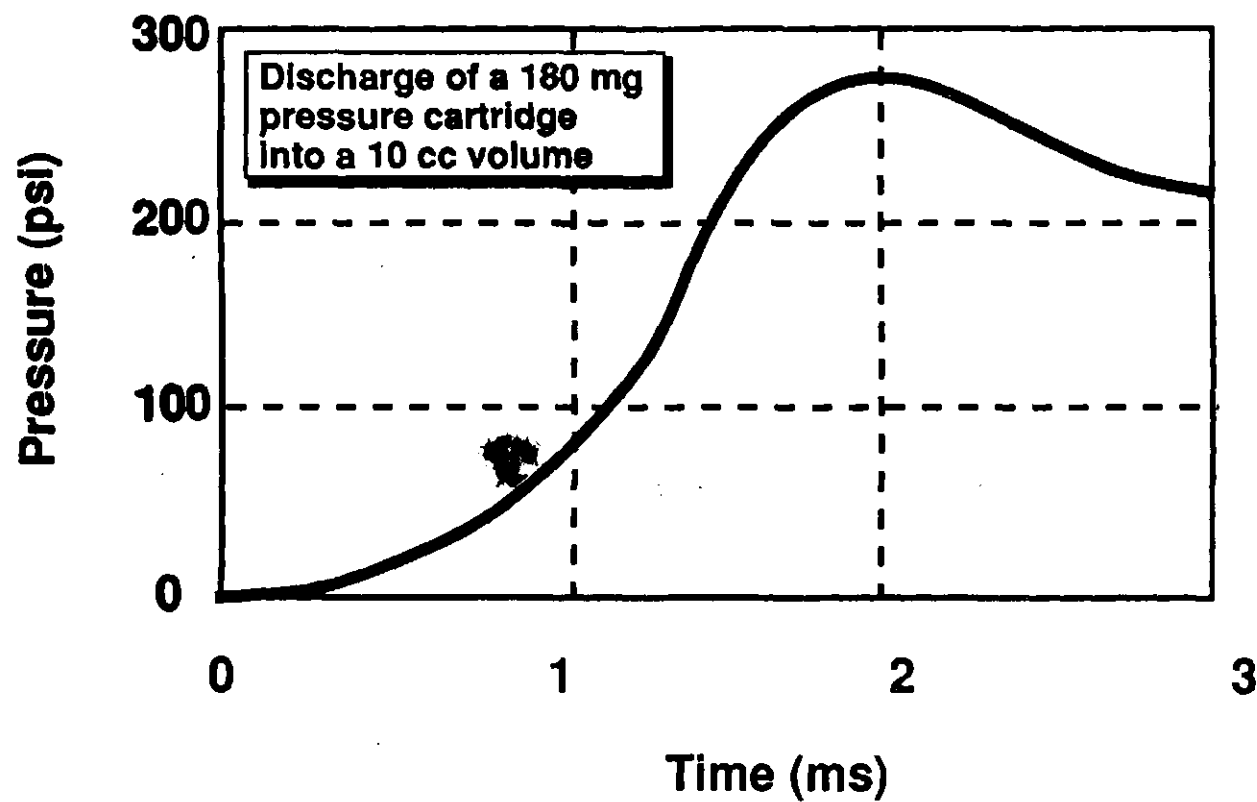
High pressure cartridges are  
used to generate a hot jet of gas



Injection: Hercules 111mp  
Charge: 100 mg  
Enclosure: 250  
Time: 30 sec



**Pressure cartridges release 200 Joules in 1 - 2 milliseconds**



# 10 F-3 Photographs of Burning LP 1846

44

# Velocity of the Gas/Liquid Interface Profile



***Relevant gas generation mechanisms and plasma behavior will be studied at medium pressure***

---

**Pressures: 1-15 kpsi**

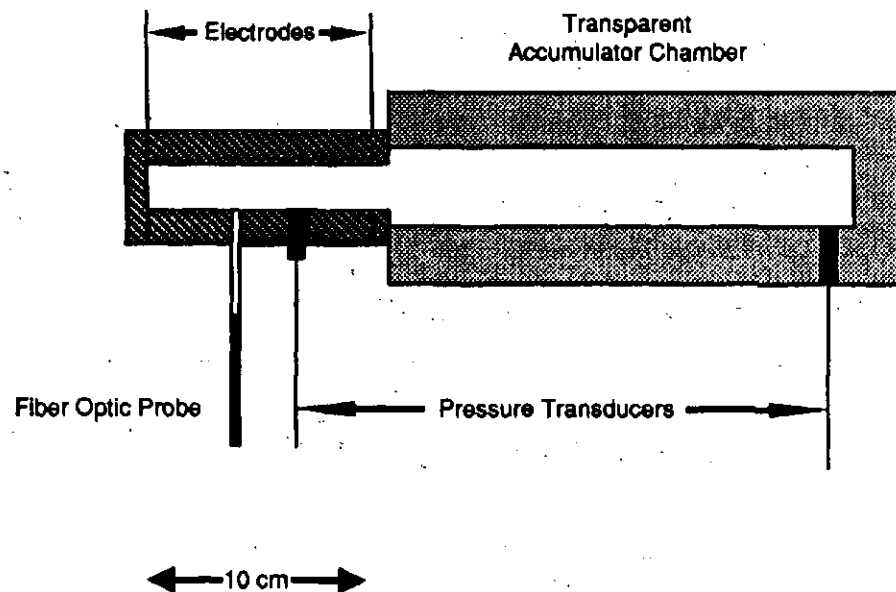
| <b>Process/Location</b>                       | <b>Diagnostic Technique</b> <ul style="list-style-type: none"><li>• <b>Measurement</b></li></ul>                                                                                                                                                                                                                                                                                                                                                                                       |
|-----------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Gas Generation/<br/>Mixing Chamber</b>     | <b>Photography/image processing</b> <ul style="list-style-type: none"><li>• <b>Characterize mixing over a range of conditions.</b></li></ul> <b>(Maximum pressure overlaps with high pressure studies)</b>                                                                                                                                                                                                                                                                             |
| <b>Plasma Formation/<br/>Plasma Cartridge</b> | <b>Time resolved emission</b> <ul style="list-style-type: none"><li>• <b>Plasma stability</b></li></ul> <b>Spectrally resolved emission</b> <ul style="list-style-type: none"><li>• <b>Plasma temperature</b></li><li>• <b>Electron density</b></li><li>• <b>Sheath temperature</b></li><li>• <b>Identify Species</b></li></ul> <b>Heat transfer probes</b> <ul style="list-style-type: none"><li>• <b>Radiative heat transfer</b></li><li>• <b>Conductive heat transfer</b></li></ul> |



***A Medium Pressure Apparatus will be used to study plasma characteristics and flow-field mixing***

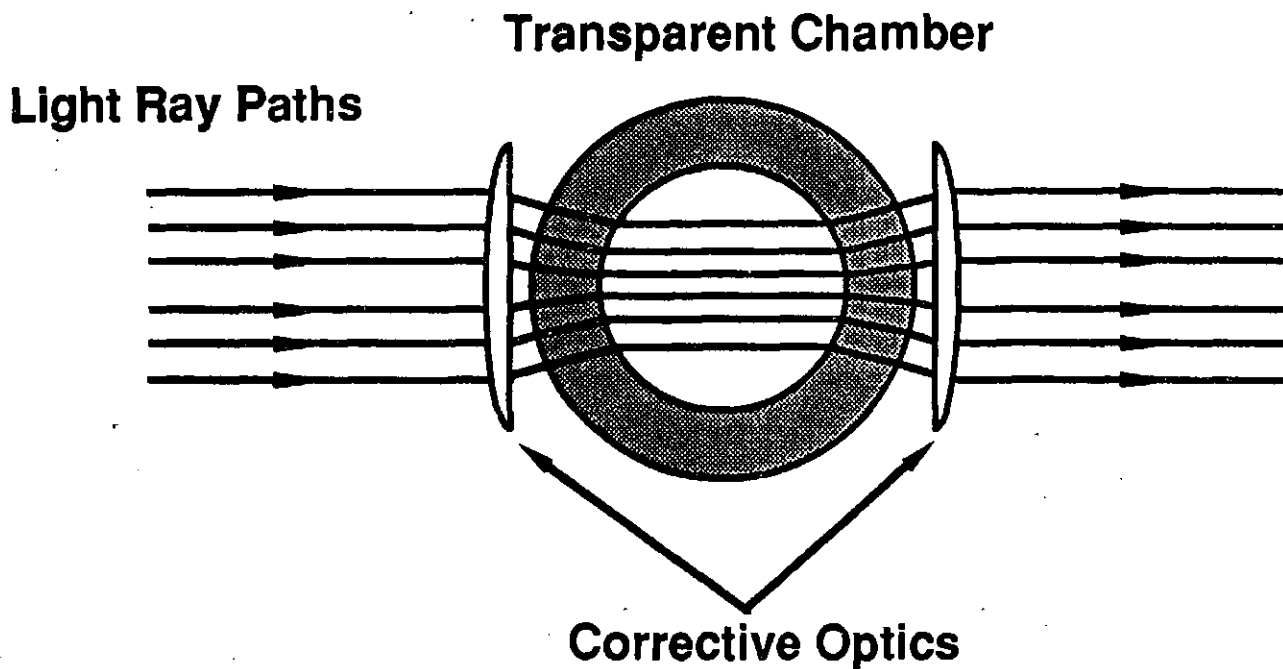
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**Schematic of medium pressure apparatus**



**The transparent chamber with corrective optics will allow for Schlieren photographic measurements**

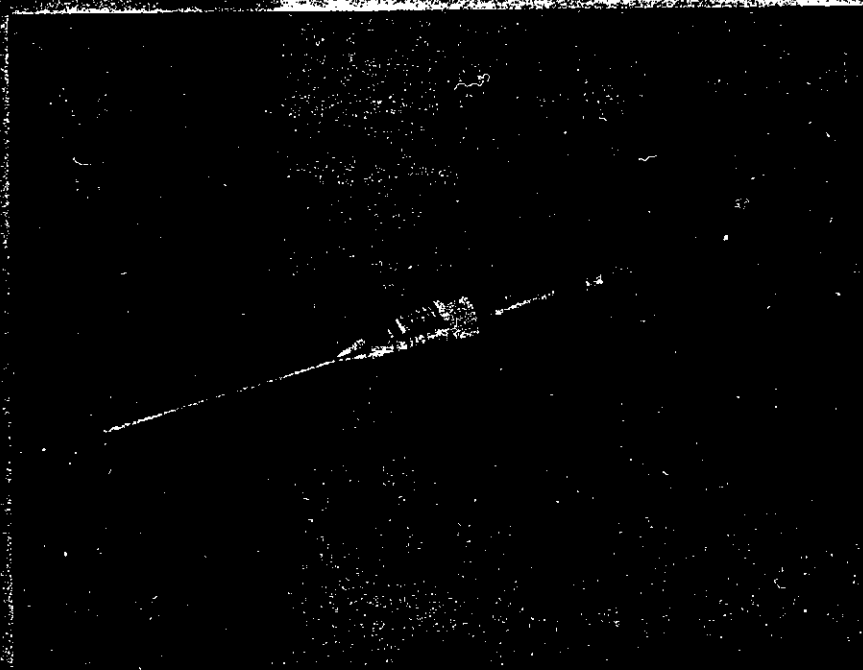
**End View of Chamber:**



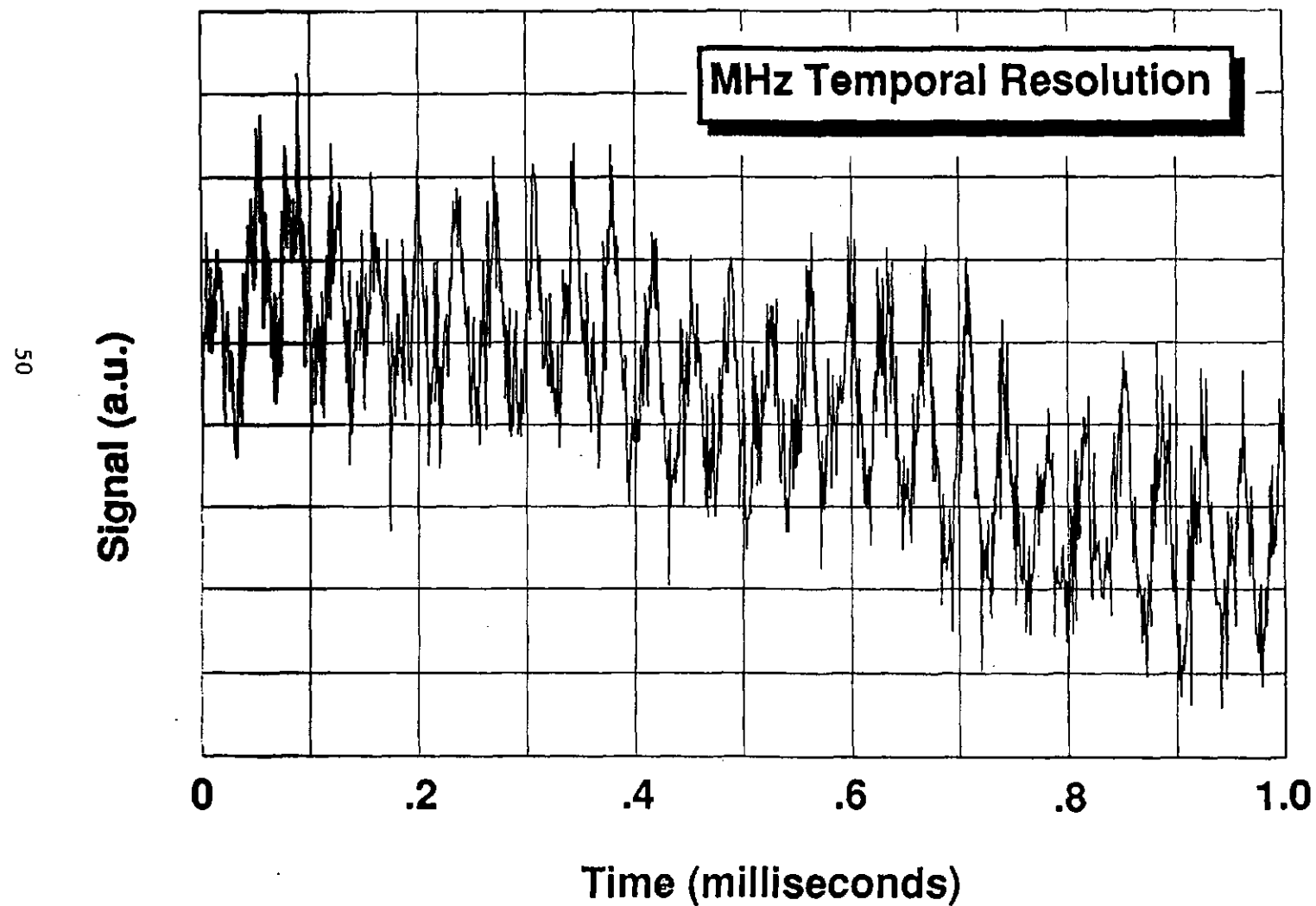


## *Fiber optic probes will provide spectral information from the plasma cartridge and in high pressure experiments*

Fiber Optic Probers have been designed and used to measure light emission from the Sandia Liquid Propellant Injector/Combustor at high pressures.

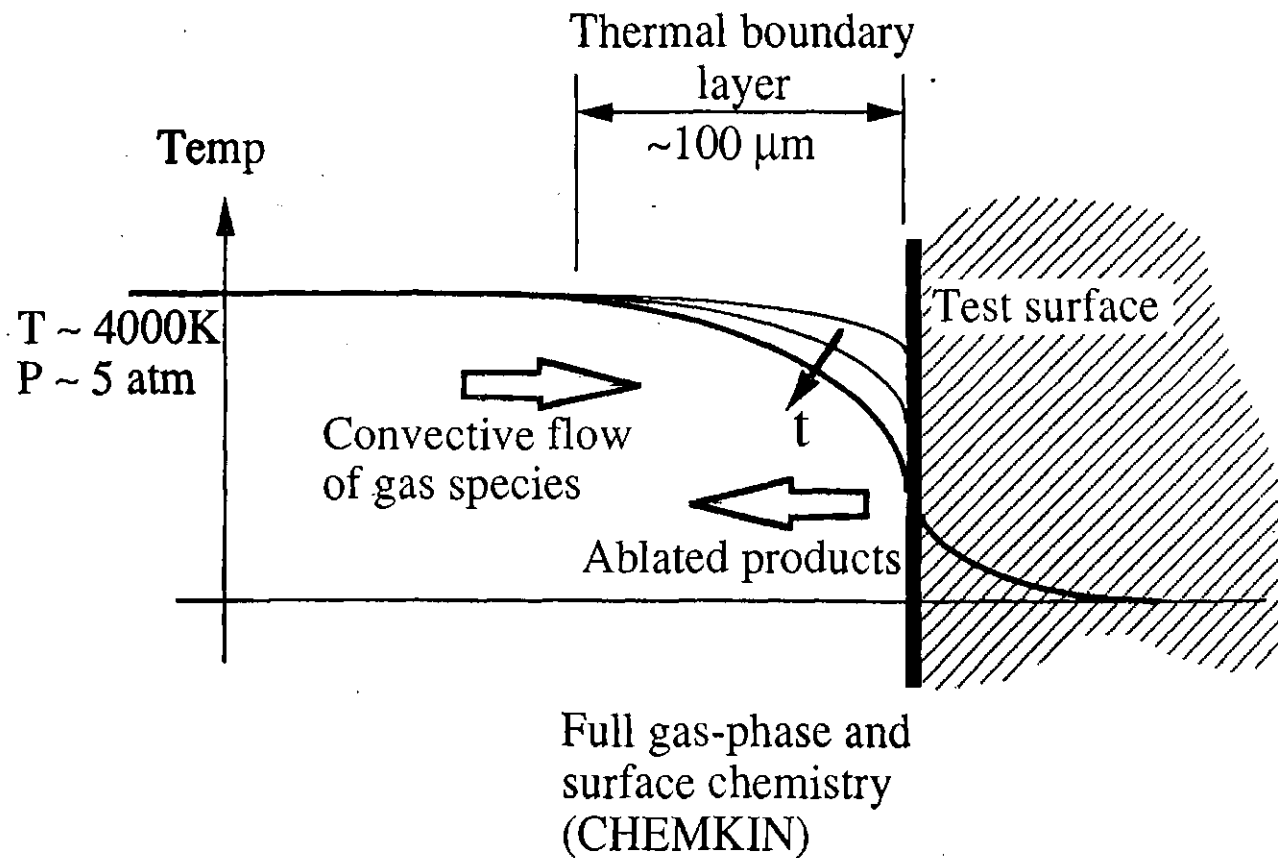


***Fiber optics will provide spectral and/or temporal information***



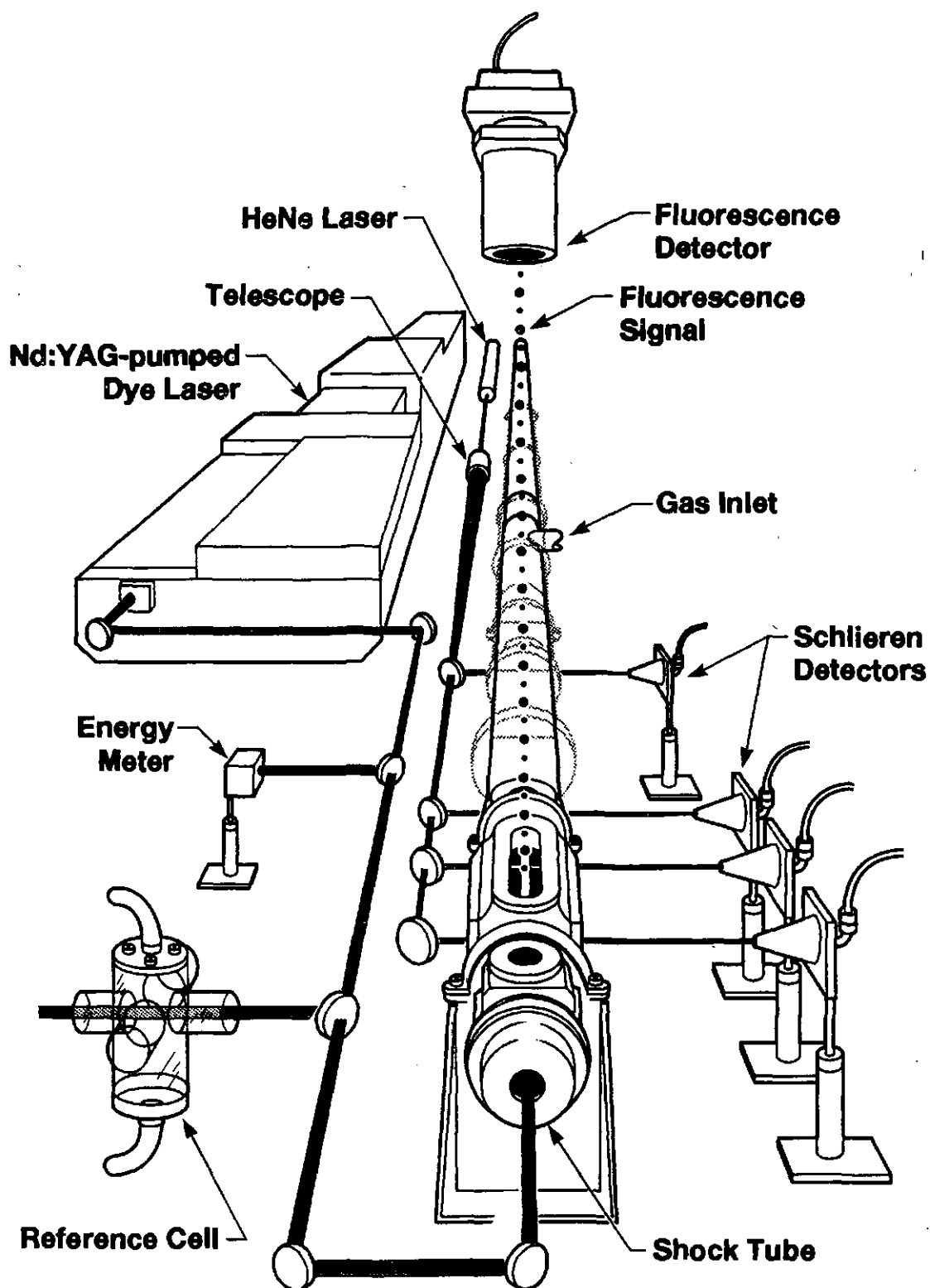


*The shock tube provides a controlled environment to observe both thermal and chemical ablation processes*



# Experimental Schematic

---

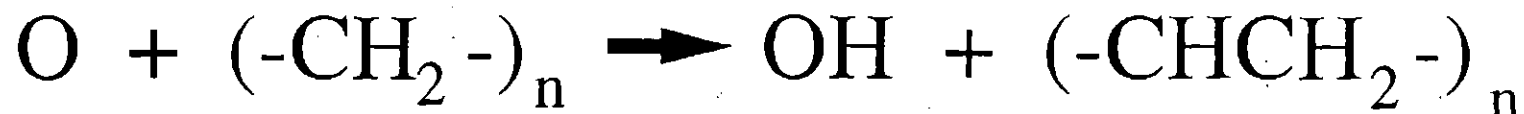


*Chemical ablation is initiated by seeding  
the shock tube*

---



The O-atoms attack the surface and generate OH

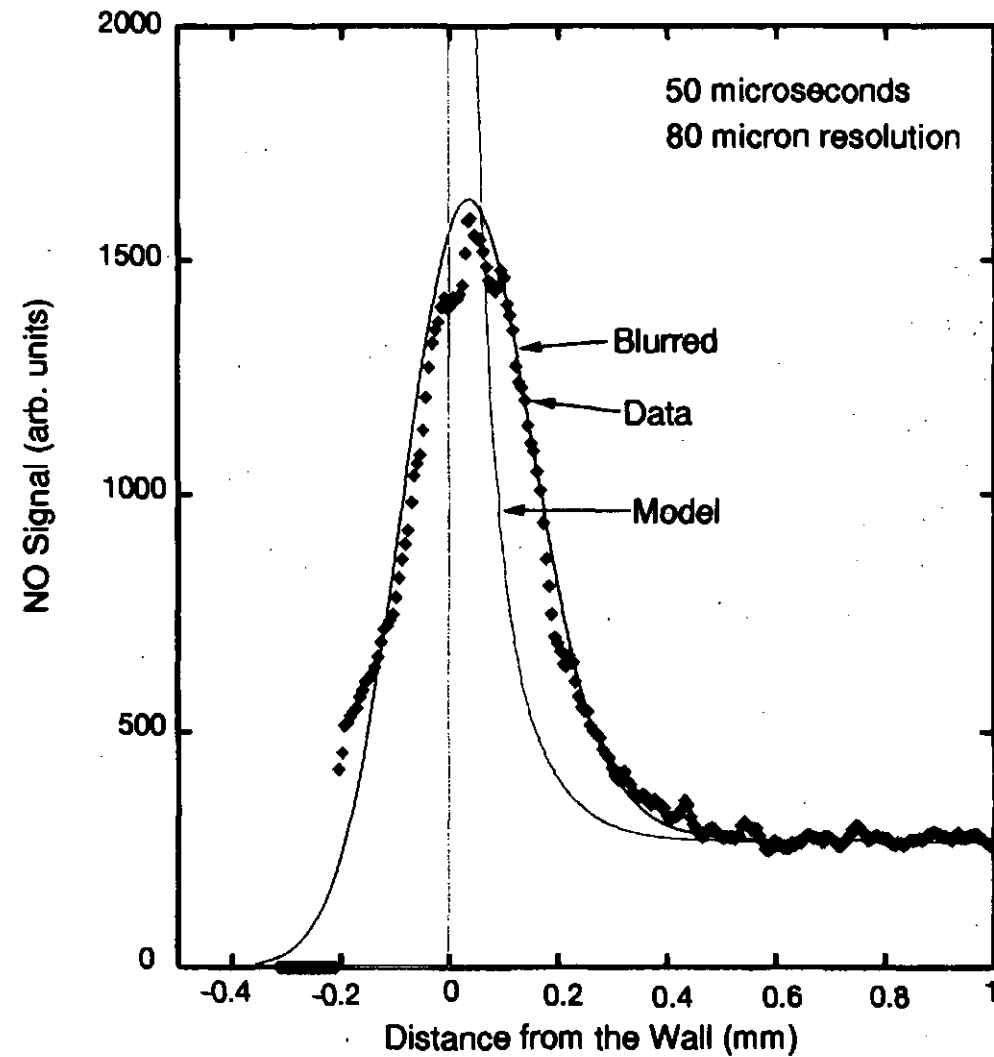


OH is observed using LIF



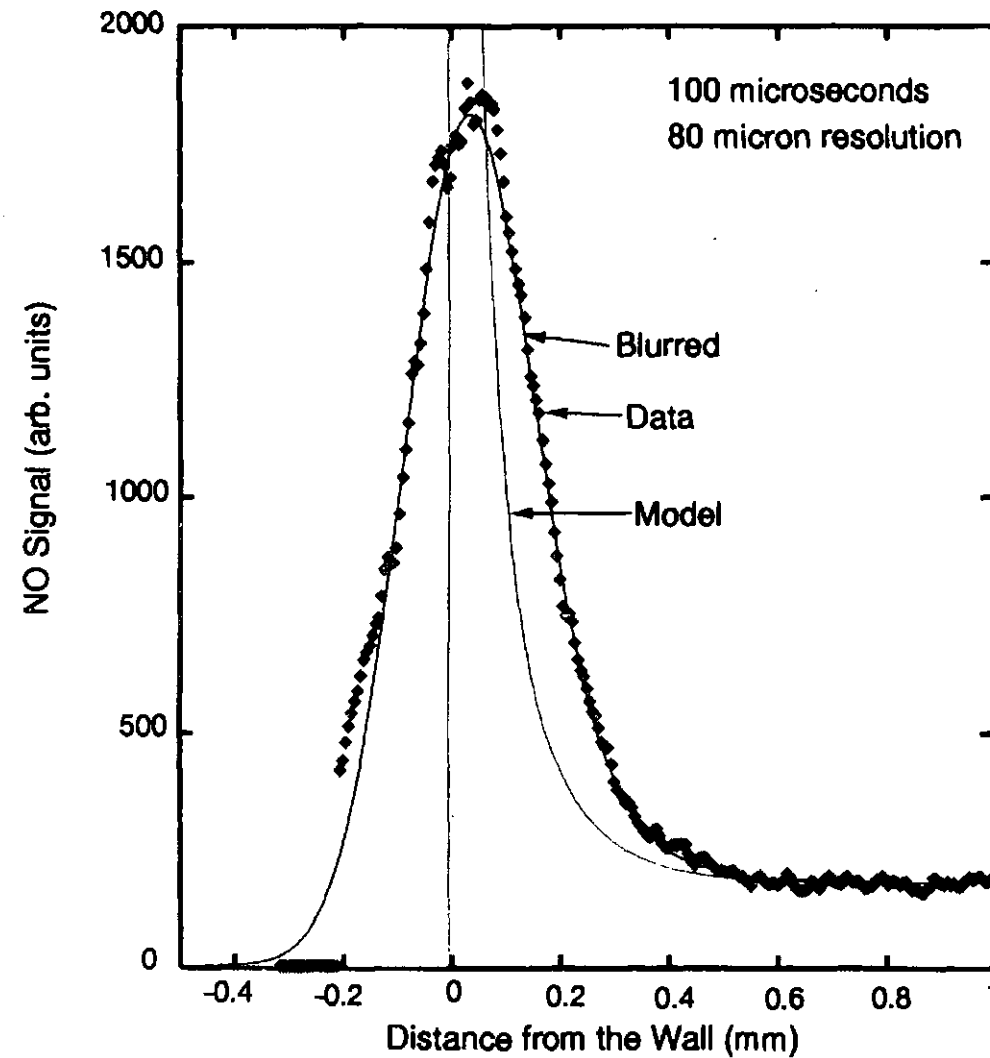
***Data and model agree when the model is blurred  
to account for instrument function***

---



***Data and model agree when the model is blurred  
to account for instrument function***

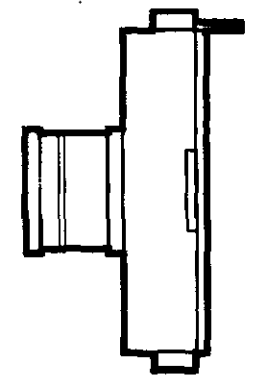
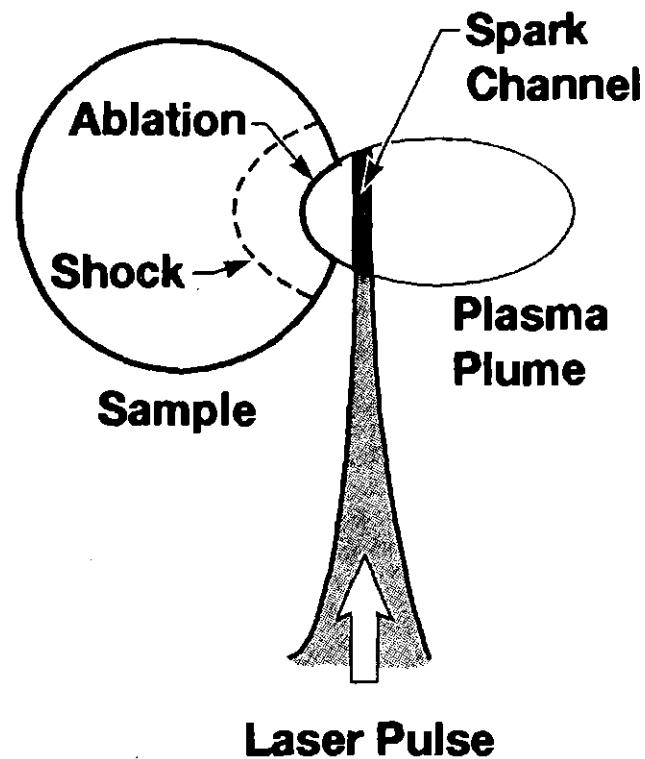
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## *ETC Combustion is being studied using Laser - Plasma Ablation*

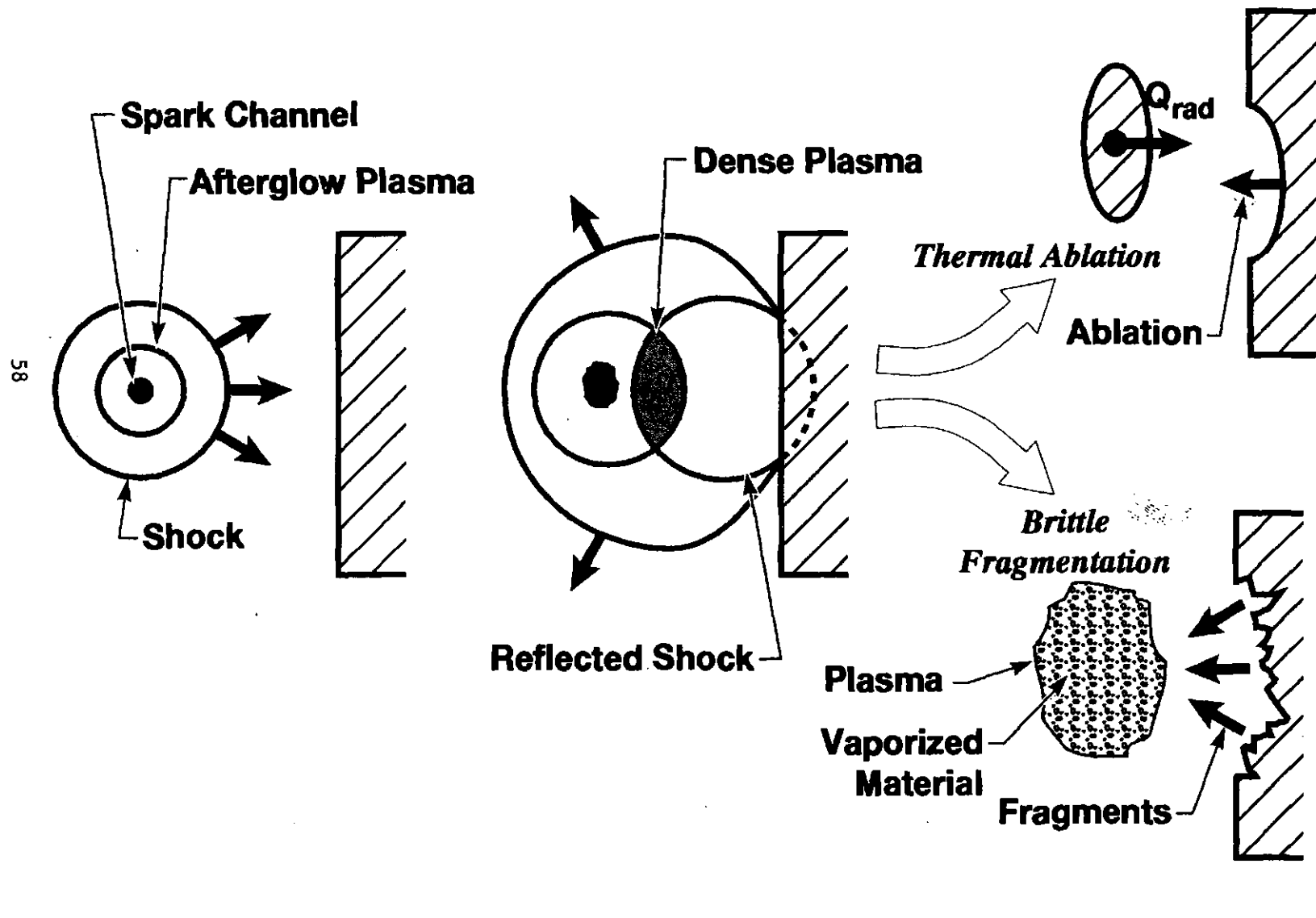
- Spectroscopy
- Imaging



**Camera**



## *Laser - induced plasmas help discern various ETC processes*



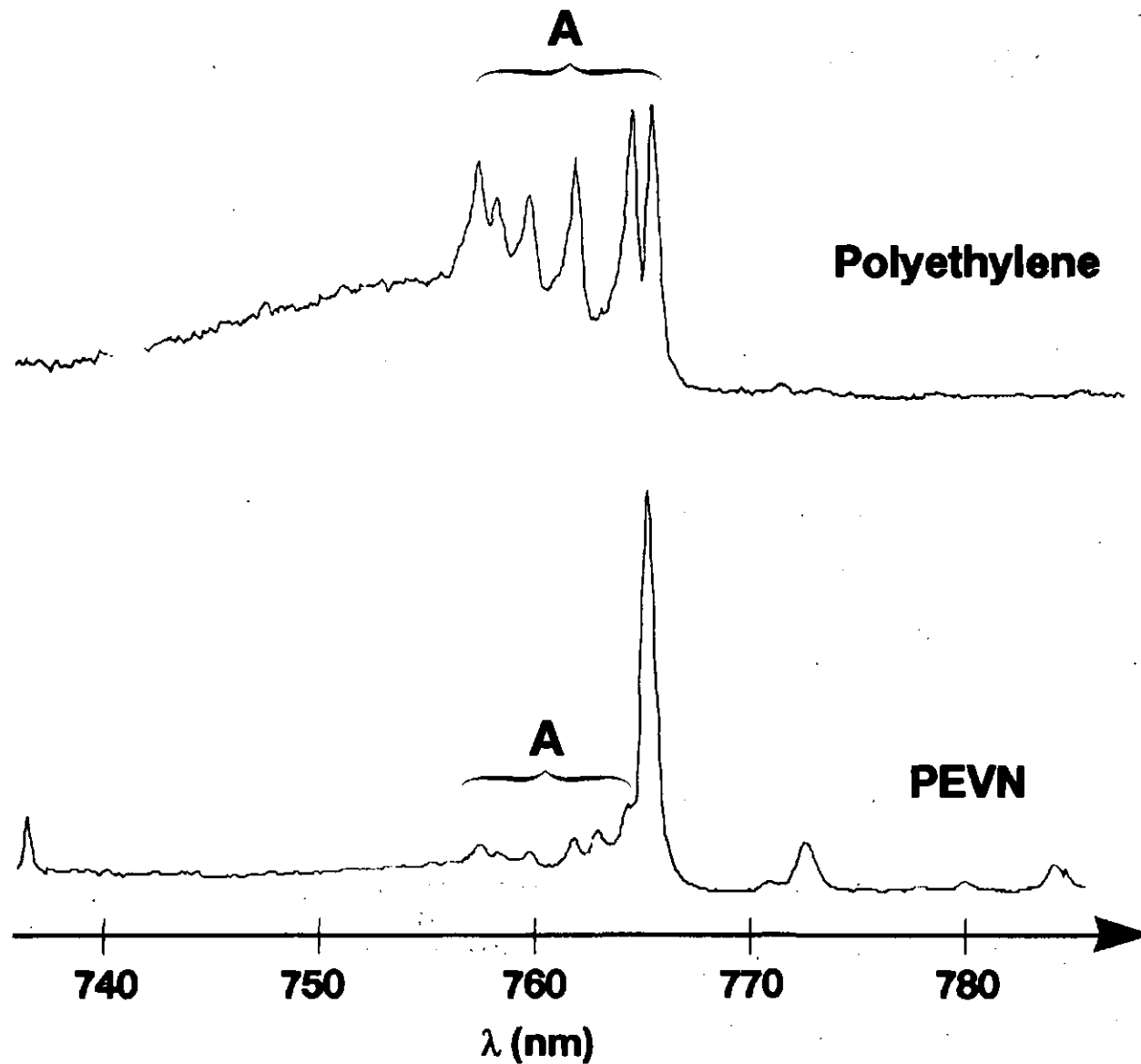
## ***Variations in Test Conditions***

---

- **Plasma power density ranges from  $10^8$  to  $10^{11}$  W/cm<sup>3</sup>**
- **Samples of PE, PEVN, etc.**
- **Reflected shock conditions to  $> 6000$  K,  $> 10^3$  atm**
- **Plasma formation in air, He, Ar, vacuum, and water**
- **Temporal resolution of 20 ns, Spatial resolution of 20  $\mu$ m**
- **Spectroscopy from 0.2 to 1.0  $\mu$ m**



# ***Laser - Ablation Spectroscopy Reveals Plasma Species for Different Materials***



## ***Time - Resolved Imaging Shows Ablation Rates for Different Materials***

---

Polyethylene at low pressure



**0 delay**



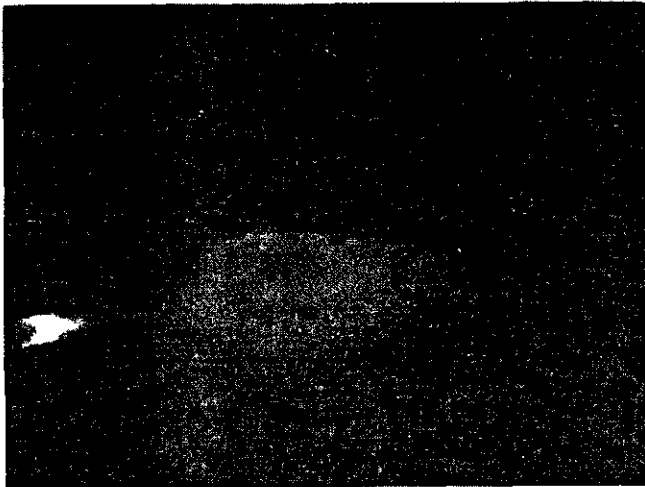
**50 ns delay**



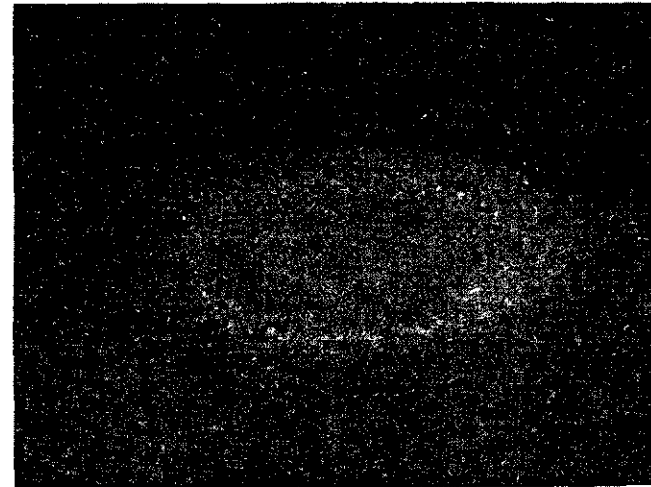
## *Ablation Rates may be related to the Energetics of Materials*

---

PEVN at low pressure



**0 delay**



**50 ns delay**



## ***Laser Plasmas Simulate Conditions on an Optically Accessible Laboratory Scale***

---

- **Highest power density achieved in Sandia tests ( $\geq 10^{10} \text{ W/cm}^2$ )**
- **Pressures and temperatures in the same range as gun conditions**
- **High repetition rate (10 Hz) allows us to perform a large matrix of tests studying ablation, and possibly mixing**
- **Provides a diagnostics testbed for full scale tests**



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**DEVELOPMENT OF AN UPWIND/IMPLICIT COMPUTATIONAL MODEL  
FOR THE ADVANCEMENT OF ARMY ETC GUNS**

N. Sinha, A. Hosangadi, and S. M. Dash  
Science Applications International Corporation  
Fort Washington, PA

**ABSTRACT**

A first-principles, state-of-the-art computational model based on the CRAFT Navier-Stokes solver is under development for the U.S. Army to simulate fluid dynamic and electro-thermo-chemical processes in ETC guns. The model will incorporate physics submodules developed from diagnostics by the team of SAIC, BRL and SNL scientists as well as national and international efforts coordinated with the Army.

This presentation will provide an overview of the 1D/2D/3D finite-volume upwind (Roe/TVD)/implicit numerics in CRAFT and its strongly-coupled treatment of combustion chemistry and multi-phase non-equilibrium processes (presently limited to dilute particulates). Current work focussed on the ETC gun problem includes dynamic grid capabilities with solution adaptive features, and research towards incorporating complex equations of state into higher-order Riemann based solvers such as the Roe/TVD scheme implemented. A building-block approach upgrade of CRAFT to simulate ETC processes will be described along with representative calculations which exhibit present capabilities.

# **DEVELOPMENT OF AN UPWIND/IMPLICIT COMPUTATIONAL MODEL FOR THE ADVANCEMENT OF ARMY ETC GUNS**

**N. Sinha, A. Hosangadi, and S. M. Dash  
Science Applications International Corporation  
Fluid and Propulsion Sciences Operation  
501 Office Center Drive, Suite 420  
Fort Washington, PA 19034-3211  
Phone: 215/542-1200 FAX: 215/542-8076**

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**JULY 9-11, 1991**

**Presented at:**

***JANNAF WORKSHOP ON ETC MODELING AND DIAGNOSTICS***

**U.S. ARMY BALLISTICS RESEARCH LABORATORY  
ABERDEEN PROVING GROUND, MARYLAND**

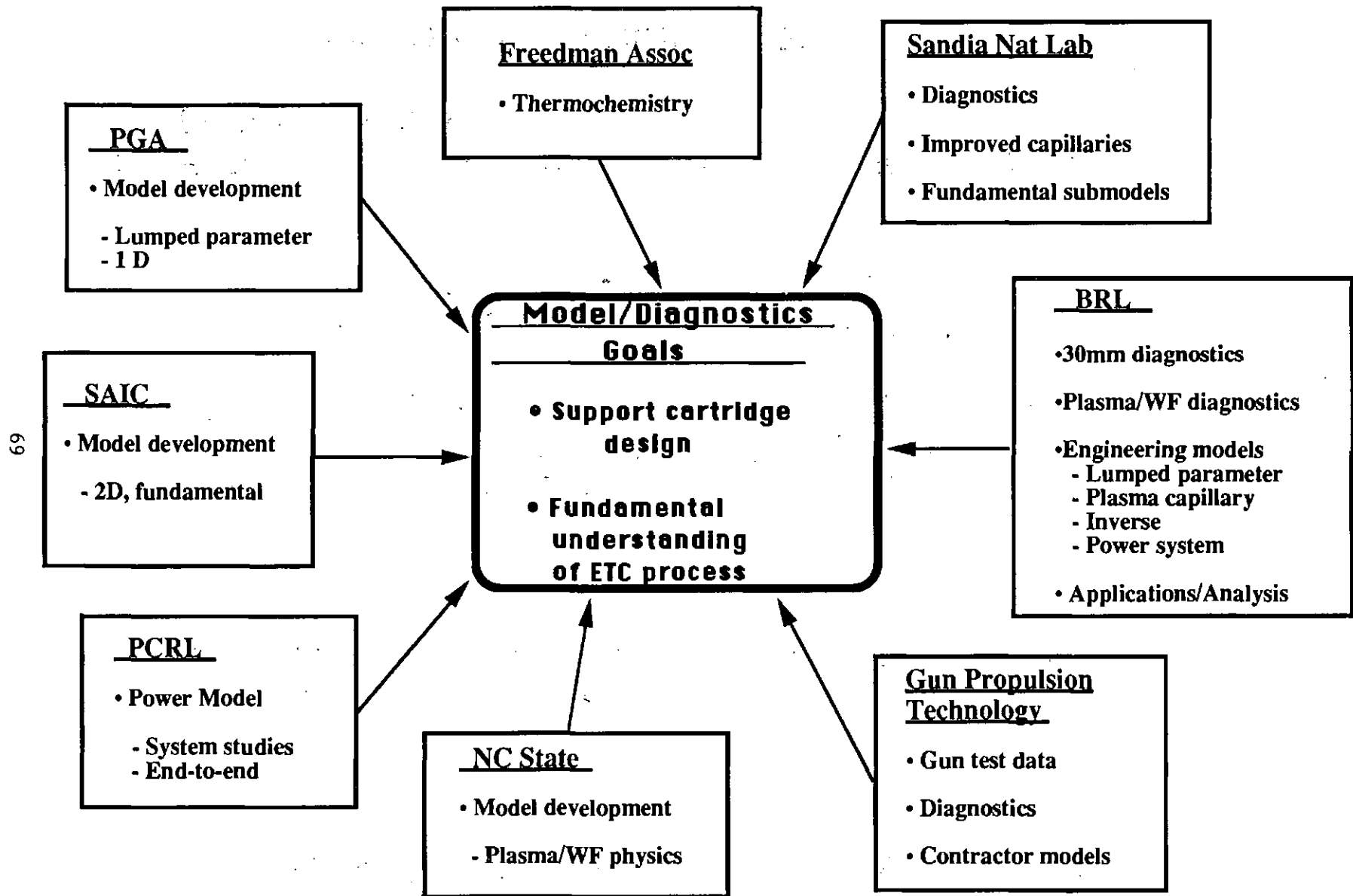
## TOPICS

- **APPROACH TO BE TAKEN**
- **CRAFT 1D/2D/3D UPWIND/IMPLICIT FINITE-VOLUME CODE**
  - **HISTORY**
  - **EQUATIONS/NUMERICS**
  - **STRONGLY-COUPLED CHEMISTRY**
  - **COUPLED ANALYSIS OF DILUTE PARTICULATES**
  - **DYNAMIC GRID**
- **RELATED APPLICATIONS**
- **CRAFT/ETC DEVELOPMENT**
  - **ADAPTION TO ETC ENVIRONMENT**
  - **COMPLEX EQUATIONS OF STATE/RIEMANN PROBLEM**
  - **GAS/LIQUID PROBLEMS**
- ⋮
- **PRELIMINARY APPLICATIONS (BRL PROGRAM INITIATED 6/1/91)**

## **BRL APPROACH FOR ETC GUN SIMULATION**

- **EMPHASIS ON UNDERSTANDING "PHENOMENOLOGY" AND INFLUENCE OF THERMOCHEMISTRY AND PHYSICS ON GUN PERFORMANCE**
- **EXPERIMENTAL DATA USED TO SUPPORT DEVELOPMENT OF "FIRST-PRINCIPLES" CFD SIMULATION CODE AND TO ENHANCE UNDERSTANDING OF PHENOMENOLOGY**
  - **NO ATTEMPTS TO "TUNE" THERMOCHEMICAL/ PHYSICAL PARAMETERS TO MATCH DATA**
- **BUILDING BLOCK APPROACH FOR UNDERSTANDING PHENOMENOLOGY**
  - **EXPLORE INDIVIDUAL EFFECTS**

## Army ETC Modeling & Diagnostics



## FEATURES OF CRAFT FOR ETC GUN SIMULATION

| FEATURE                                            | ADVANTAGE                                                                                                                                                                                                  |
|----------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1D/2D/AXI/3D RUN OPTIONS                           | CAN DO FAST PRELIMINARY DESIGN STUDIES (1D) AND DETAILED SIMULATION (2D/AXI/3D) IN SINGLE CODE                                                                                                             |
| FINITE-VOLUME IMPLICIT CONSERVATIVE FORMULATION    | CONSERVATIVE/FINITE-VOLUME NUMERICS YIELDS ACCURATE FLUX BALANCES - EQUATIONS STRONGLY COUPLED; IMPLICIT NUMERICS ELIMINATES STABILITY/ STEP-SIZE PROBLEMS AND PERMITS RESOLVING NEAR-WALL BOUNDARY LAYERS |
| ROE/TVD UPWIND NUMERICS                            | ROE IS REIMANN BASED DIFFERENCING FOR ACCURATE CONVECTIVE/WAVE TRACKING; TVD IS HIGHER-ORDER EXTENSION; NO ARTIFICIAL DISSIPATION REQUIRED FOR STABILITY                                                   |
| BLOCK MATRIX INVERSION WITH INNER NEWTON ITERATION | ROBUST INVERSION PROCEDURE PERMITS TAKING LARGE TIME-STEPS; INNER ITERATIONS PERMITS ELIMINATING ALL FACTORIZATION/LINEARIZATION ERRORS WITHIN STEP                                                        |
| STRONGLY-COUPLED, FULLY-IMPLICIT CHEMISTRY         | CHEMICAL SPECIES ARE PART OF COUPLED EQUATION SET FOR ACCURACY/ROBUSTNESS; CHEMICAL SOURCE TERMS TREATED FULLY-IMPLICITLY TO ELIMINATE STIFFNESS                                                           |
| STRONGLY-COUPLED, FULLY-IMPLICIT TURBULENCE MODELS | TURBULENCE MODEL EQUATIONS ARE PART OF COUPLED EQUATION SET FOR ACCURACY/ROBUSTNESS; TURBULENCE SOURCE TERMS TREATED FULLY-IMPLICITLY TO ELIMINATE STIFFNESS                                               |
| IMPLICIT/UPWIND DISPERSED PHASE SOLVER             | PARTICULATE EQUATIONS SOLVER ON SAME GRID AS FLUID PHASE USING SAME IMPLICIT/UPWIND NUMERICS; STRONG FLUID/PARTICLE COUPLING AND IMPLICIT SOURCE TERM TREATMENT                                            |
| DYNAMIC GRID, SOLUTION ADAPTIVE MODULE             | GRID MOVES/DEFORMS IN ACCORDANCE WITH BOUNDARY MOTION (PROJECTILE) AND REDISTRIBUTES USING NASA/AMES SAGE MODULE                                                                                           |

## EVOLUTION OF METHODOLOGY IN CRAFT CODE

- **UPWIND/IMPLICIT FINITE-VOLUME METHODOLOGY (ROE/TVD) APPLIED TO EXTERNAL AERODYNAMIC FLOWFIELDS ~ 1986-1988.** Reference: Walters and Thomas, "Advances in Upwind Relaxation Methods," State of the Art Surveys on Computational Fluid Mechanics, ASME Pub., 1988.
- **EXTENSIONS OF ROE/TVD METHODOLOGY TO MULTI-COMPONENT/REAL GAS FLOWS WITH CHEMICAL/THERMAL NONEQUILIBRIUM ~ 1988-1989.** Reference: Liu and Vinokur, "Upwind Algorithms for General Thermo-Chemical Nonequilibrium Flows," AIAA Paper 89-0201, Jan. 1989.
- **EXPLORATORY STUDIES OF ROE/TVD NUMERICS FOR UNSTEADY FLOWS, ACCURATE WAVE PROPAGATION IN DUCT (RESONANCE TUBE) ~ 1989.** Reference: Ridder and Beddini, "Time-Accurate Finite-Volume Method for Propulsion Chamber Flows," AIAA Paper 89-2554, July 1989.
- **EXTENSIONS OF ROE/TVD METHODOLOGY FOR PROPULSIVE FLOWS WITH COMBUSTION CHEMISTRY, ADVANCED TURBULENCE MODELS ~ 1989-1991.** Reference: Dash, "Advanced Computational Models for Analyzing High-Speed Propulsive Flowfields," 1990 JANNAF Propulsion Meeting, Oct. 1990.
- **EXTENSIONS OF ROE/TVD METHODOLOGY FOR UNSTEADY ROCKET PLUME PROBLEMS WITH MULTI-PHASE NONEQUILIBRIUM ~ 1989-1991.** Reference: Sinha, Hosangadi and Dash, "The CRAFT NS Code and Preliminary Applications to Unsteady, Reacting, Multi-Phase Plume Flowfield Problems," 1991 JANNAF Plume Meeting, May 1991.
- **EXPLORATORY STUDIES OF ROE/TVD METHODOLOGY FOR GUN FLOWFIELDS WITH DYNAMIC GRID EXTENSIONS ~ 1990-1991.** Reference: Hosangadi and Sinha, "Development of a Dynamic Grid Navier-Stokes Solver for Computing Electro-Thermo-Chemical Gun Configurations," SAIC/TR-88, Dec. 1990.

## **SYNERGISM OF CRAFT WITH OTHER DoD & NASA EFFORTS**

- **NUMERICS IN CRAFT REPRESENTS CURRENT STATE-OF-THE-ART FOR VISCOUS, CHEMICALLY-REACTING FLOWS**
- **ALL CURRENT NATIONAL PROGRAMS ARE IMPLEMENTING SUCH NUMERICS FOR REAL PROBLEMS**
  - **NATIONAL AEROSPACE PLANE (NASP) PROGRAM  
(GASP CODE, USA CODE, SCHAFT/CRAFT CODES, ...)  
→ SCRAMJET PROPULSION**
  - **SDIO PROGRAM (GASP CODE, SCHAFT/CRAFT CODES)  
→ MISSILE JETS/PLUMES**
  - **HIGH-SPEED RESEARCH PROGRAM (HSRP)  
→ AIRCRAFT JETS/PLUMES**
- **6.1 RESEARCH PROGRAMS USING THIS CLASS OF NUMERICS AS TOOL TO EXPLORE PHYSICS**
  - **COMBUSTION INSTABILITY IN ROCKETS/RAMJETS**
  - **DIRECT OR LARGE EDDY TURBULENCE SIMULATION**
- **SAIC IS IMPLEMENTING VERSIONS OF CRAFT TO SUPPORT SUCH PROGRAMS**



## RESEARCH VERSIONS OF CRAFT NS CODE

| CODE NAME    | CRAFT/JR                                                                                                                        | CRAFT/GF                                                                                                            | CRAFT/RNP                                                                                                                   | CRAFT/LU                                                    |
|--------------|---------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------|
| APPLICATION  | HIGH-SPEED JET RESEARCH                                                                                                         | ETC GUN FLOWFIELDS                                                                                                  | ROCKET NOZZLES/ PLUMES                                                                                                      | NUMERICAL RESEARCH                                          |
| SPONSOR      | NASA/LaRC, HSRP                                                                                                                 | BRL                                                                                                                 | MICOM                                                                                                                       | INTERNAL RESEARCH                                           |
| EQUATIONS    | 1D/2D/AXI/3D                                                                                                                    | 1D/2D/AXI/3D                                                                                                        | 1D/2D/AXI/3D                                                                                                                | 1D/2D/AXI/3D                                                |
| CHEMISTRY    | PERFECT GAS, TWO-STREAM                                                                                                         | IMPERFECT GAS, COMBUSTION CHEMISTRY, MULTI-PHASE CHEMISTRY                                                          | SPF FINITE-RATE CHEMISTRY, TWO-STREAM, PERFECT GAS                                                                          | PERFECT GAS                                                 |
| TURBULENCE   | $k\epsilon$ , COMPRESSIBILITY EXTENSIONS, ARS EXTENSIONS                                                                        | $k\epsilon$                                                                                                         | $k\epsilon$ /Chien, COMPRESSIBILITY EXTENSIONS                                                                              | $k\epsilon$                                                 |
| PARTICULATES | NONE                                                                                                                            | EQUILIBRATED MIXTURE, NONEQ. LIQUID PROPELLANTS                                                                     | NONEQUILIBRIUM                                                                                                              | NONE                                                        |
| SOLUTION     | IMPLICIT/UPWIND (Roe/TVD) STRONGLY-COUPLED FLUID/ SPECIES/ TURBULENCE (8 x 8 BLOCK INVERSION), TIME-ACCURATE OR TIME-ASYMPTOTIC | IMPLICIT/UPWIND (Roe/TVD) ON DYNAMIC GRID, TIME-ACCURATE SOLUTION, STRONGLY-COUPLED EQUATIONS, VARIABLE MATRIX SIZE | IMPLICIT/UPWIND (Roe/TVD) ON FIXED GRID, TIME-ACCURATE OR TIME-ASYMPTOTIC, STRONGLY-COUPLED EQUATIONS, VARIABLE MATRIX SIZE | LU UPGRADE FOR ROBUSTNESS, FASTER CONVERGENCE (CFL ~ 25-50) |
| NEW WORK     | EXPLORING NEW TURBULENCE MODELS, NEW NONREFLECTIVE BC                                                                           | INCLUSION OF LIQUID PHASE, GAS/ LIQUID INTERFACE, DROPLET FORMATION MODEL                                           | ADAPTIVE GRIDDING FOR UNSTEADY MULTI- PHASE FLOWS                                                                           | REWRITE OF CODE STRUCTURE TO OPTIMIZE LU STORAGE FOR 3D     |

# CRAFT NS EQUATIONS

$$\begin{aligned} & \frac{\partial}{\partial t} \iiint Q dV + \iint (E_{i+1/2} - E_{i-1/2}) d\eta d\zeta \\ & + \iint (F_{j+1/2} - F_{j-1/2}) d\xi d\zeta + \iint (G_{k+1/2} - G_{k-1/2}) d\xi d\eta \\ & = \frac{1}{Re} \iint (R_{i+1/2} - R_{i-1/2}) d\eta d\zeta + \iint (S_{j+1/2} - S_{j-1/2}) d\xi d\zeta \\ & + \frac{1}{Re} \iint (T_{k+1/2} - T_{k-1/2}) d\xi d\eta + \iiint D dV \end{aligned}$$

$$Q = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ e \\ \rho_1 \\ \rho_2 \\ \vdots \\ \rho_{n-1} \\ \rho k \\ \rho \epsilon \end{pmatrix}; E = \begin{pmatrix} \rho \hat{U} \\ \rho \hat{U} u + t_x P \\ \rho \hat{U} v + t_y P \\ \rho \hat{U} w + t_z P \\ (e + P) \hat{U} \\ \rho_1 \hat{U} \\ \rho_2 \hat{U} \\ \vdots \\ \rho_{n-1} \hat{U} \\ \rho \hat{U} k \\ \rho \hat{U} \epsilon \end{pmatrix}; D = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \dot{\omega}_1 \\ \dot{\omega}_2 \\ \vdots \\ \dot{\omega}_{n-1} \\ P - p\epsilon \\ \frac{\epsilon}{k} (C_1 P - C_2 \rho \epsilon) \end{pmatrix}; R = \begin{pmatrix} 0 \\ \ell_x \tau_{xx} + m_y \tau_{xy} + n_z \tau_{xz} \\ \ell_x \tau_{yx} + m_y \tau_{yy} + n_z \tau_{yz} \\ \ell_x \tau_{zx} + m_y \tau_{zy} + n_z \tau_{zz} \\ \ell_x \beta_x + m_y \beta_y + n_z \beta_z \\ \mu (\ell_x \rho_{1x} + m_y \rho_{1y} + n_z \rho_{1z}) \\ \vdots \\ \mu (\ell_x \rho_{nx} + m_y \rho_{ny} + n_z \rho_{nz}) \\ \mu (\ell_x k_x + m_y k_y + n_z k_z) \\ \mu (\ell_x \epsilon_x + m_y \epsilon_y + n_z \epsilon_z) \end{pmatrix}$$

## DYNAMIC GRID COMPUTATIONS

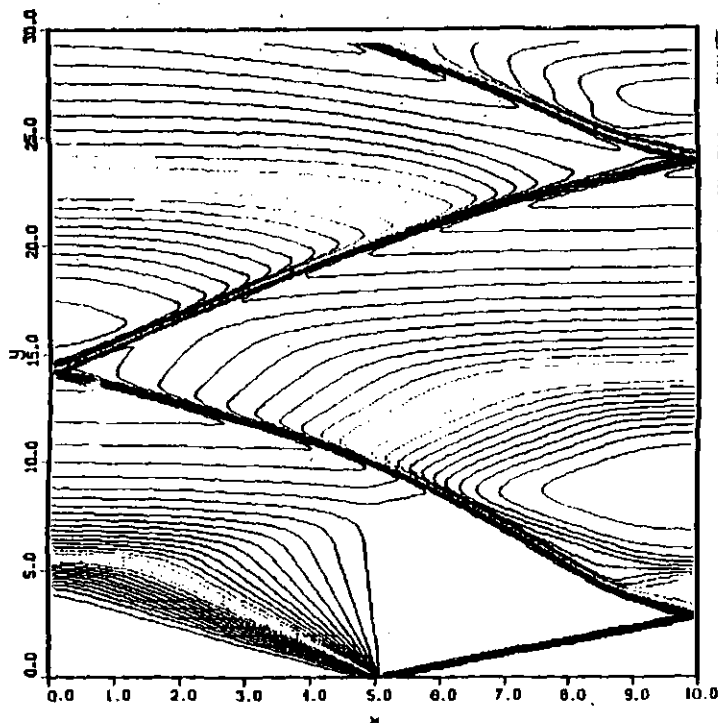
|                           |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|---------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p><b>EQUATIONS</b></p>   | $\int_{t_2} Q dv - \int_{t_1} Q dv + \int_{t_1}^{t_2} \oint_{S(t)} \vec{n} \cdot \vec{f} ds dt = \int_{t_1}^{t_2} \int_{V(t)} p dv b dt$ <div style="display: flex; justify-content: space-around; margin-top: 10px;"> <span>Term I</span> <span>Term II</span> <span>Term III</span> </div> <div style="margin-top: 10px;"> <p><b>Term I:     PRIMARY CONSERVED VARIABLES</b></p> <p><b>Term II:    FLUX TERMS</b></p> <p><b>Term III:   SOURCE TERMS</b></p> <p><b>V(t):       TIME VARYING VOLUME</b></p> </div>                                           |
| <p><b>METHODOLOGY</b></p> | <p><b>TREAT GRID AS PURELY GEOMETRIC QUANTITY, I.e., DEFINITION OF CONTRAVARIANT VELOCITY UNCHANGED</b></p> <p><b>EVALUATE FLUX TERM BY ASSUMING GRID IS HELD CONSTANT AT TIME-AVERAGED VALUE</b></p> <p><b>EVALUATE SOURCE TERM FOR THE GRID AT THE NEW TIME LEVEL, THUS GIVING:</b></p> $\left( \frac{Q^{n+1} - Q^n}{\Delta t} \right) V^{n+1} + Q^n \left( \frac{V^{n+1} - V^n}{\Delta t} \right) + F_n^{n+1} \bar{S} \Delta t = \rho^{n+1} V^{n+1}$ <p><math>F_n = \vec{n} \cdot \vec{F}</math>, and <math>\bar{S}</math> is the time averaged metric</p> |
| <p><b>NUMERICS</b></p>    | <ul style="list-style-type: none"> <li>• SPECIFY GRID MOVEMENT AS A FUNCTION OF TIME</li> <li>• EVALUATE <math>F_n</math> AS A THIRD-ORDER UPWIND BASE FLUX</li> <li>• SOLVE LINEARIZED IMPLICIT OPERATOR USING ADI PROCEDURE</li> <li>• USE NEWTON ITERATION FOR HIGHER ORDER ACCURACY IN TIME</li> </ul>                                                                                                                                                                                                                                                    |

# SHOCK TUBE COMPUTATIONS - PRESSURE VARIATIONS

PRESSURE  
10:1 PRESSURE RATIO

CONTOUR LEVELS

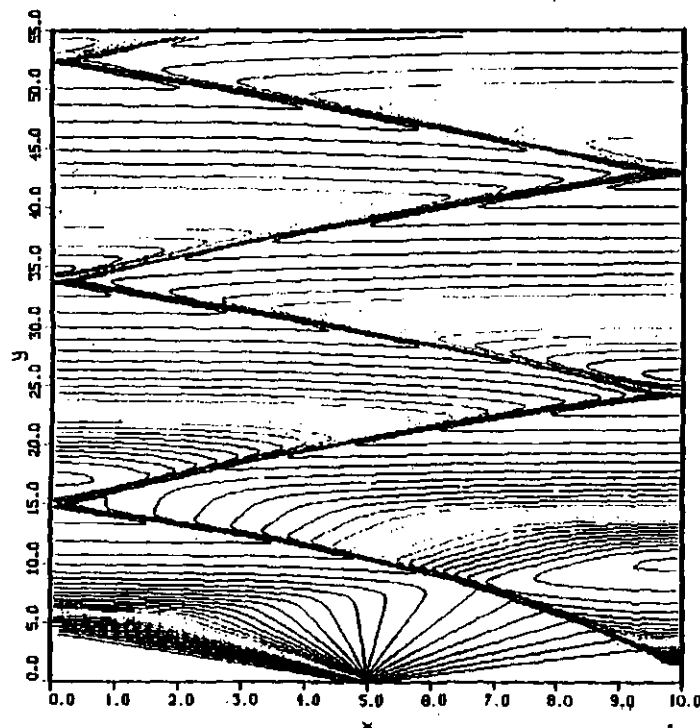
0.07500  
0.10000  
0.12500  
0.15000  
0.17500  
0.20000  
0.22500  
0.25000  
0.27500  
0.30000  
0.32500  
0.35000  
0.37500  
0.40000  
0.42500  
0.45000  
0.47500  
0.50000  
0.52500  
0.55000  
0.57500  
0.60000  
0.62500  
0.65000  
0.67500  
0.70000  
0.72500  
0.75000  
0.77500  
0.80000  
0.82500  
0.85000  
0.87500

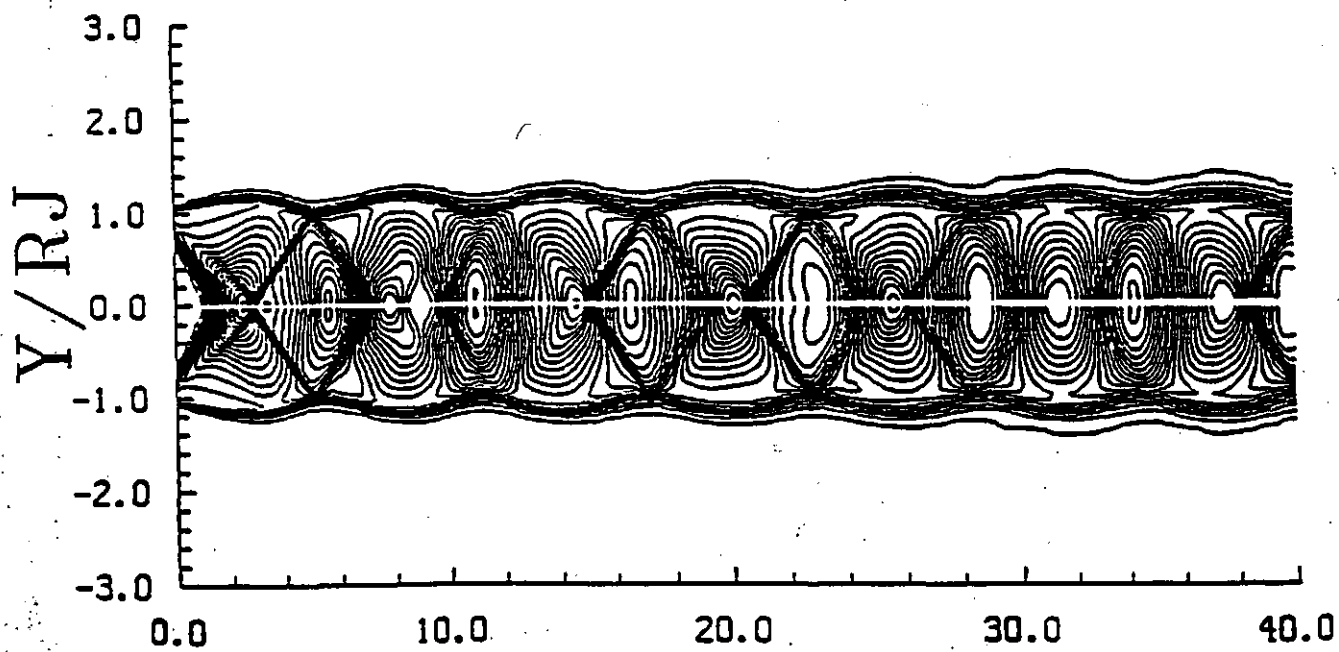
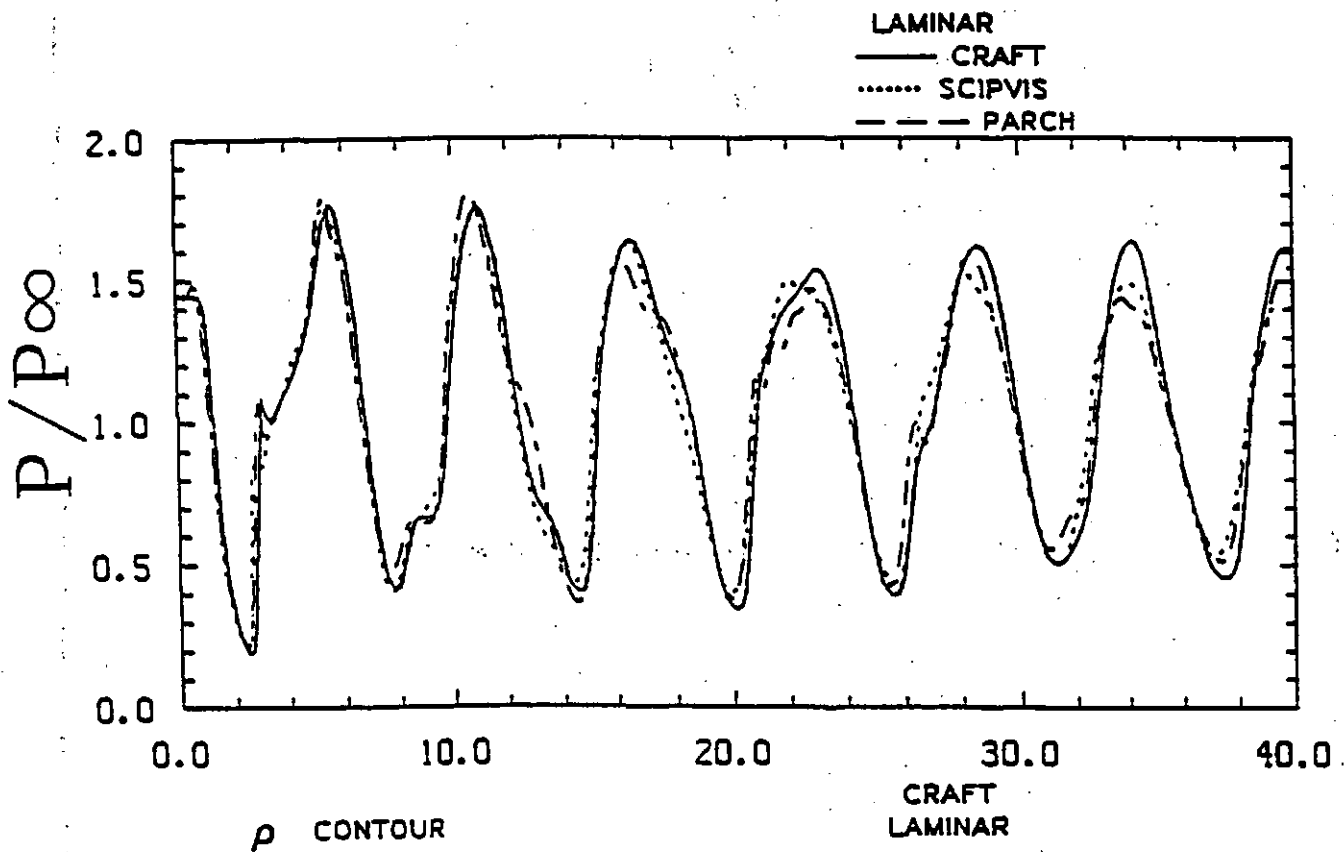


PRESSURE  
1000:1 PRESSURE RATIO

CONTOUR LEVELS

0.00000  
2.50000  
5.00000  
7.50000  
10.0000  
12.5000  
15.0000  
17.5000  
20.0000  
22.5000  
25.0000  
27.5000  
30.0000  
32.5000  
35.0000  
37.5000  
40.0000  
42.5000  
45.0000  
47.5000  
50.0000  
52.5000  
55.0000  
57.5000  
60.0000  
62.5000  
65.0000  
67.5000  
70.0000  
72.5000  
75.0000  
77.5000  
80.0000  
82.5000  
85.0000  
87.5000

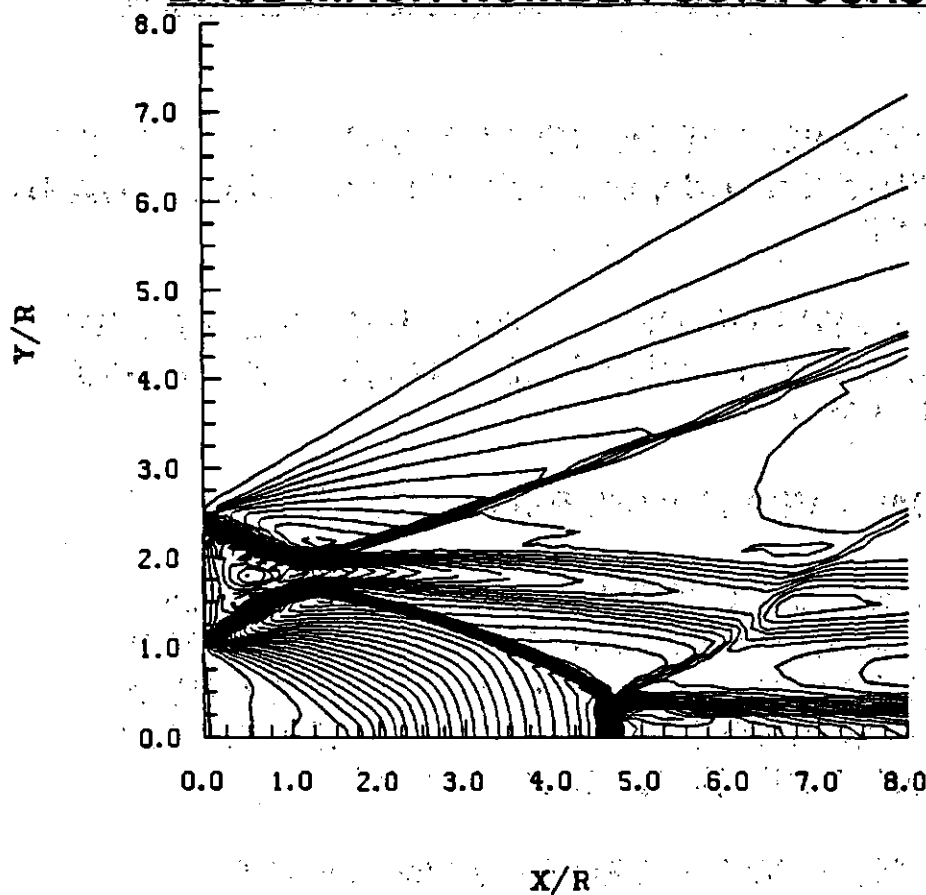




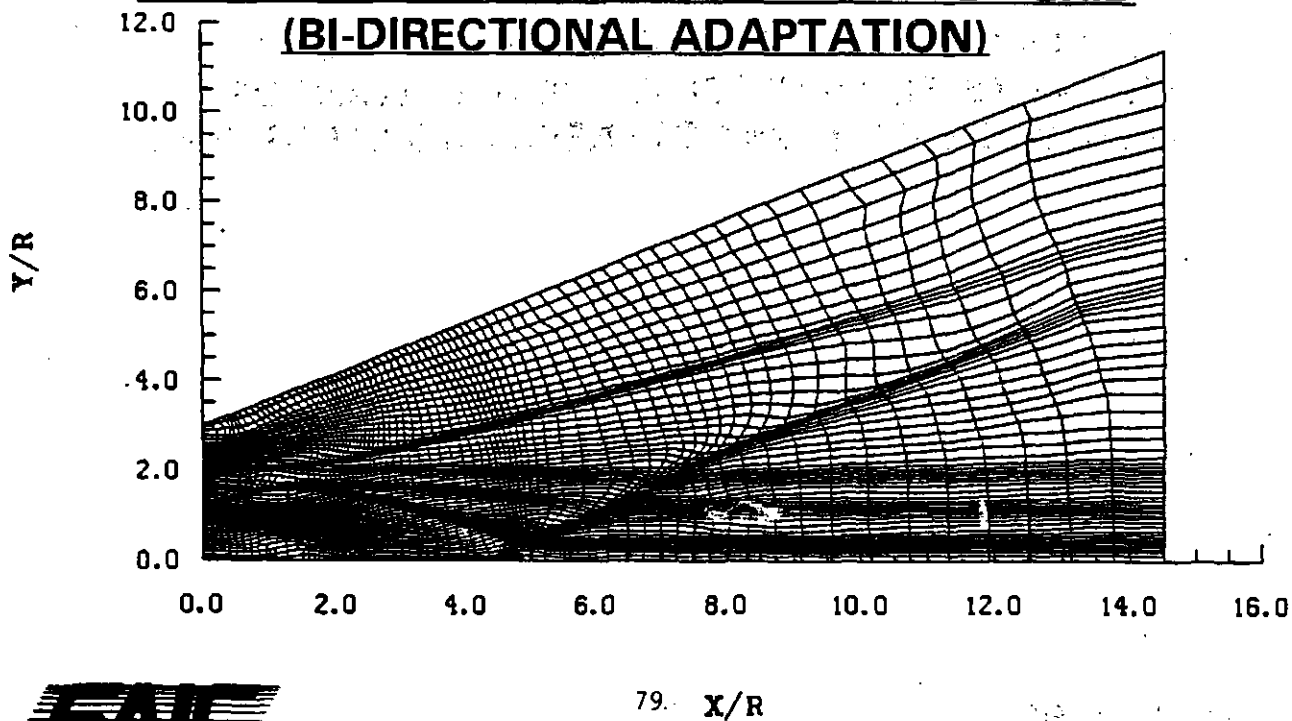
## **SOLUTION ADAPTIVE GRID GENERATION**

- **NASA/AMES RESEARCH CENTER SAGE 2D/3D CODE  
"A Simplified Self-Adaptive Grid Method, SAGE," NASA  
TM-102198.**
- **MODIFIED VERSION OF TECHNIQUE DEVELOPED BY  
Diewert and Nakahashi of NASA/AMES (AIAA PAPER  
85-1525, 1985)**
- **BASED ON VARIATIONAL PRINCIPLES**
- **PROCEDURE ANALOGOUS TO APPLICATION OF  
TENSION AND TORSION SPRING FORCES PROPOR-  
TIONAL TO LOCAL FLOW GRADIENT AND FINDING  
EQUILIBRIUM (REDISTRIBUTED) POSITION OF THE  
RESULTING SYSTEM OF GRID POINTS**
- **USER-DEFINED WEIGHTED COMBINATION OF  
ADAPTION VARIABLES**
- **CURRENTLY SAGE BEING OPTIMIZED FOR ETC  
PROBLEMS TO YIELD "BEST" COMBINATION OF  
ORTHOGONALITY, SMOOTHNESS AND CLUSTERING**

## **REID AND HASTINGS BASE MACH NUMBER CONTOURS**

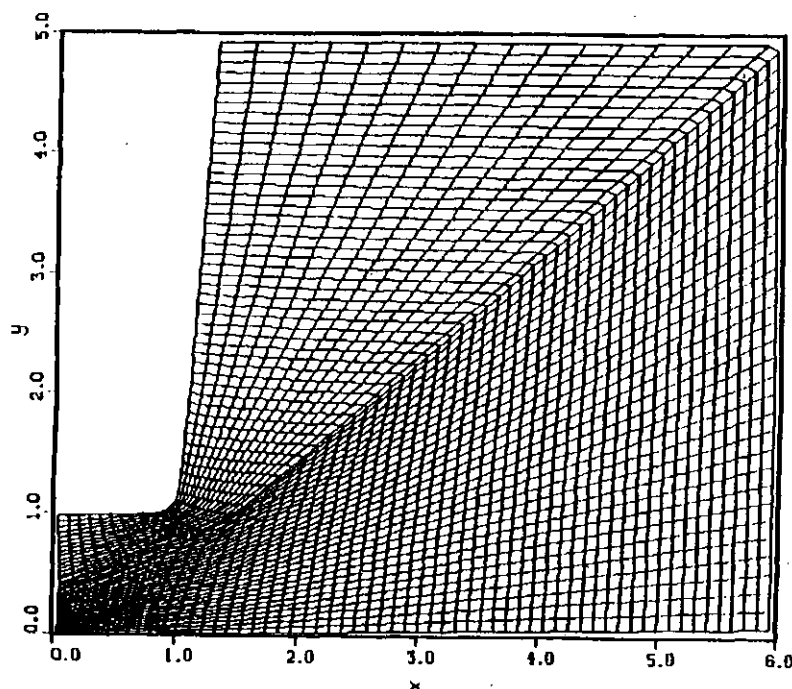


## **BASE FLOW COMPUTATION 145 x 121 GRID (BI-DIRECTIONAL ADAPTATION)**



# TRANSIENT UNDEREXPANDED JET INJECTION INTO MIXING CHAMBER

## INITIAL PRESSURE RATIO = 5

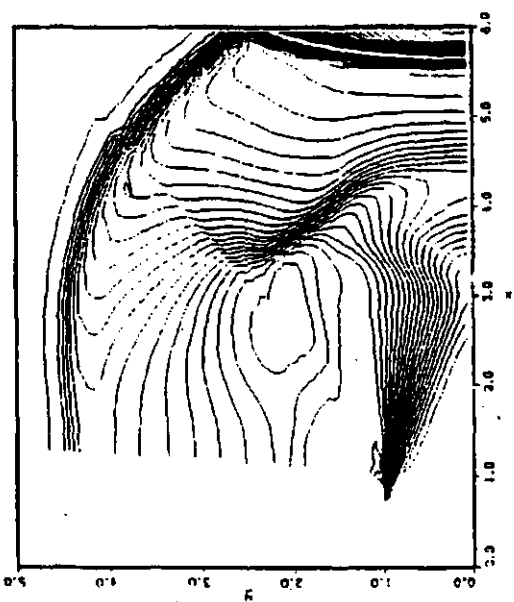


08

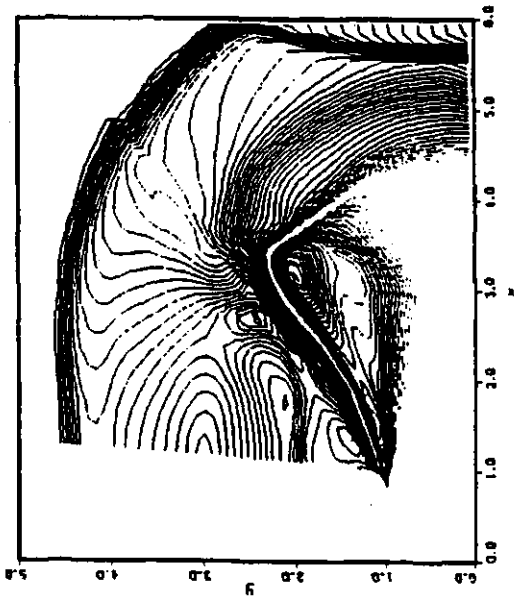


An Employee-Owned Company  
Science Applications International Corporation

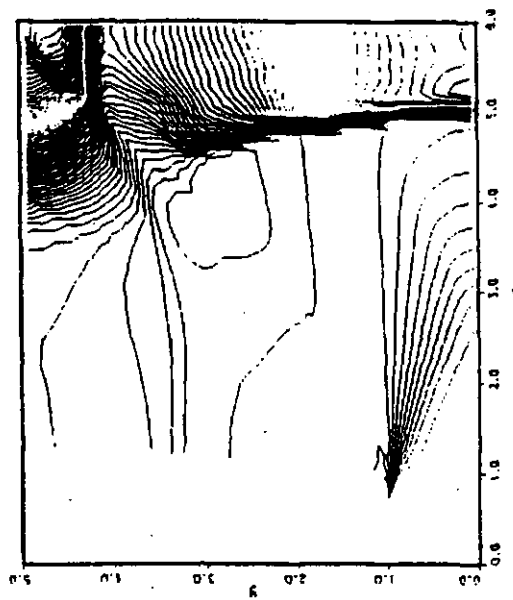




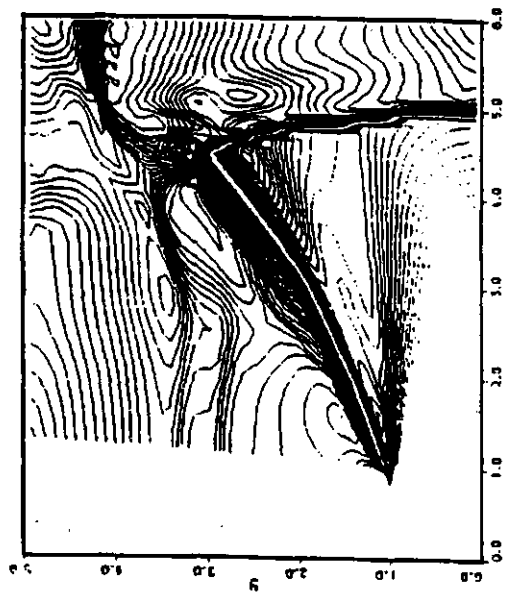
a) Pressure



b) Mach Number

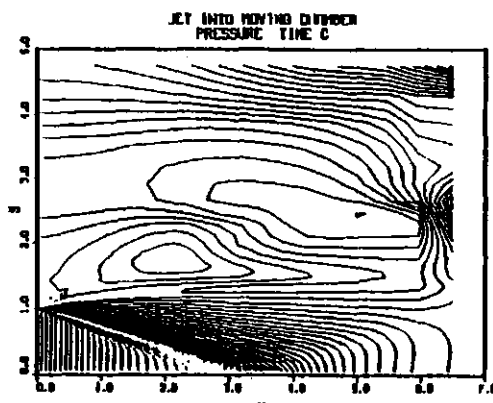
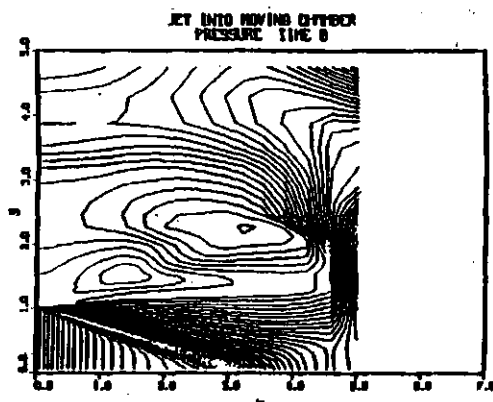
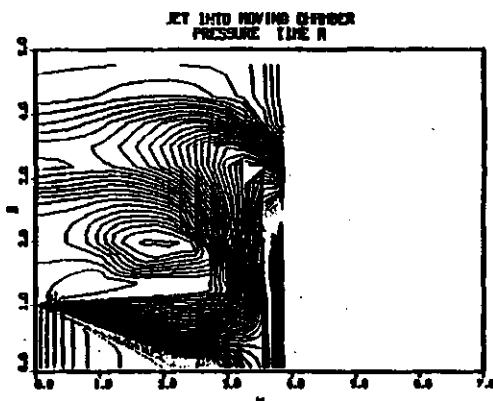


a) Pressure



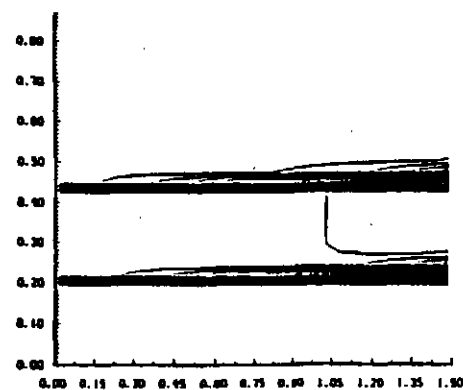
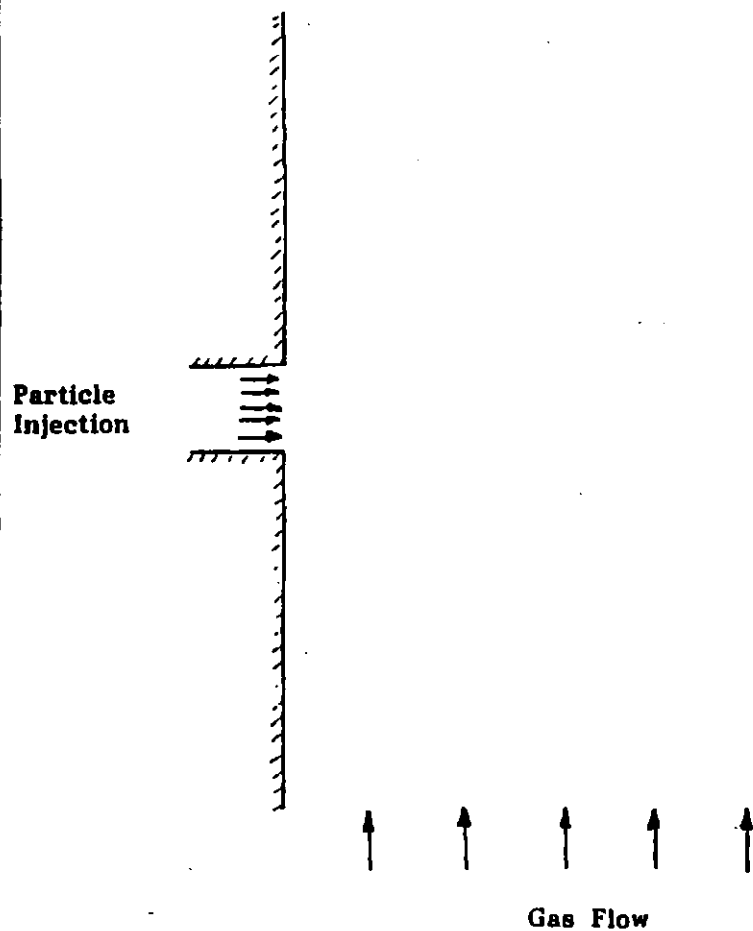
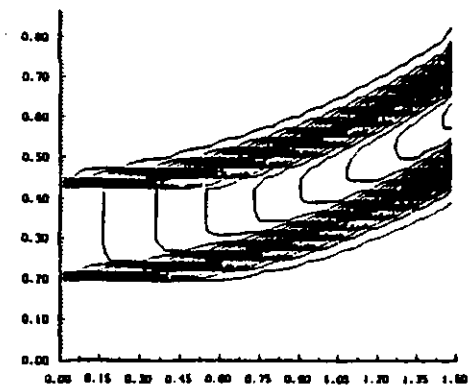
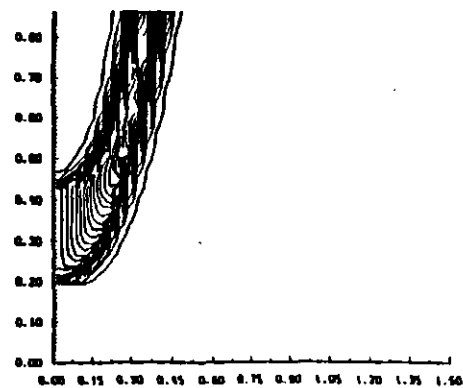
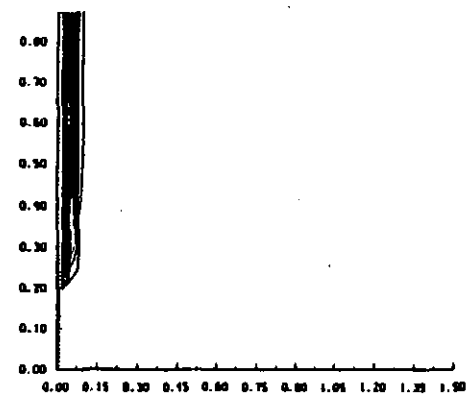
b) Mach Number

# JET INTO CHAMBER WITH MOVING WALLS PRESSURE SNAPSHOTS

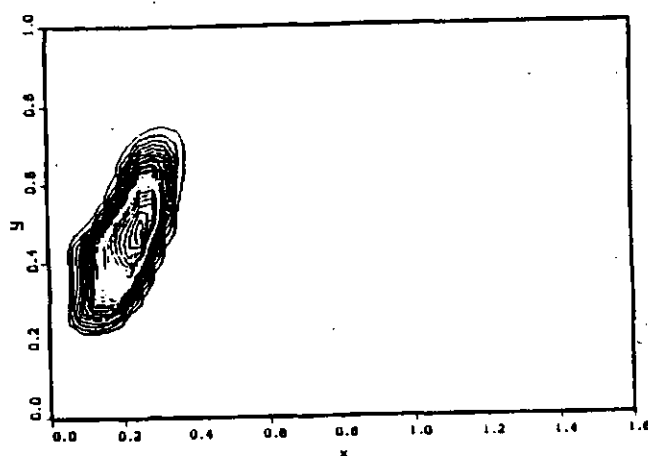


## FEATURES OF THE PARTICLE-CLOUD SOLVER

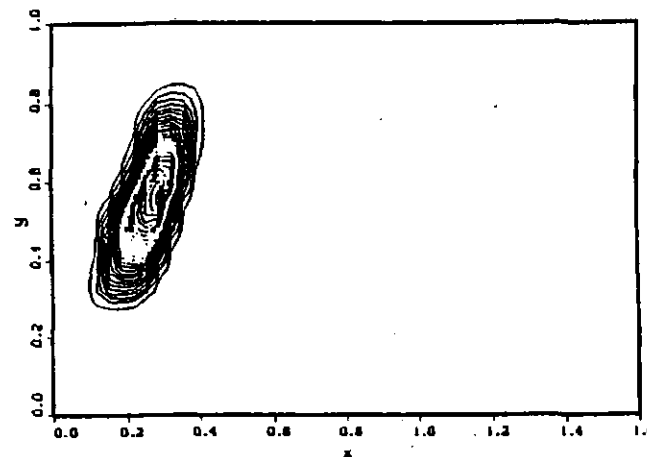
| FEATURES            | PARTICLE CLOUD SOLVER                                                                                                                                                                                                                                                                                                                                                                                                                           |
|---------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| EQUATIONS           | <ul style="list-style-type: none"> <li>• 1D/2D/3D TIME MARCHING PARTICLE-CLOUD EQUATIONS</li> <li>• FULLY COUPLED PARTICLE DENSITY, VELOCITY, AND TEMPERATURE EQUATIONS</li> <li>• DRAG TERMS MODELED FOR NON-EQUILIBRIUM PARTICLE INTERACTIONS</li> <li>• DRAG RELATIONS OF HERMSEN AND HENDERSON AVAILABLE</li> <li>• PHASE CHANGE OF PARTICLES INCORPORATED</li> </ul>                                                                       |
| NUMERICS            | <ul style="list-style-type: none"> <li>• LIMITING PARTICLE STREAMLINE CAPTURED AS A DISCONTINUITY IN THE PARTICLE-CLOUD DENSITY</li> <li>• ROE TVD UPWIND ALGORITHM FULLY CONSISTENT WITH GAS PHASE NUMERICS</li> <li>• IMPLICIT TREATMENT OF PARTICLE SOURCE AND FLUX TERMS</li> <li>• ADI BLOCK INVERSION</li> <li>• TIME ACCURATE/TIME ASYMPTOTIC NUMERICS</li> <li>• NEWTON ITERATION TO REMOVE APPROXIMATE FACTORIZATION ERRORS</li> </ul> |
| BOUNDARY CONDITIONS | <ul style="list-style-type: none"> <li>• WALL WITH PARTICLES STICKING</li> <li>• WALL WITH PARTICLES SLIPPING</li> <li>• INFLOW</li> <li>• OUTFLOW</li> </ul>                                                                                                                                                                                                                                                                                   |

(a) 600 $\mu$ m Case(b) 60 $\mu$ m Case(c) 6 $\mu$ m Case(d) .6 $\mu$ m Case

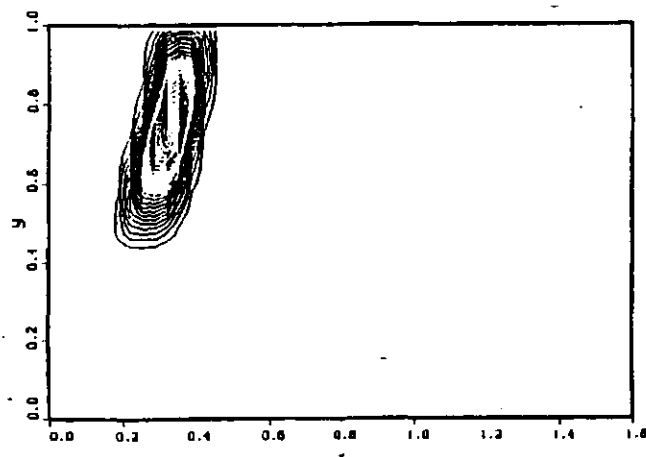
6 $\mu$ m Finite-Duration Transverse Particle  
Injection: Density Contours of Particle  
Packet at Four Time Intervals



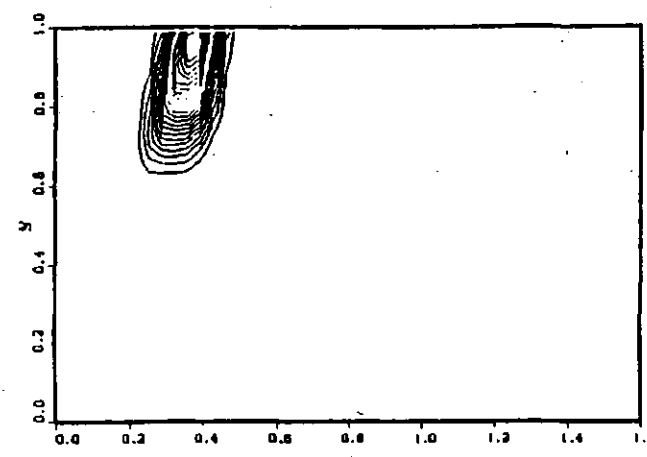
(a)



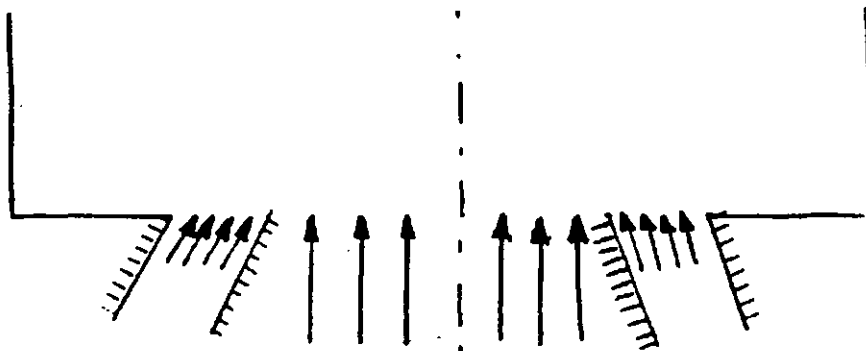
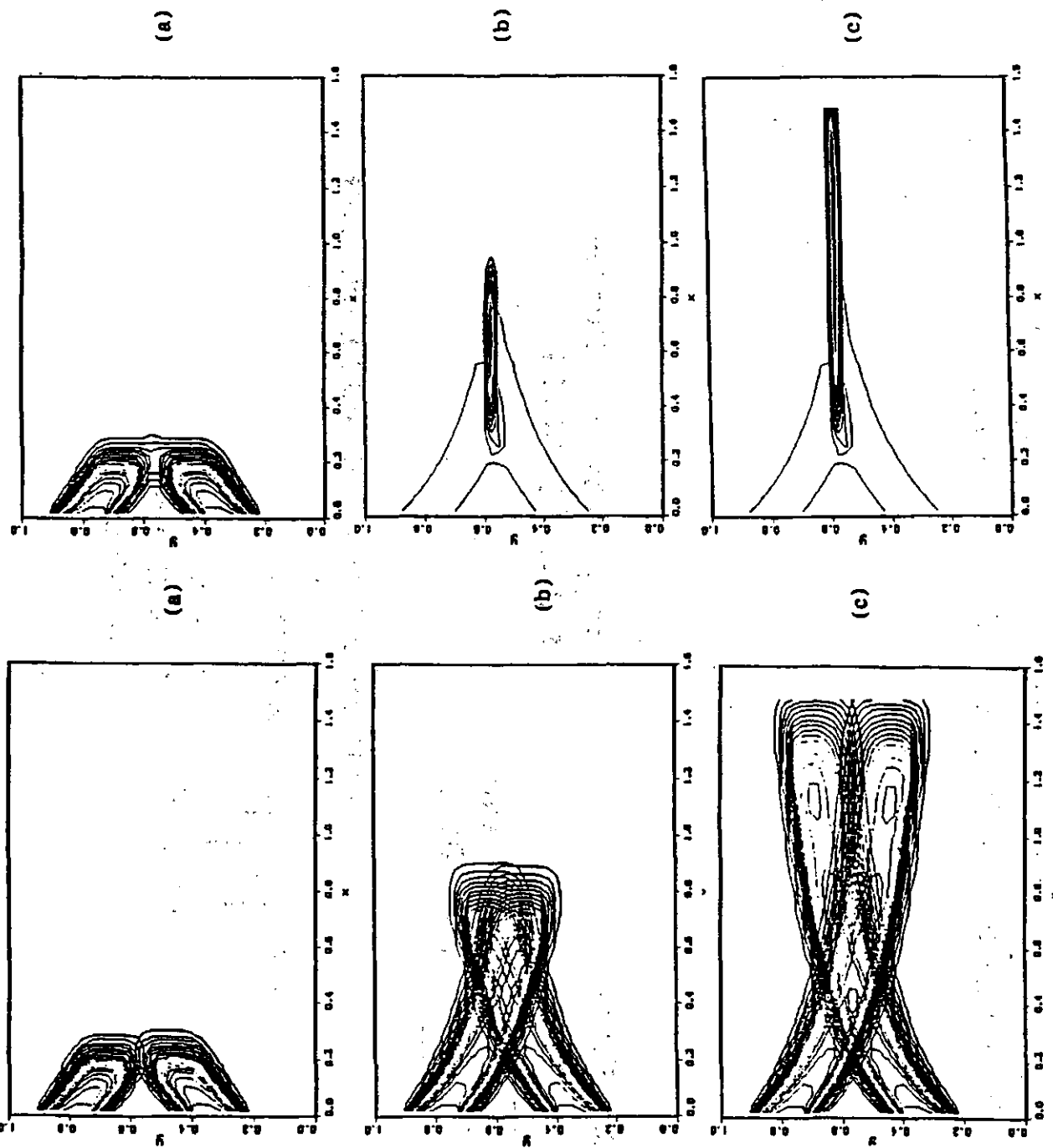
(b)



(c)

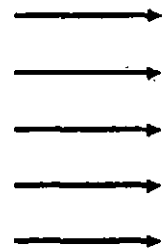


(d)



# MULTI-PHASE PERPENDICULAR JET INJECTION PARAMETRIC VARIATION OF PARTICLE-SIZE

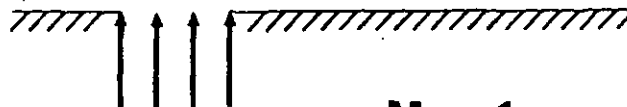
GAS FLOW



$M = 2$   
 $P = 1 \text{ atm}$   
 $T = 500^\circ\text{K}$

50% MASS LOADING OF  
PARTICLES IN JET

$25\mu$ ,  $5\mu$ ,  $2.2\mu$  PARTICLES RESPECTIVELY



GAS/PARTICLE  
INJECTION

$M = 1$   
 $P = 2 \text{ atm}$   
 $T = 1000^\circ\text{K}$

## **BUILDING-BLOCK APPROACH FOR ETC GUN SIMULATION**

### **1. NUMERICAL STUDIES WITH EXISTING VERSION OF CRAFT**

- PLASMA JET-WORKING FLUID INTERACTIONS**
  - : GRID DYNAMICS/ADAPTIVE GRIDDING**
  - : THERMOCHEMICAL EFFECTS**
  - : BL/WALL TEMPERATURES**
  - : INJECTOR EFFECTS/SINGLE vs  
MULTIPLE**
  - : STRONGLY-COUPLED PROJECTILE  
SOLUTION**

### **2. NEAR-TERM UPGRADES**

- COMPLEX EQUATIONS OF STATE → Roe/TVD  
[RESEARCH]**
- VOLUMETRIC EFFECTS/DROPLETS**
- INTERIOR BALLISTIC/CAPILLARY COUPLING**
- DROPLET FORMATION/COMBUSTION**
- RADIATIVE EFFECTS**

### **3. PHENOMENOLOGICAL STUDIES**

- HOMOGENOUS vs NON-HOMOGENOUS  
MIXTURE ASSUMPTIONS**
- COMBUSTION CHEMISTRY-SIMPLIFIED  
vs MULTI-STEP REPRESENTATION**
- MIXING/PENETRATION OF PLASMA JET-  
ke vs LES TURBULENCE MODELING**

•  
•  
•



## **EQUATION OF STATE (EOS) AND CHARACTERISTIC-BASED UPWIND SCHEMES**

- RIEMANN SOLVER (Roe/TVD, Godunov, etc.)  
ORIGINALLY FORMULATED FOR IDEAL GAS DYNAMICS
- MORE RECENTLY, ADVANCES FOR MULTI-COMPONENT, REAL GAS FLOWS WITH CHEMICAL NONEQUILIBRIUM (Vinokur, Liu – 1988-89)
- ETC FLOWFIELDS CHARACTERIZED BY VERY COMPLEX EOS WITH COMPLICATED CONSTITUTIVE MODELING, PHASE CHANGES, etc. (NON-CONVEX EOS)
  - EXACT RIEMANN SOLUTION ENTAILS PROHIBITIVE COSTS FOR LARGE-SCALE COMPUTATIONS
  - RECENTLY, EFFICIENT ALTERNATIVE RIEMANN SOLVERS FORMULATED WHICH COMPARE FAVORABLY WITH MORE RIGOROUS GODUNOV SCHEME

### **GODUNOV BASED RIEMANN SOLVER**

Collins, P. and Glaz, H.M., "Efficient Solution Algorithms for the Riemann Problem for Real Gases," *J. Computat. Physics*, 59 (1985), pp. 264-298.

### **ALTERNATIVE RIEMANN SOLVERS**

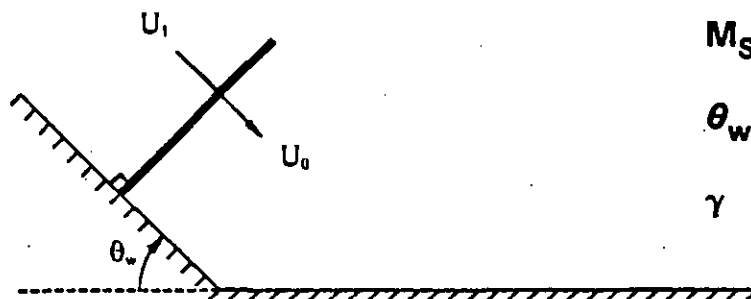
Bell, J.B., Colella, P. and Trangenstein, J.A., "Higher-Order Godunov Methods for General Systems of Hyperbolic Conservation Laws," *J. Computat. Physics*, 82 (1989), pp. 362-397.

Davis, S.F., "Simplified Second-Order Godunov Type Methods," *SIAM J. Sci. Statist. Comput.*, 9 (1988) pp. 445-473.

Harten, A. Lax, P.D., and van-Leer, B., "On Upstream Differencing and Godunov-type Schemes for Hyperbolic Conservation Laws, *SIAM, Rev.*, 25 (1983) pp. 35-61.

# FLOW STRUCTURE / EOS

## OBLIQUE SELF-SIMILAR SHOCK REFLECTION

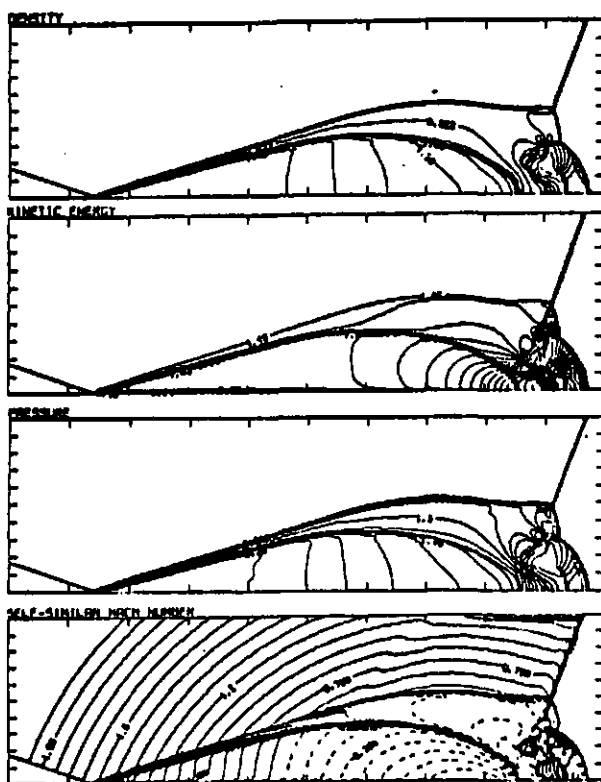


$$M_S = 5.7$$

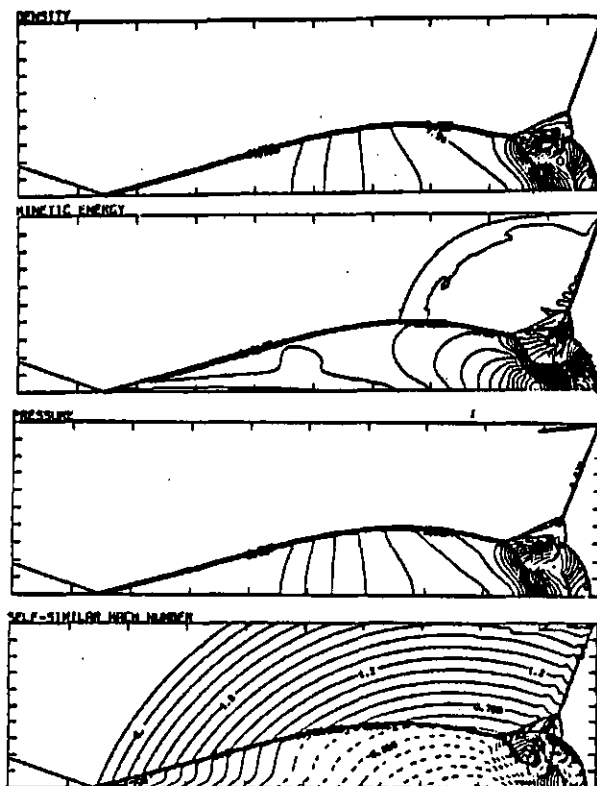
$$\theta_w = 20^\circ$$

$$\gamma = 1.4$$

Figure 1. Schematic diagram for flowfield initialization.



(a)



(b)

### NON-CONVEX EOS

#### MODIFIED POLYTROPIC

$$\rho = V^{-\gamma} + f(v)$$

(PHASE CHANGE)

### CONVEX EOS

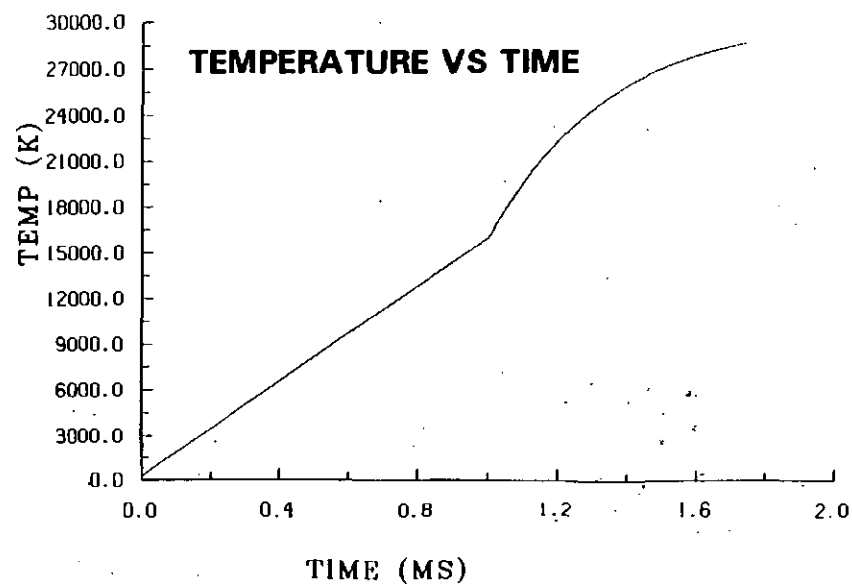
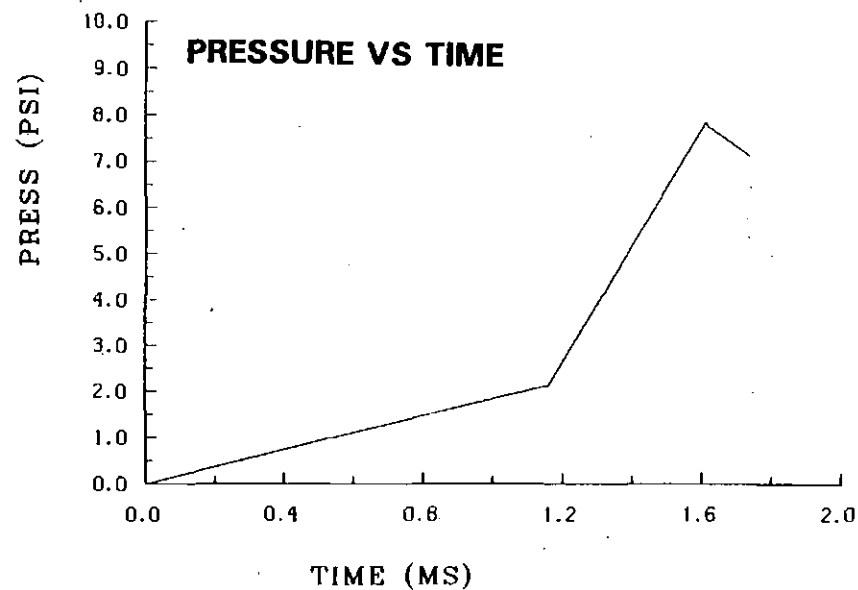
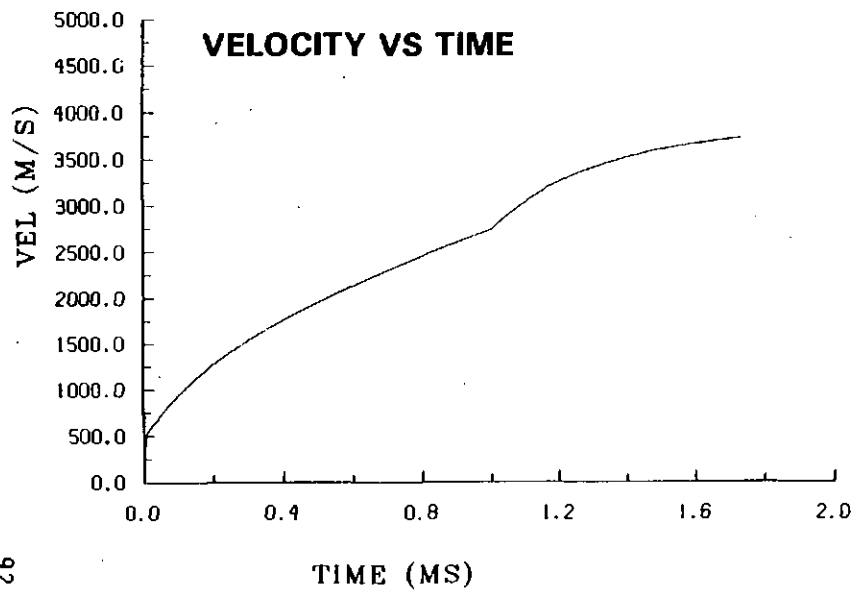
#### POLYTROPIC

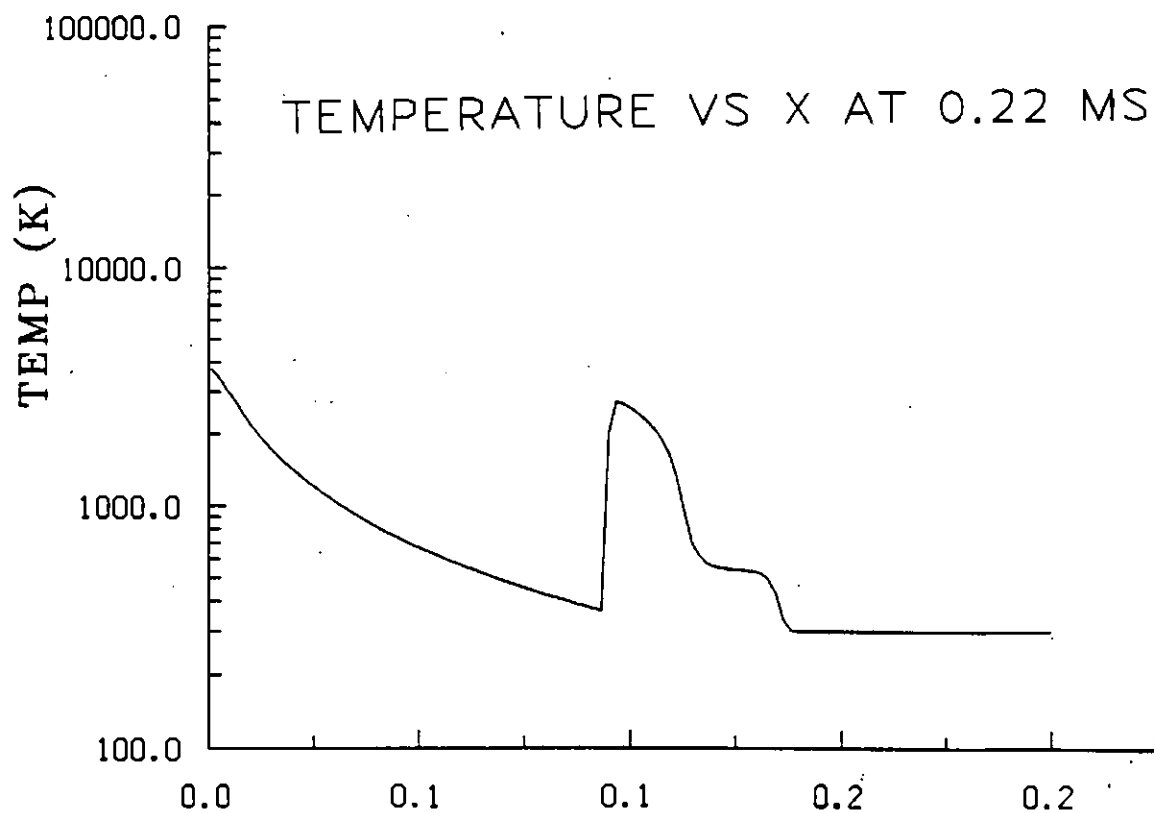
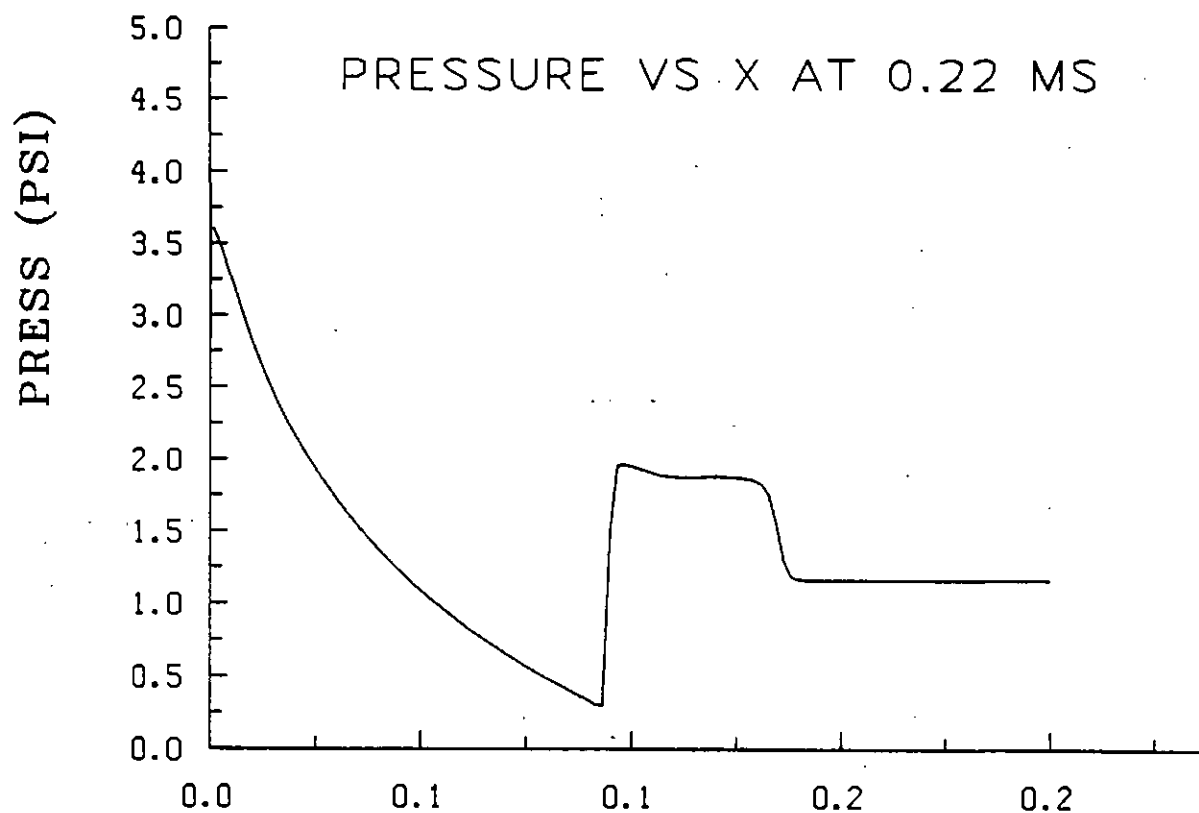
$$\rho = V^{-\gamma}$$

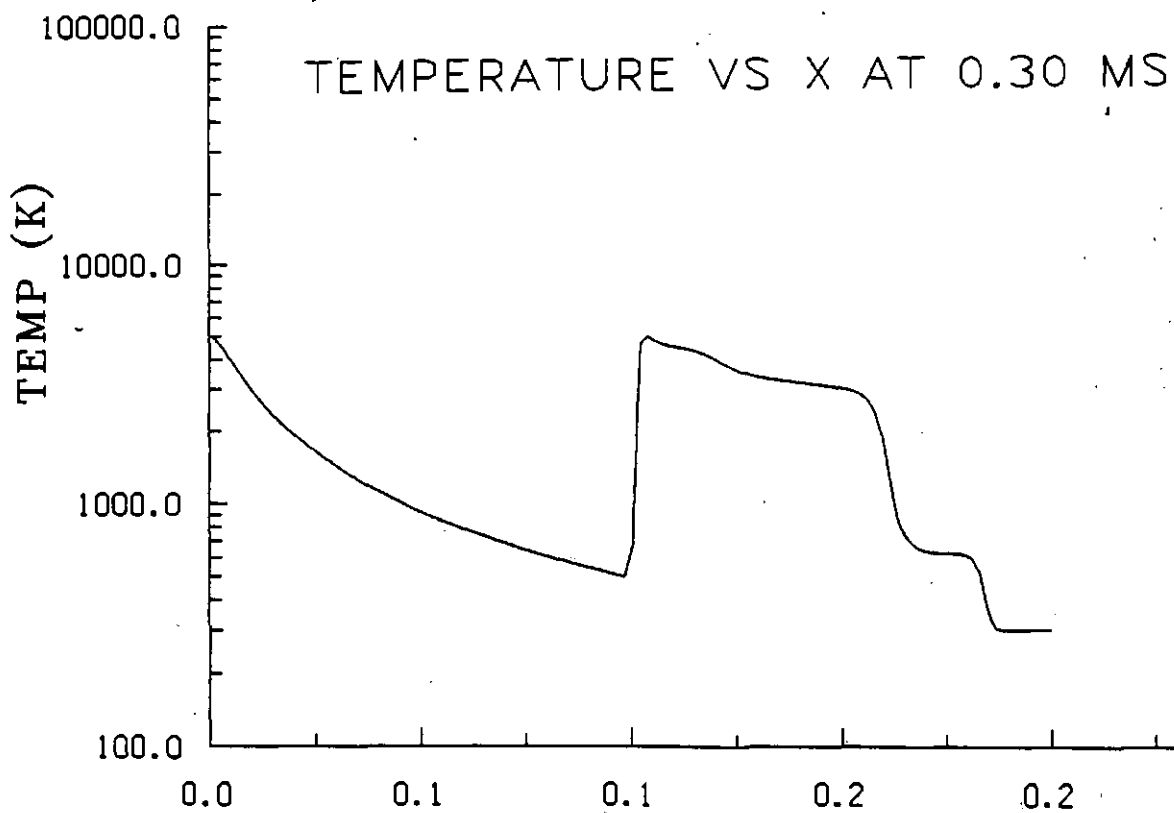
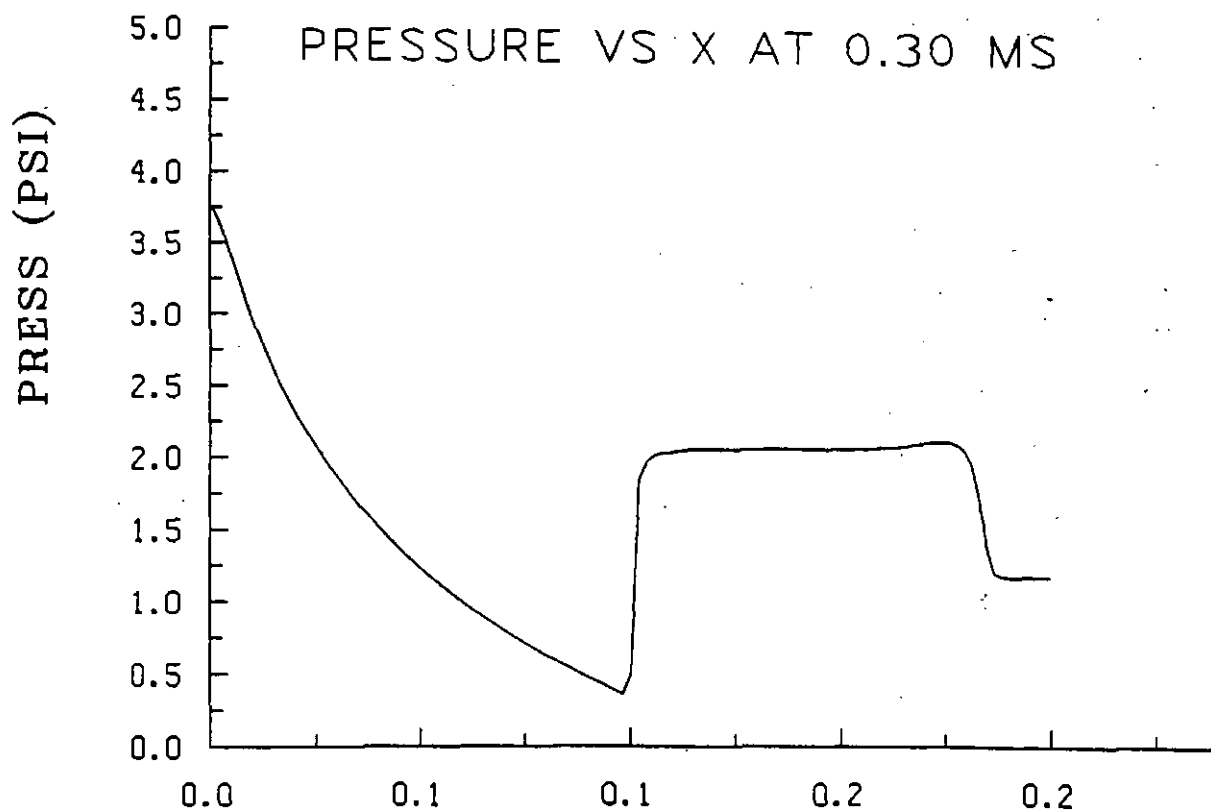
## **2D Greenfarm Simulation**

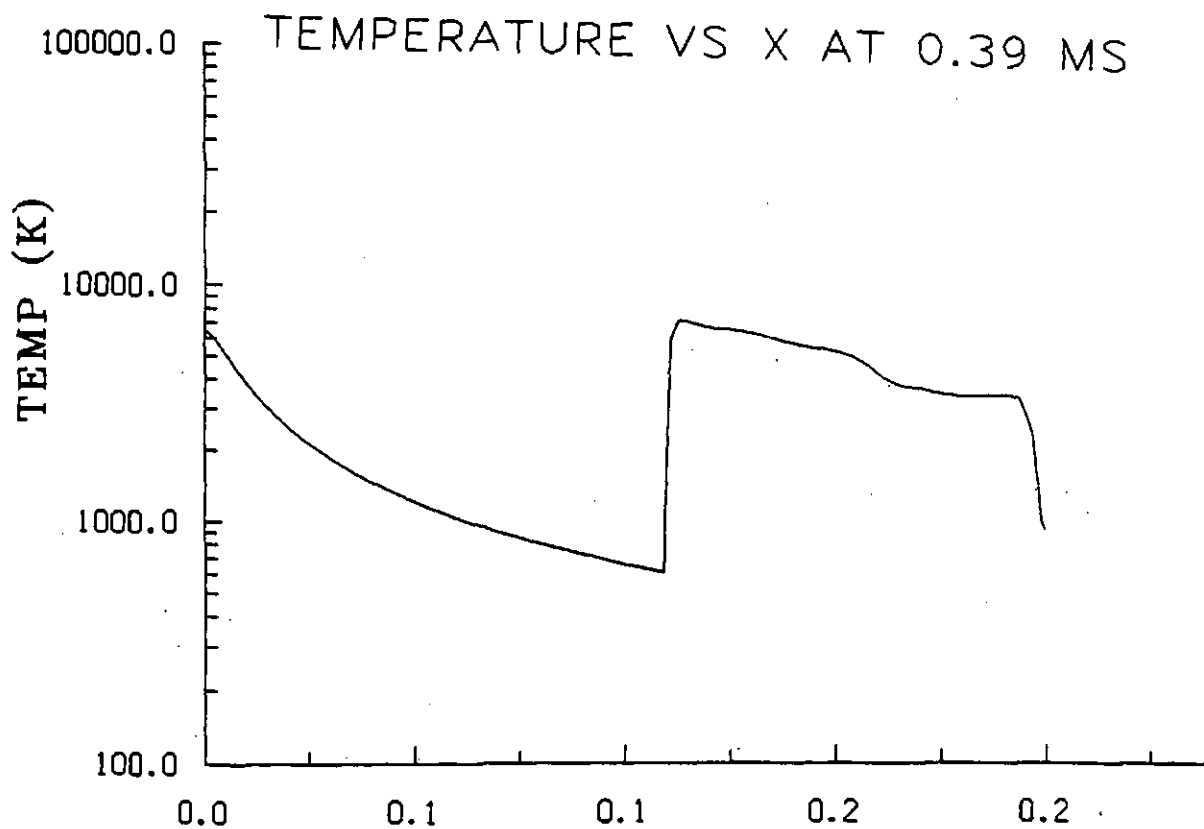
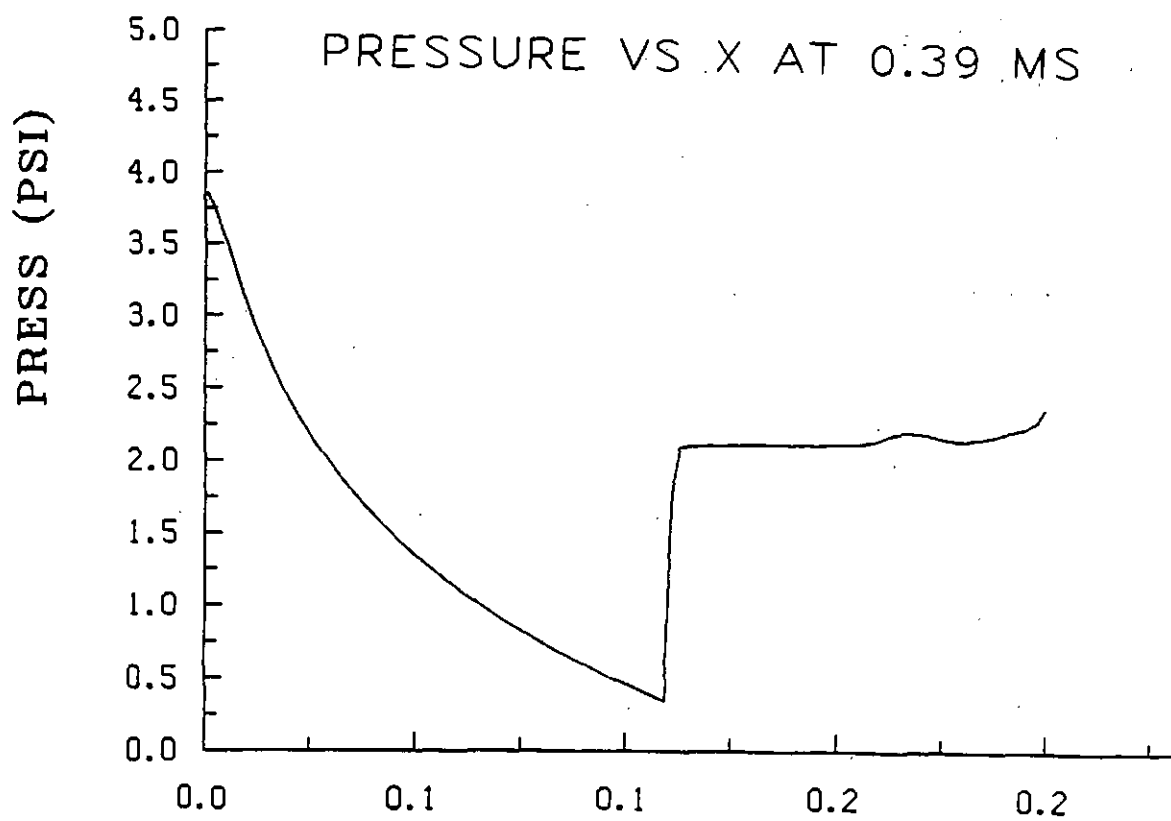
- **120mm**
- **Experimental data exhibits pressure waves**

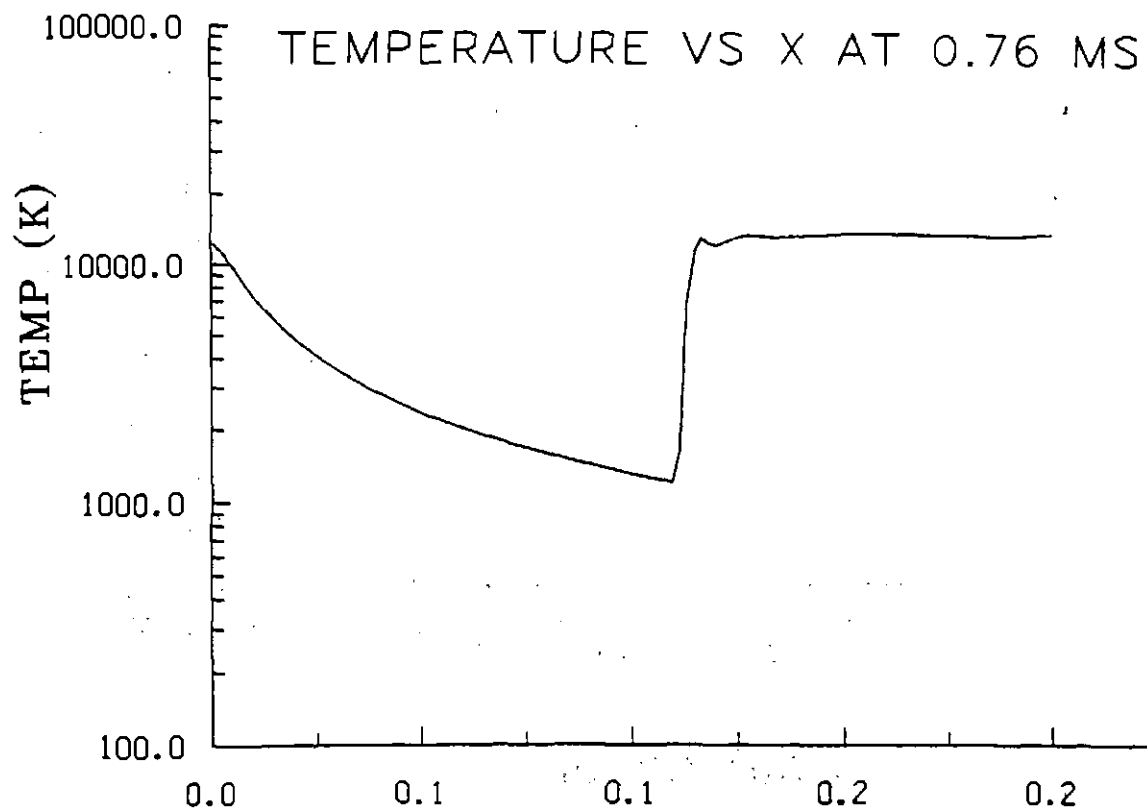
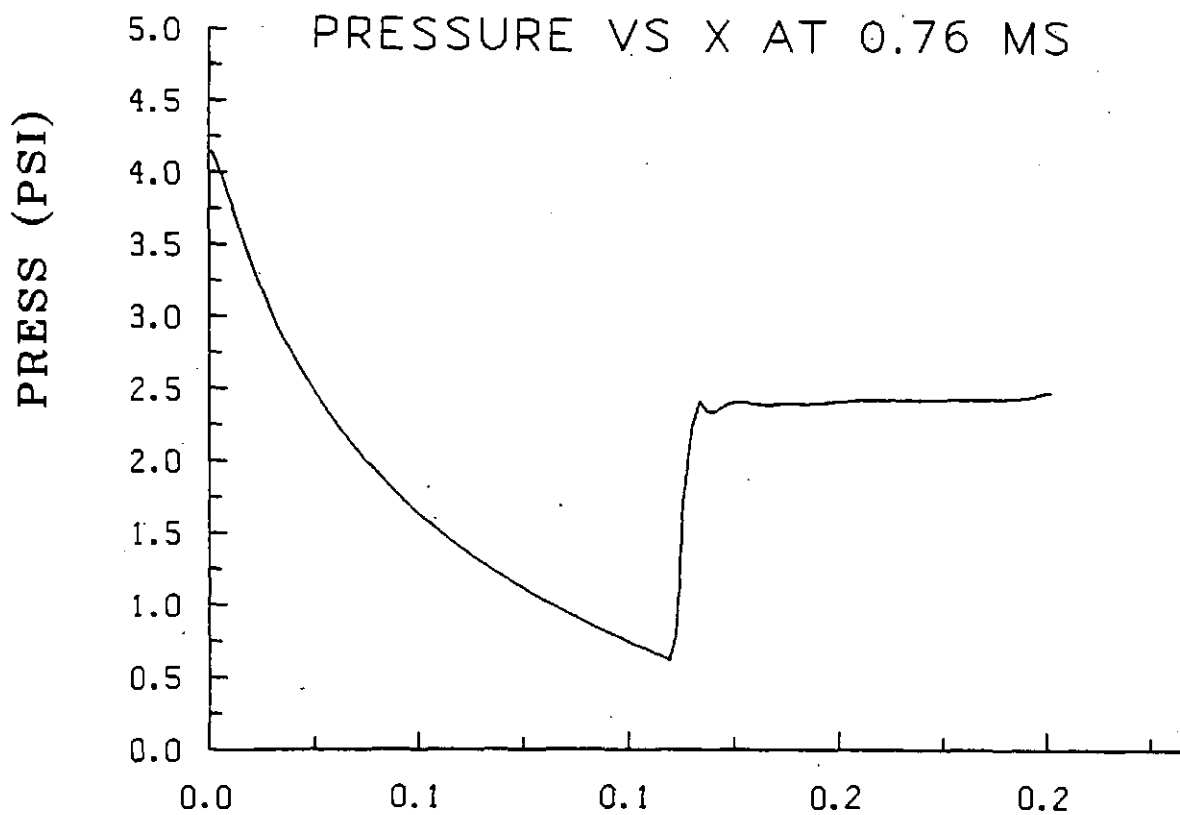
## INFLOW FOR GREEN FARM SIMULATION





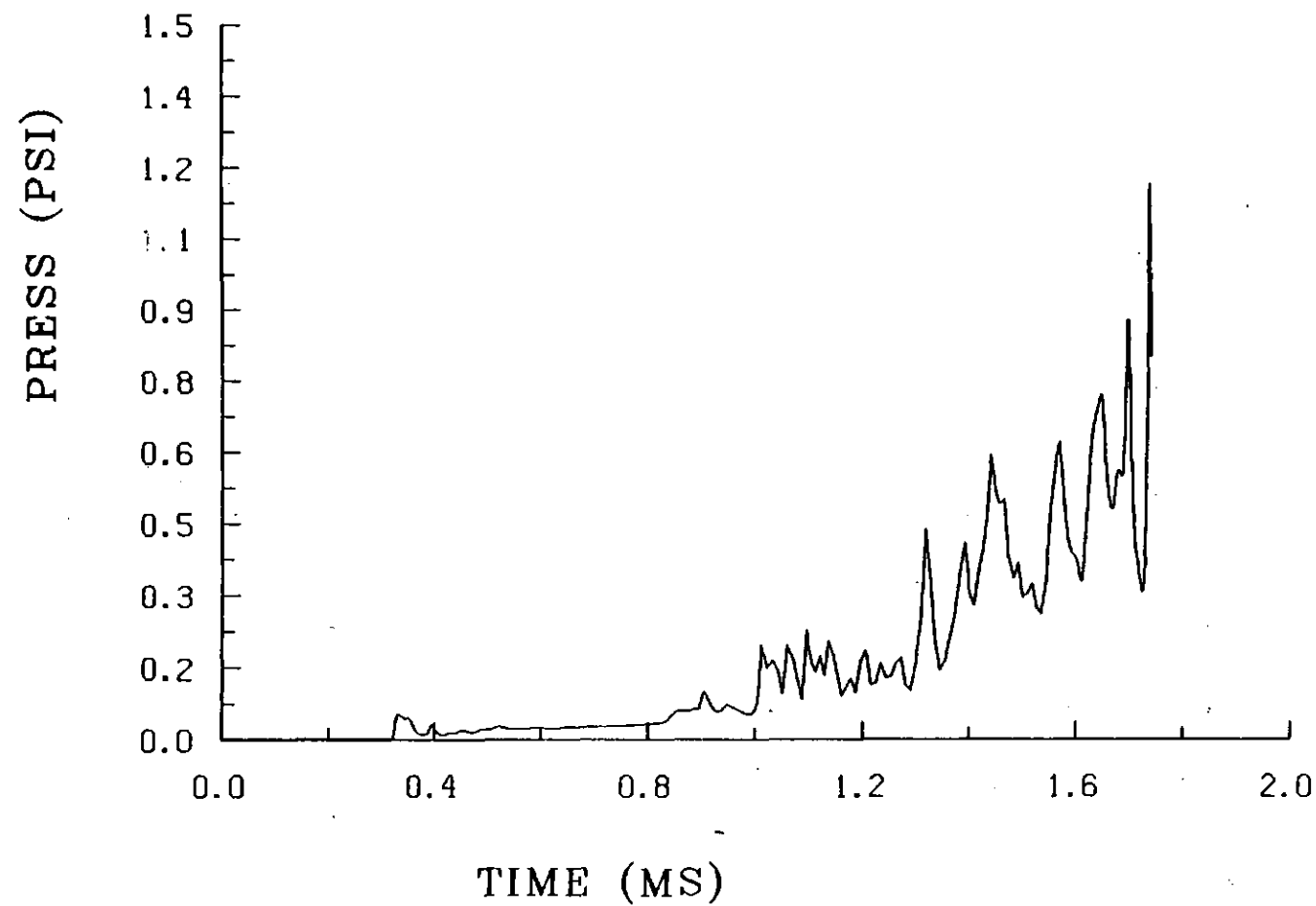


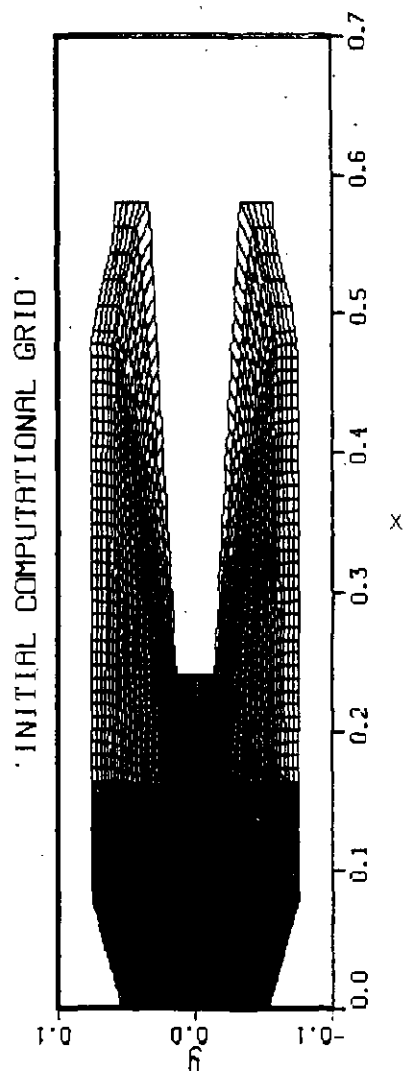






# BASE PRESSURE VS TIME





## **2D Greenfarm Simulation**

- **Model provides excellent resolution**
- **Dynamic gridding & moving projectile**
- **Pressure waves interact with geometry**
- **Complicated flow structure**

# Summary

- **CRAFT applicable to ETC flows**
  - **state-of- the-art numerics**
  - **synergistic with other DoD & NASA efforts**
  - **emphasis on first-principles model**
  - **core model for submodules developed by DoD & DOE labs, university, contractors**
- **Preliminary application to Greenfarm data**
  - **excellent resolution of flow structure**
  - **geometric effects evident**
  - **pressure waves observed**
- **Building-block approach**
  - **plasma-working fluid interaction**
  - **liquid EOS**

## RECENT ADVANCES IN CAP<sub>tm</sub> GUN MODELING

Dave Cook and Jahn Dyvik  
FMC Corporation  
Minneapolis, MN 55421-1498

### ABSTRACT

The FMC Corporation is continuing the effort to develop and adapt ETC interior ballistics models to reflect experimental performance of present gun designs. A new version of a 2-D interior ballistics code with an empirical combustion model has been applied to recently obtained 30-mm data. FMC is also testing alternative propellants in the 30-mm gun, and efforts to describe their thermochemistry and ballistic performance will be discussed.

FMC is currently firing 60-mm ETC guns under contracts to the Navy and DNA, as well as under IR&D. These efforts are testing a number of new cartridge designs. A modeling effort has recently been completed which describes two of these new designs using a variable area, 1-D interior ballistics code. This code contains the same gas generation model as the 2-D code, but includes additional features such as a flexible computational domain and an empirical reaction kinetics model. When these new computational algorithms mature, and cartridge designs are decided, the new 1-D features will be incorporated into the 2-D code.



# ***Recent Advances in CAP<sub>tm</sub> Gun Modeling***

102

***Dave Cook  
Jahn Dyvik***



## ***Overview***

- **Status of 2-D Modeling at FMC**
- **1-D Interior Ballistics Code Development**
- **Recent 1-D Applications at 60-mm**
- **Impact of 1-D Calculations on Future 2-D Work**



## ***Status of 2-D Modeling at FMC***

- The 2-D model of the CAP<sub>tm</sub> process contains three coupled sub-models, a PFN routine, a plasma injector routine, and a 2-D interior ballistics code which solves the viscous Navier-Stokes equations.
- The first version of this code was validated using mostly large caliber data. Recently, the numerics have been changed to a donor cell approach and an artificial diffusion model has been added.
- This new version has been compared to 30-mm ballistics data. Agreement is good, however, some of the details in calculated pressure traces indicate a more complex combustion model is necessary.





## ***Empirical Combustion Model***

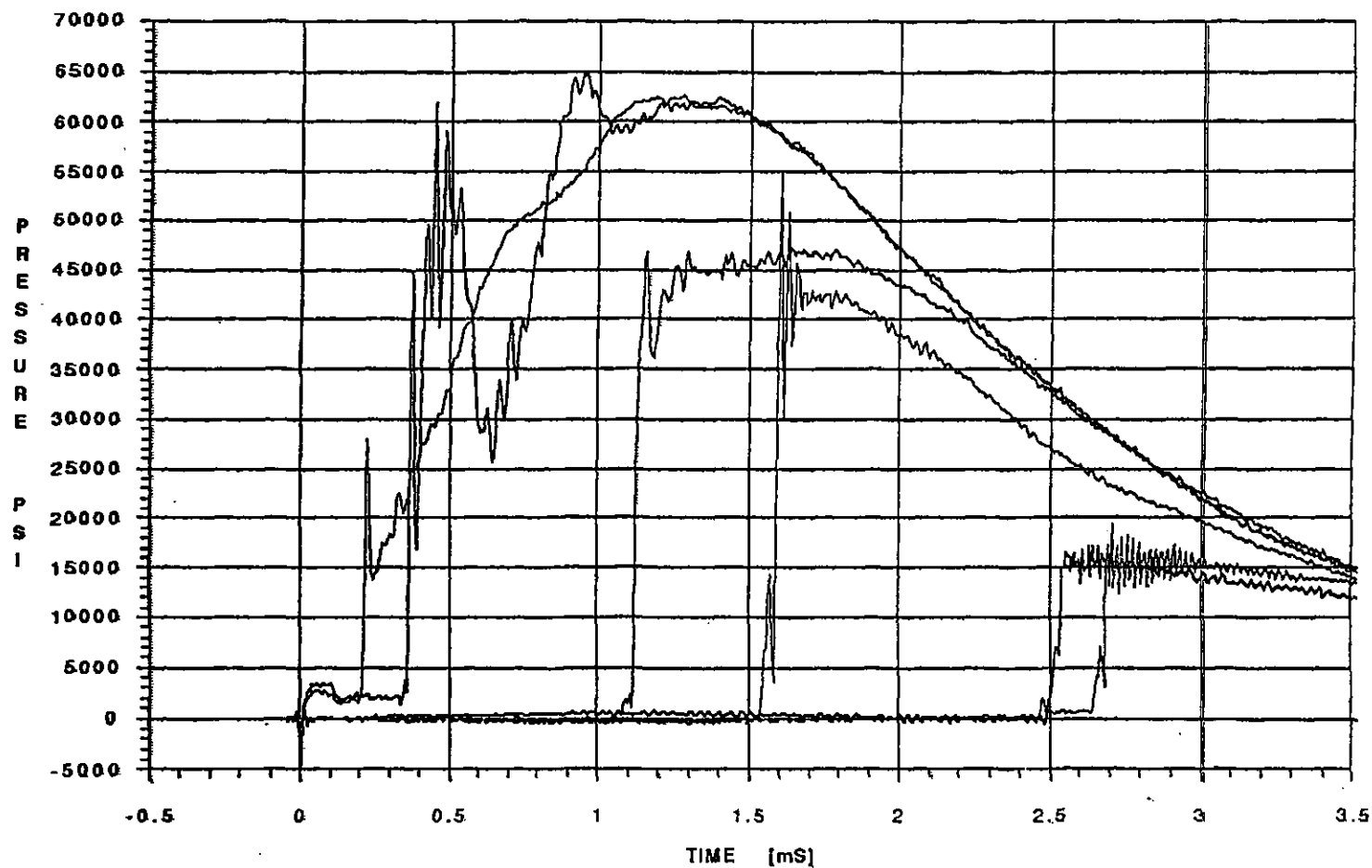
- **Three functions are used to describe the energy released from propellant combustion. They are:**
  - 1) **the gas generation rate throughout the chamber, i.e. the "global" rate function,**
  - 2) **the spatial distribution of the gas generation rate, and**
  - 3) **An Arrhenius equation for the gas phase reaction rate**
- **The "global" rate function contains two parameters. They describe the distribution centroid and width. These are the most critical parameters and must be chosen by considering electrical input, propellant properties, projectile mass, etc.**
- **The spatial distribution function is calculated by considering the normalized product of two densities. The product function of gas and liquid density is likely to be a maximum near the gas-liquid interface. It may be reasonable to assume the spatial maximum of the gas generation rate is near this interface. Two exponential parameters are used to shift the product maximum if desired.**



FMC

# DNA / SAIC ETC PROGRAM

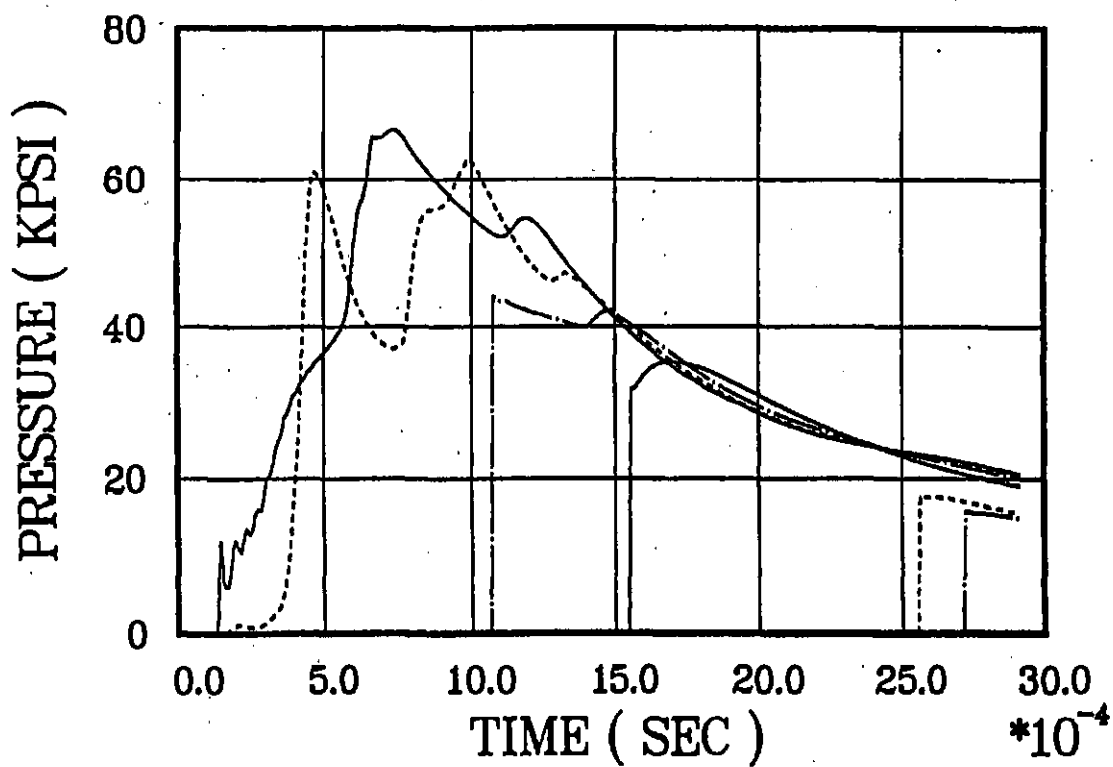
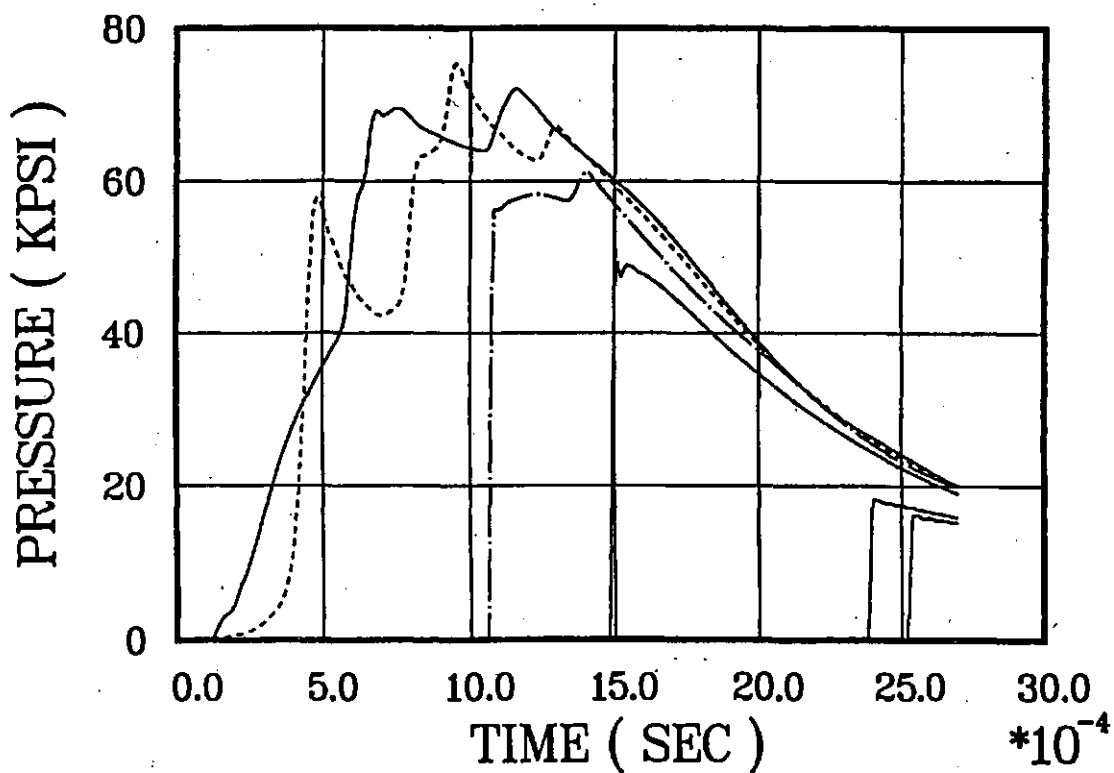
30-mm DNA SHOT 2





FMC

### 30-mm 2-D CALCULATIONS





## ***Thermochemistry***

- **2-D 30mm and 1-D 60mm calculations have been performed using peroxide/hydrocarbons as a propellant.**
- **FMC is currently testing propellants other than peroxide/hydrocarbons with superior properties for weaponization. Tests include propellants consisting of HAN/hydrocarbons. Thermochemical properties have been determined using Blake.**
- **Thermochemical studies using Blake are being performed to characterize other advanced propellant concepts as well.**



## ***Motivation for 1-D Code Development***

- **FMC employs workstations at remote testing sites, where real time execution of models is an issue. 1-D calculations often give adequate representation of routine ballistic measurements in a fraction of 2-D execution time.**
- **Relative simplicity of 1-D codes allows impact of cartridge design details on ballistic performance to be estimated rapidly. A generalized 2-D computational domain requires much greater effort.**
- **Theoretical sub-models can be tested quickly within a 1-D environment. Generalization from lower to higher dimensionality is often easier than starting from scratch.**



## ***Formulation of 1-D Models***

- **The 1-D models are collections of subroutines that describe the PFN, plasma injector, and the reacting flow. They solve 1-D Euler equations with artificial diffusion.**
- **A donor cell method is used. A constant number of cells of equal thickness expand to allow for projectile motion.**
- **The cell volume and face area are design dependent. Cartridge features, such as chamberage, can be introduced by spatial dependence of cell volume and face area. As the grid expands, new areas and volumes are calculated.**
- **Source terms in the Euler equations are also design dependent.**

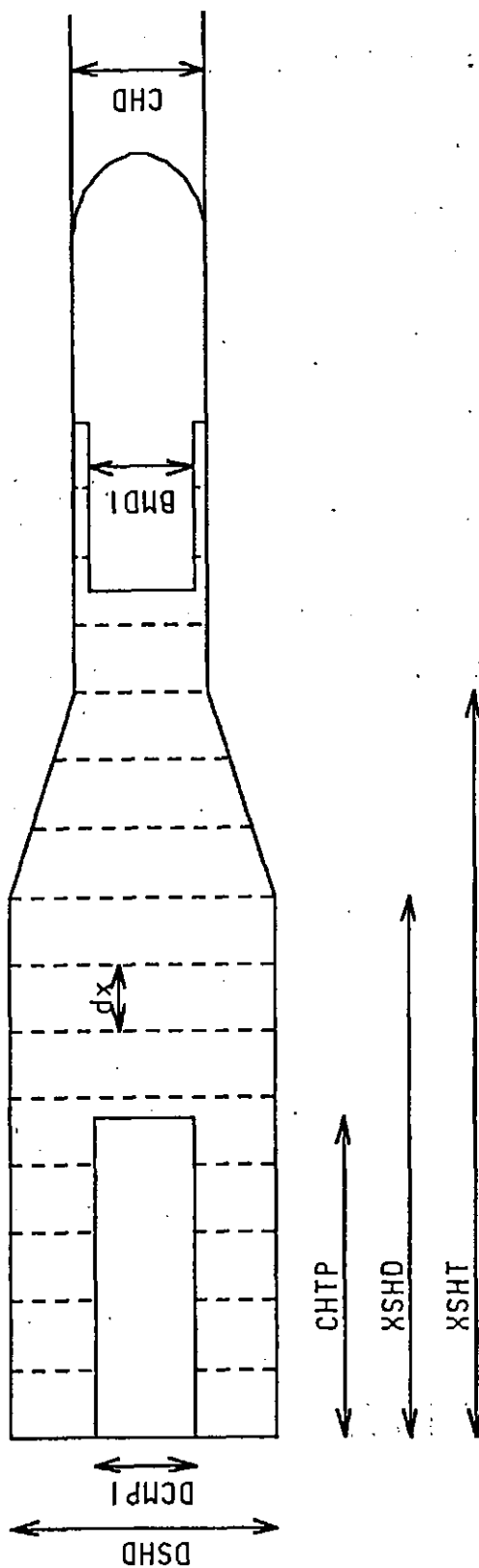


## ***1-D Model Setup - Navy 60-mm Cartridge Design A***

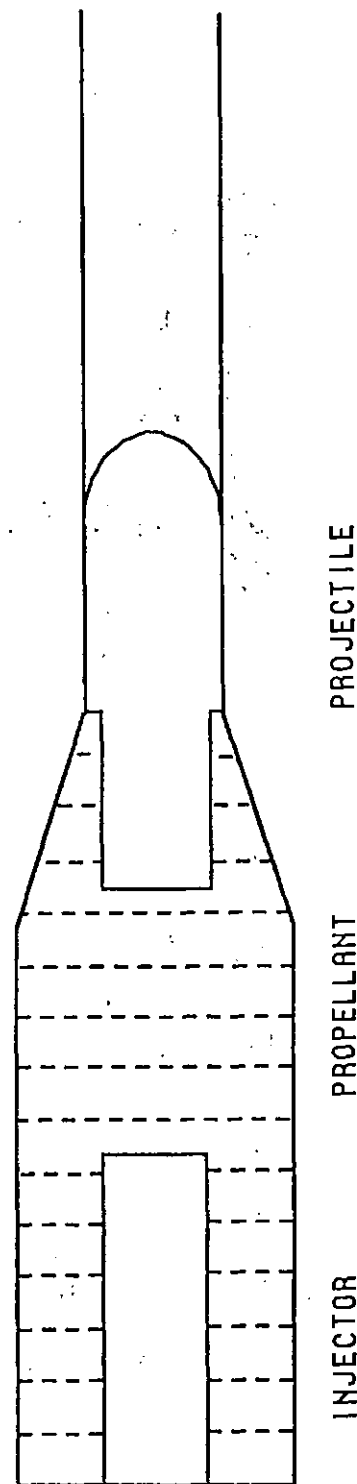
The area & volume of each computational cell has been independently calculated to reflect the following design features:

- The injector flow is introduced into the interior of the computational domain; flow is in the reverse direction. The empirical propellant - plasma model has been changed to account for this.
- The domain was changed to describe the shape of the projectile tail. Algorithms for computation of the base pressure and work performed were also changed. Artificial diffusion was added to smooth the abrupt change in area at the projectile tail interface.

# DESIGN A - 1D FLEXIBLE GEOMETRY



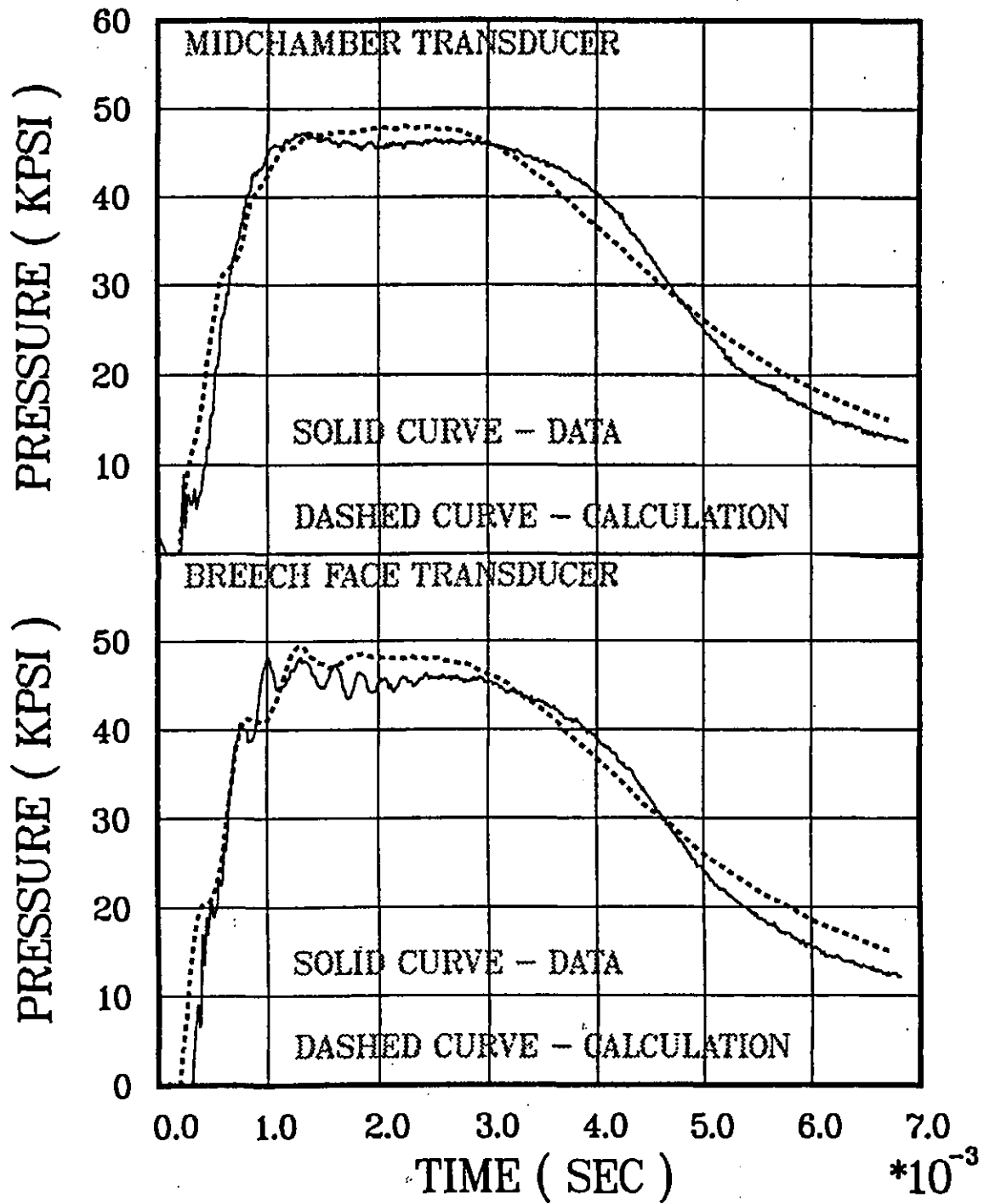
## INITIAL CONFIGURATION







# NAVY 60-mm SHOT #46



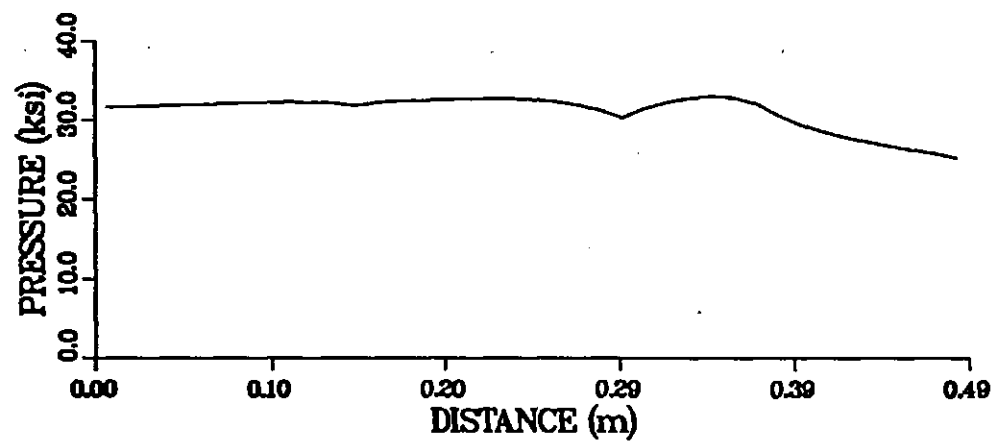
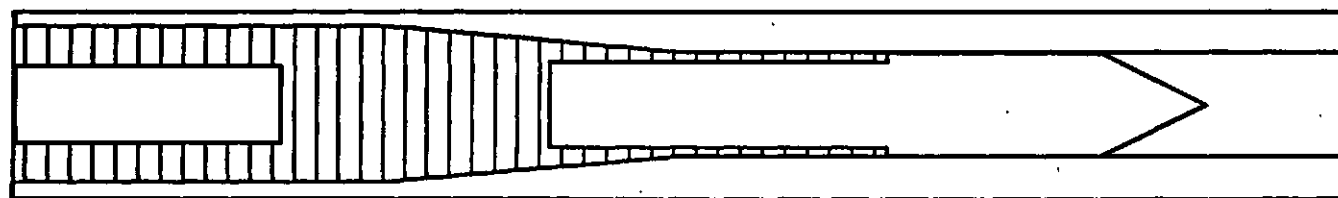


FMC

## CAP 1-D PRESSURE DISTRIBUTION

TIME = 1.65ms

TRAVEL = 11.61cm



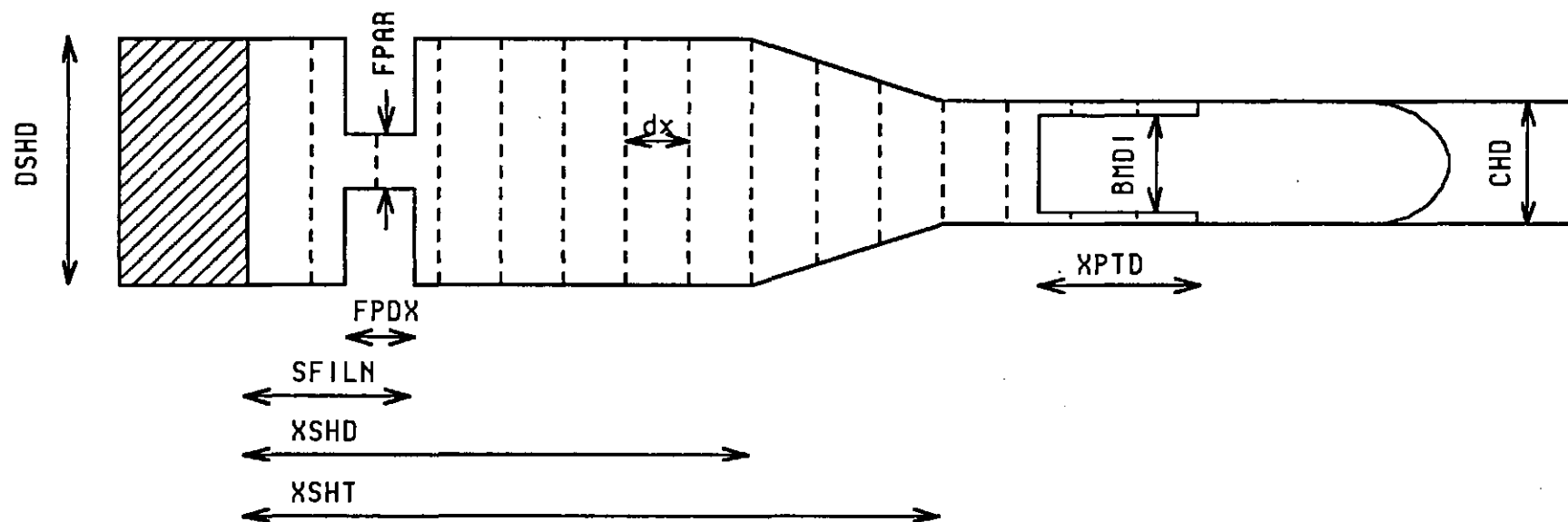


## ***1-D Model Setup - DNA 60-mm SFI Design***

**The following adaptations have been made to the baseline algorithms:**

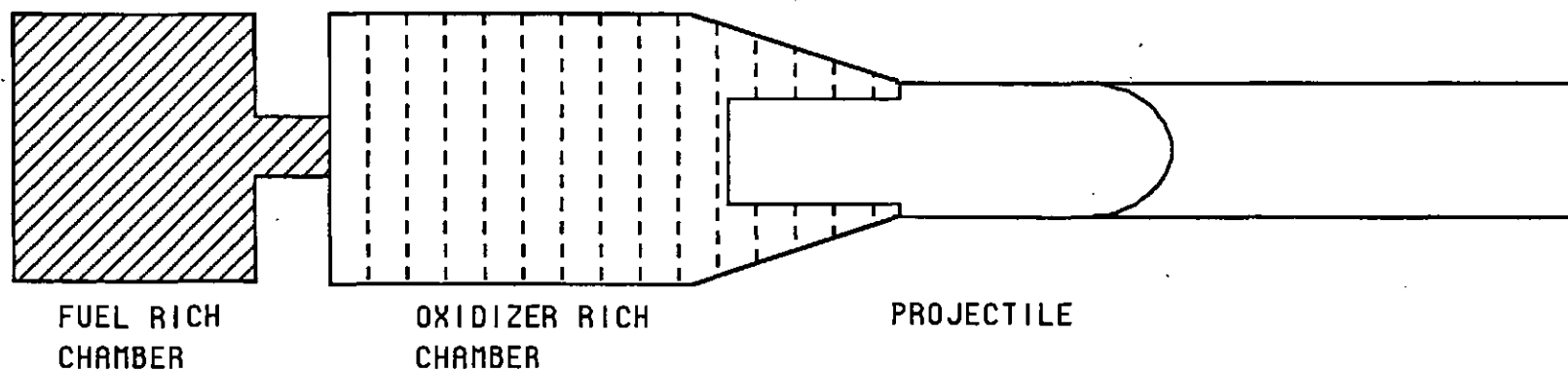
- **The grid extends only from the area forward of the fuel rich propellant to the rear of the projectile. A regression velocity for the fuel rich propellant surface is calculated so that the injector volume is added to the domain.**
- **The resistance of the injector is modeled by adjusting the geometry of a cylindrical volume to match experimental results. Mass flow from a polyethylene tube. The mass flow is assumed to be largely fluid, not gas.**

# SFI - 1D FLEXIBLE GEOMETRY



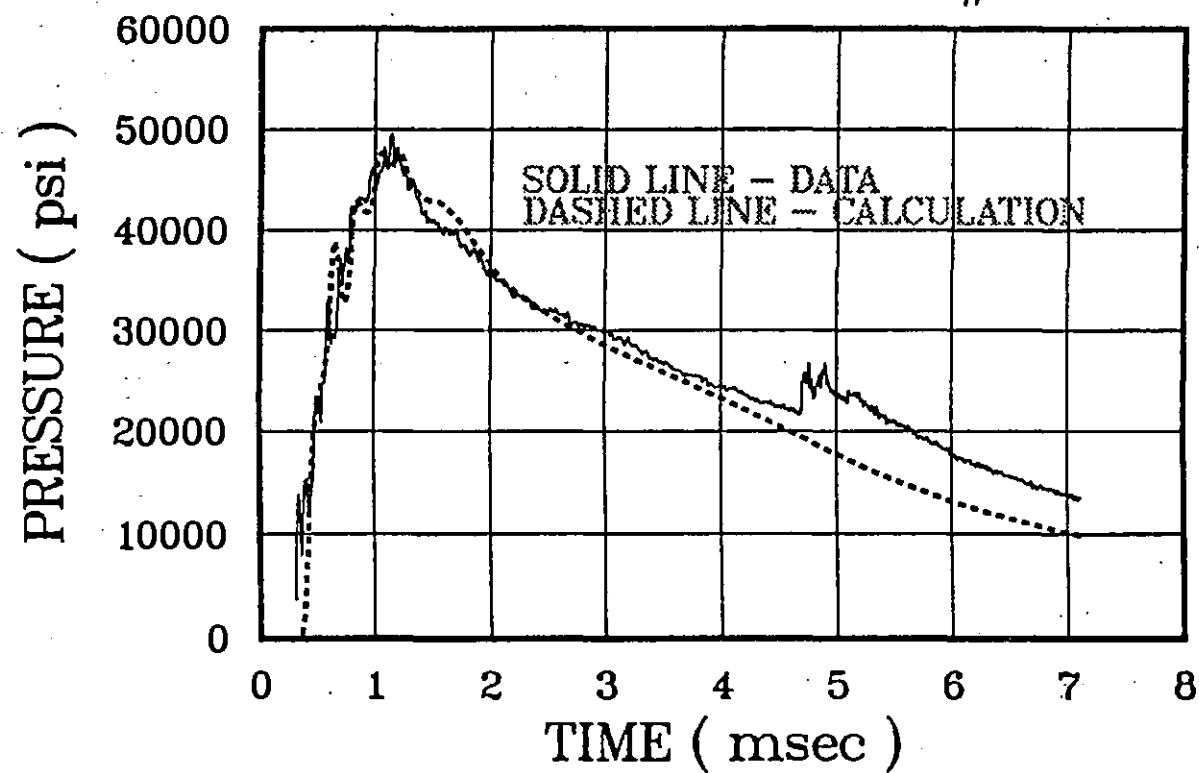
116

## INITIAL CONFIGURATION





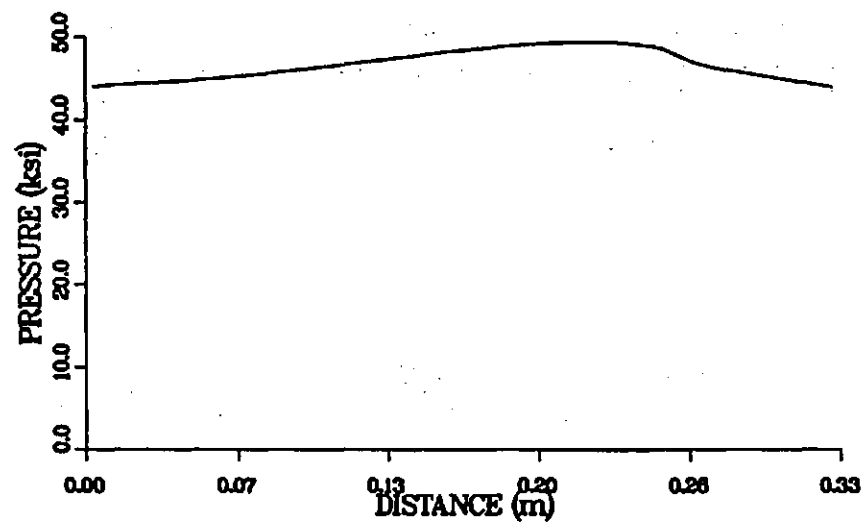
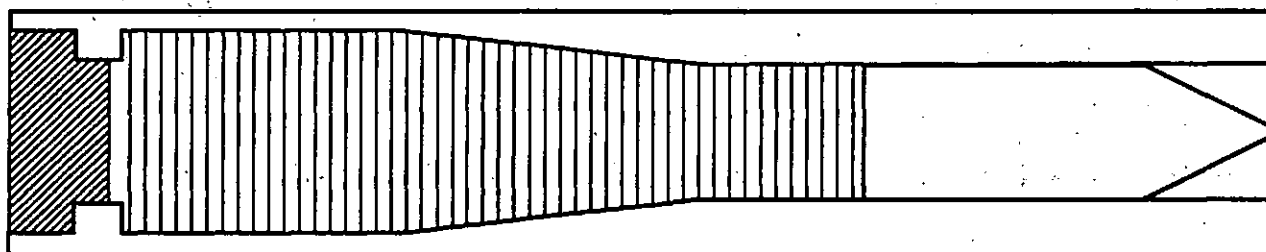
## 60-mm DNA SHOT #1



## CAP 1-D PRESSURE DISTRIBUTION

TIME = 1.15 ms

TRAVEL = 7.08 cm





## ***Impact of 1-D Calculations on 2-D Work***

- **Effects due to cartridge geometry, i.e. chamberage, projectile tail boom, etc., were found to have significant impact on ballistic calculations. The 2-D computational domain must be generalized to better reflect the hardware.**
- **The species equations and reaction kinetics model first used in the 60-mm DNA SFI calculations were found to have several beneficial effects. For instance, spatial variation in chamber o/f cannot be included without tracking species equations. Also, the "lag" time that the Arrhenius equation introduces between the chemical energy release rate and gas generation rate inhibited the fuel-oxidizer reaction during electrical pulse onset.**

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## 30-MM ETC BALLISTIC DIAGNOSTIC FACILITY

K. White, I. Stobie, B. Bensinger, S. Driesen,  
H. Burden, G. Katulka, and A. Juhasz  
US Army Ballistic Research Laboratory  
Aberdeen Proving Ground, MD 21005-5066

### ABSTRACT

The BRL has installed a 30-mm Electrothermal Chemical ballistic diagnostic facility, built under contract by the FMC Corporation. The fixture has the capability of going to pressures as high as 650 MPa with a maximum chamber volume of 550 cc and a projectile travel of 1.53 m (50 caliber). Pressure and temperature measurements can be made in the chamber and down bore. The fixture was built in modular form such that the conventional steel chamber can be replaced by either an optically or x-ray transparent chamber, allowing for flow visualization during the electrothermal process. In addition to the gun mode, the fixture can be operated in either the closed chamber or burst disc mode to examine the effect of a static boundary condition on the ETC process.

The fixture was test fired three times in the gun mode with projectile velocities of over 1000 m/s, peak pressures of 280 MPa and with 60 kJ of electrical energy input. Two tests were performed in the burst disc mode (65 MPa).

Tests will also be conducted with water as a working fluid and with various plasma-water interface geometries. These tests are to act as a baseline test series of plasma-fluid interactions without chemical contribution from the working fluids. Pressure waves have been observed in ETC firings with reactive fluids and these tests will help to isolate the hydrodynamic processes from the combustion processes. These tests will be carried out with projectiles (moving Boundary layers) and blow-out discs to isolate the effect of the moving boundary layer on the mixing process. In-bore projectile displacement measurements will also be carried out. Tests are in progress and will be discussed.



BALLISTIC RESEARCH LABORATORY



US ARMY  
LABORATORY COMMAND

# ***30-MM ETC BALLISTIC DIAGNOSTIC FACILITY***

**K. White, I. Stobie, B. Bensinger, S. Driesen  
H. Burden, G. Katulka and A. Juhasz**

**JANNAF Workshop  
ETC Modeling & Diagnostics  
July 9 - 11, 1991**



## ***PROGRAM OBJECTIVE***



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**Develop data base of ETC firings for model validation:**

- Axial and radial plasma injection configurations,
- Inert and reactive working fluids,
- Moving boundary layer (projectile) & static,
- Short & long electrical pulse,
- Optically/x-ray transparent chamber.



## ***TEST FIXTURE***



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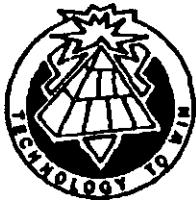
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BALLISTIC RESEARCH LABORATORY

### **30-mm fixture**

maximum chamber volume, 550 cc,  
maximum operating pressure, 650 MPa,  
projectile travel, 1.53 m (50 caliber),  
gun or blow-out disc mode,  
measurements,

pressure, chamber and barrel,  
projectile displacement, 35 GHz interferometer,  
resolution 1mm,  
optical/x-ray access chamber.



## TEST CONDITIONS



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Scaling:  $(30/120)^3 = 1/64$

|                   | 120-mm  | 30-mm  |
|-------------------|---------|--------|
| Electrical energy | 4.5 MJ  | 70 kJ  |
| Chamber volume    | 9.95 l  | 155 cc |
| Projectile mass   | 11.4 kg | 178 g  |

Problem with scaling for hydrodynamic effects.

Axial and radial plasma injection:

- Inert working fluid, water,
- Moving boundary layer, projectile,
- Short electrical pulse, 300  $\mu$ s, 70 kJ.



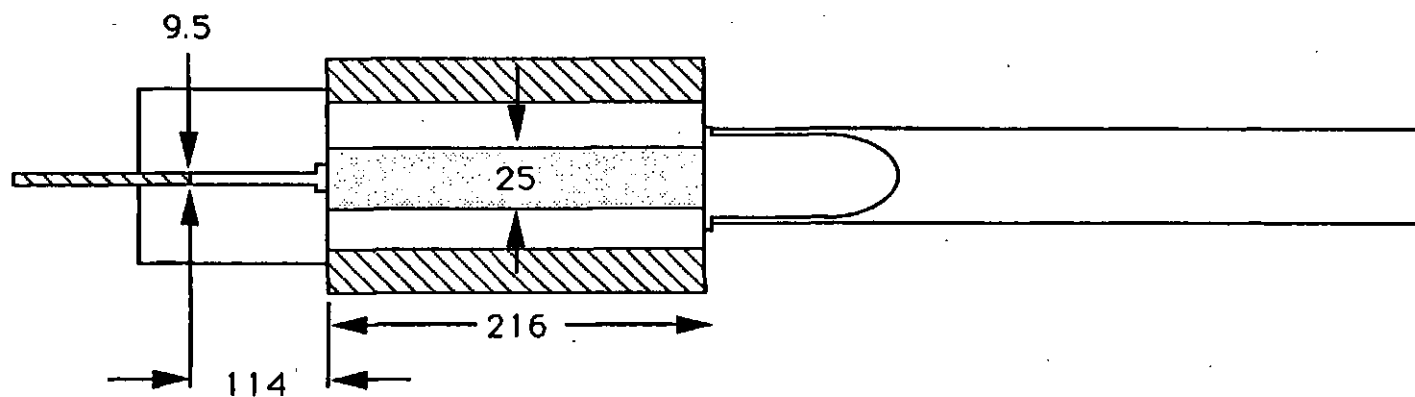
## INJECTOR & CHAMBER



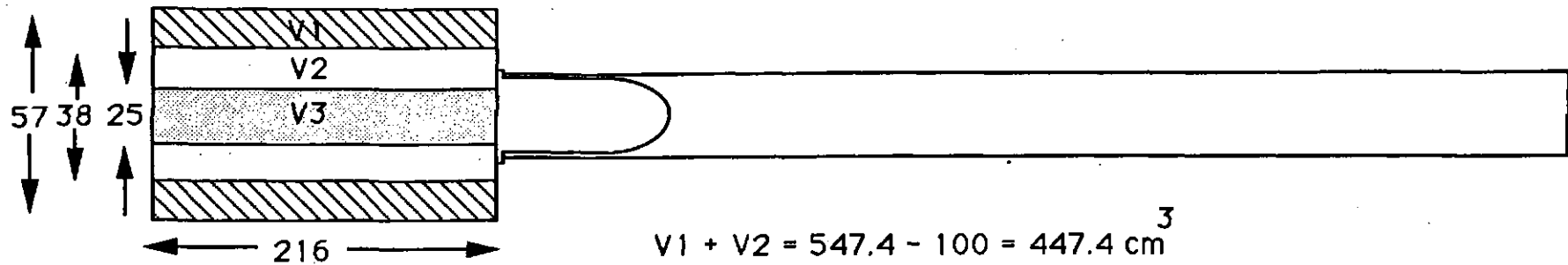
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LABORATORY COMMAND

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Radial (Center Core)



### Radial ( Center Core )

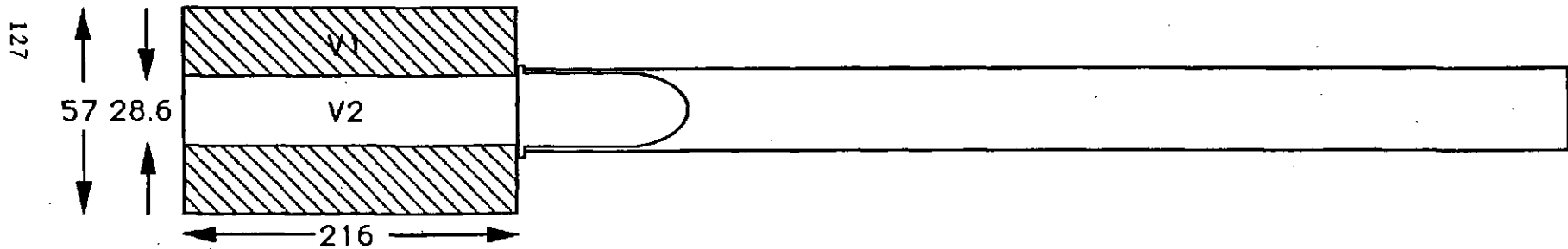


$$V1 + V2 = 547.4 - 100 = 447.4 \text{ cm}^3$$

$$V2 = 247 - 100 = 147 \text{ cm}^3$$

$$V3 = 100 \text{ cm}^3 \text{ (Styrofoam)}$$

### Axial ( Center Core )



$$V2 = 138 \text{ cm}^3$$

**M256 (120 mm)**

$$v = 9950 \text{ cm}^3$$

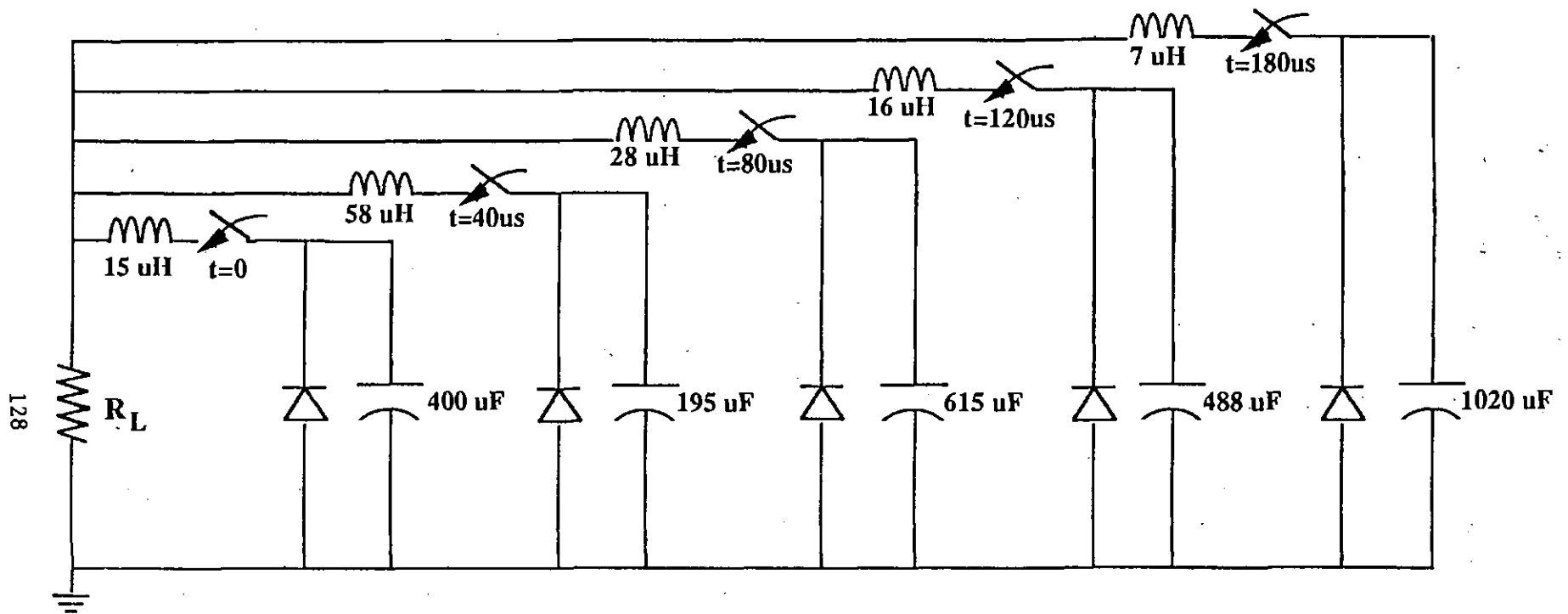
**Chamber length = 555 mm**

**Chamber Diameter = 158 mm**

**Scaled Value**

$$v = 9950 (30 / 120)^3$$

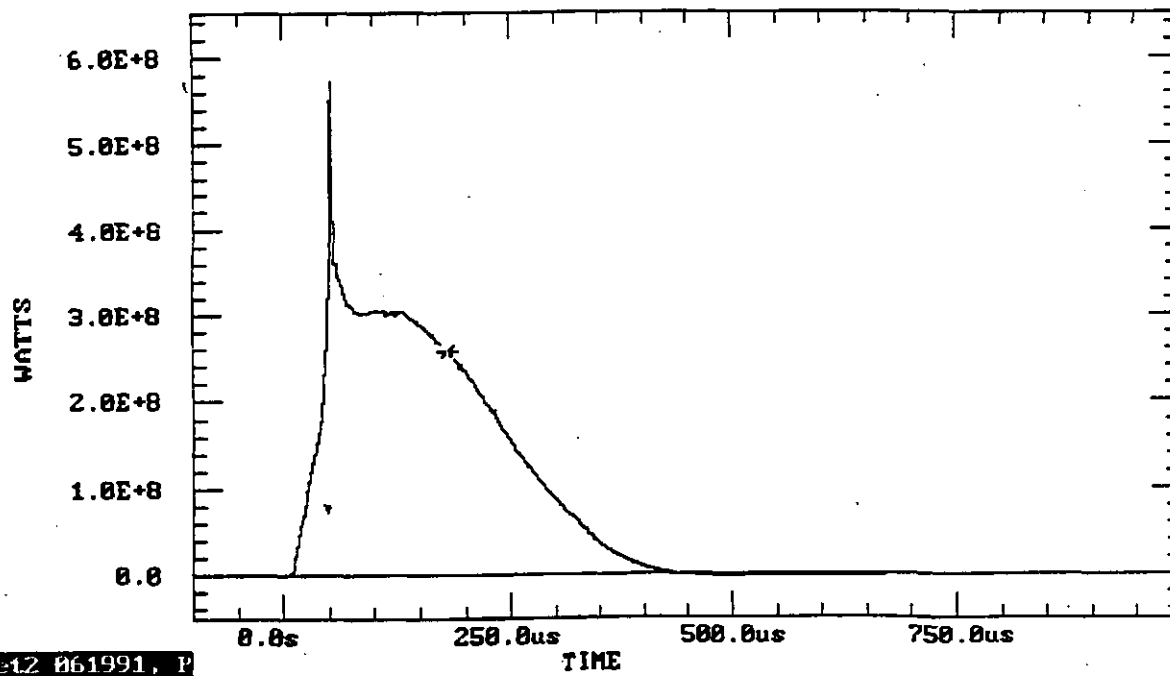
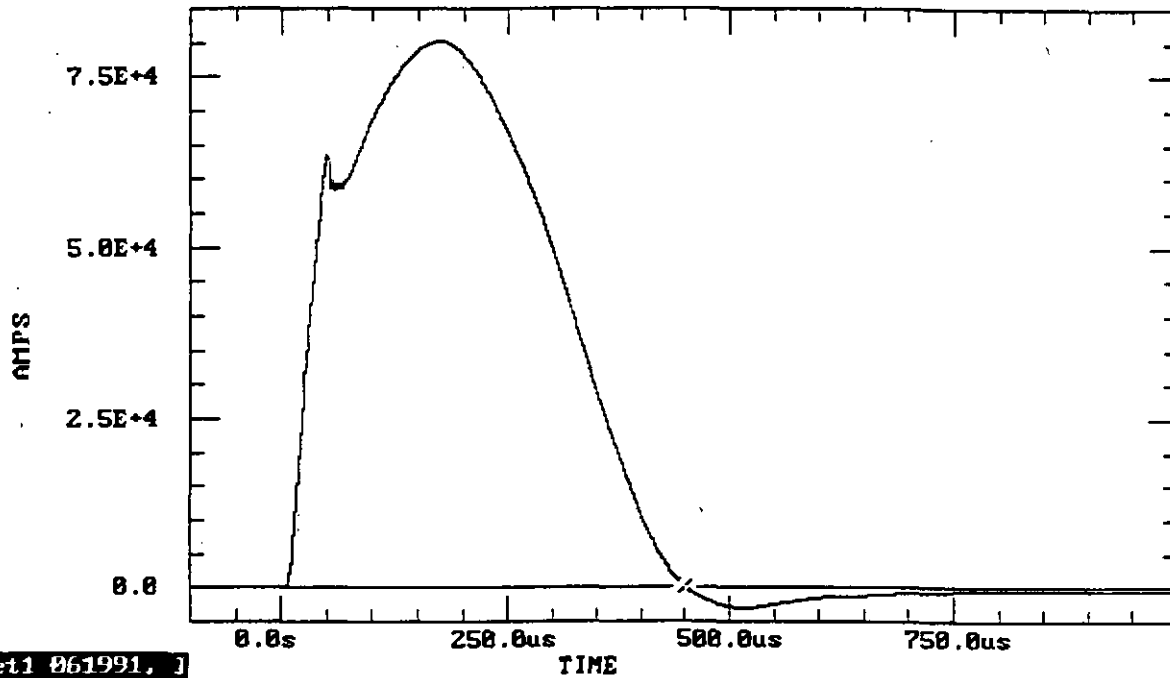
$$v = 155 \text{ cm}^3$$



**Modified BRL five module pulse forming network (135kj at 10kV)**



# PLASMA INJECTOR CURRENT & POWER



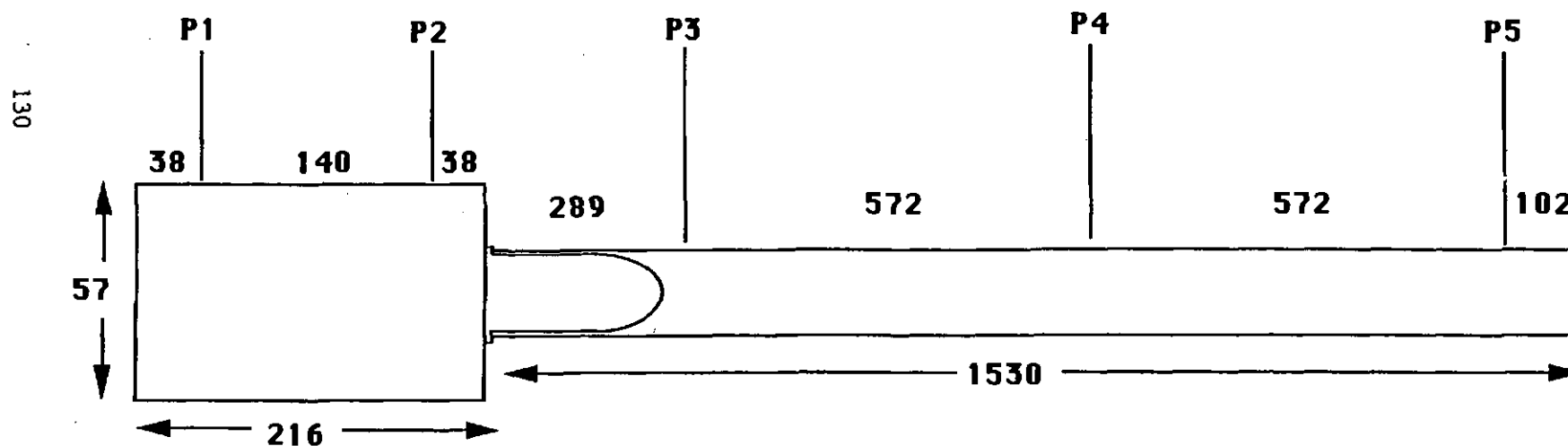


## PRESSURE GAGE LOCATION



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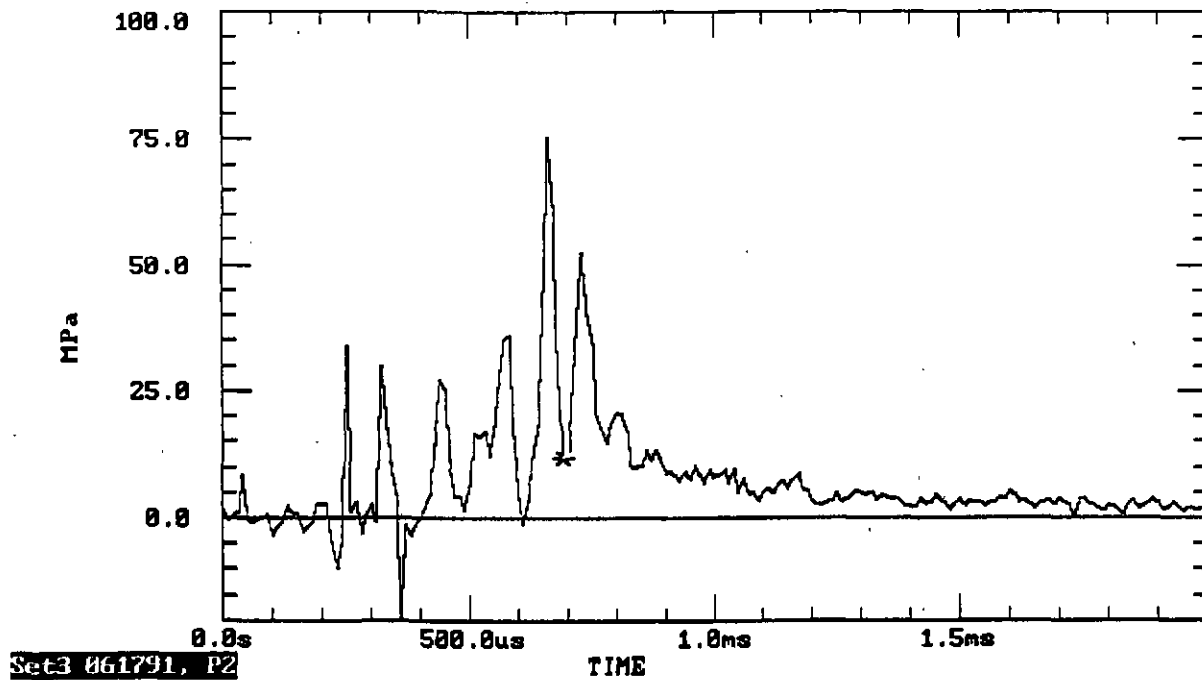
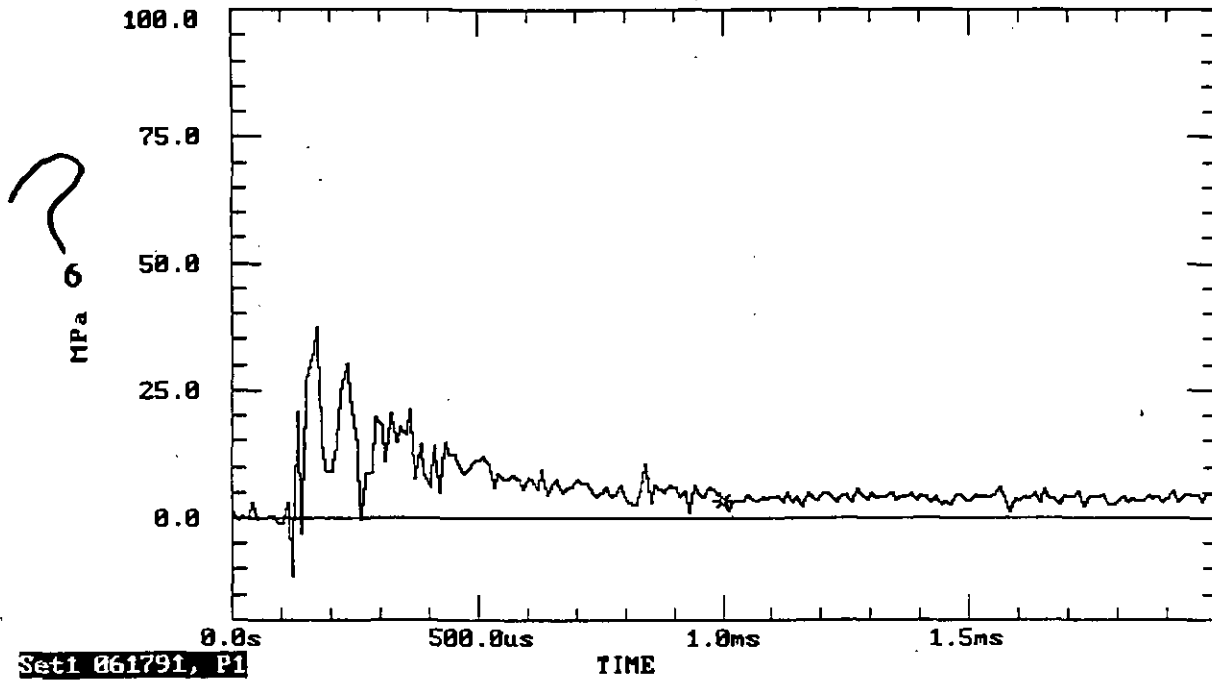
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All dimensions in mm .

Chamber Volume =  $547.4 \text{ cm}^3$

# *RADIAL INJECTION WITH LINER*





## FOURIER ANALYSIS



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Radial  
W/O Liner  
070291

P1      P2  
kHz    kHz

10.7    12.6

Axial  
W Liner  
061991

P1      P2  
kHz    kHz

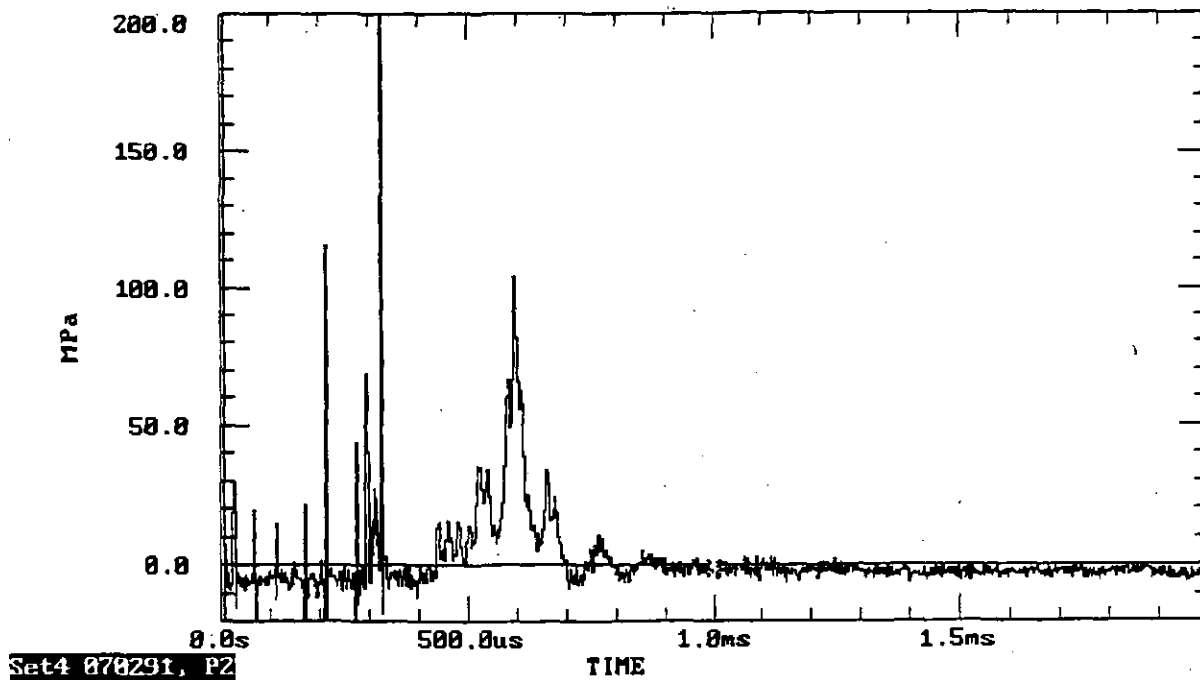
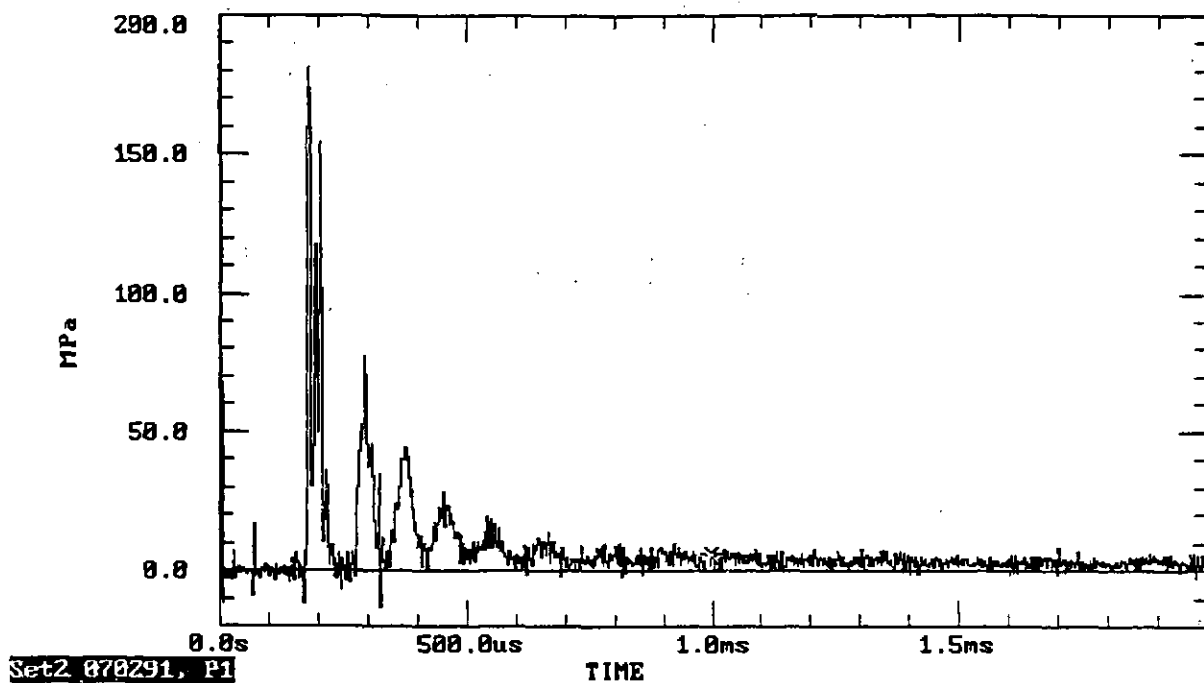
(2.3)    (2.1)  
5.7      (12.5)  
(8.8)  
14.4

Axial  
W/O Liner  
062091

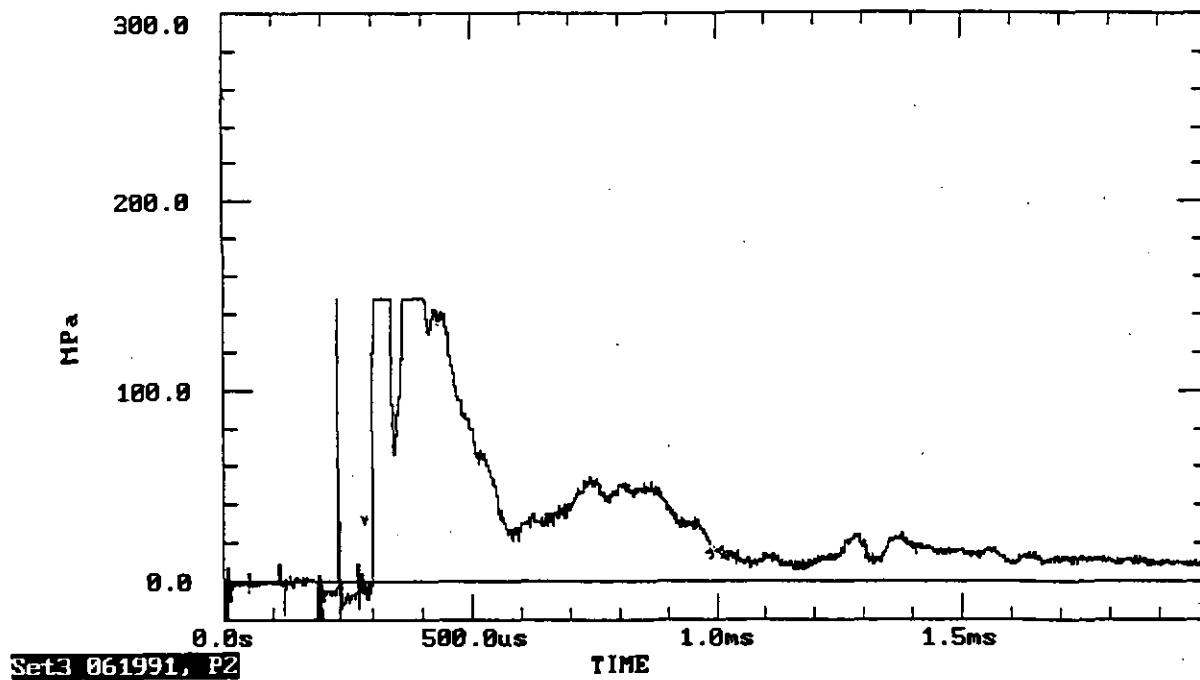
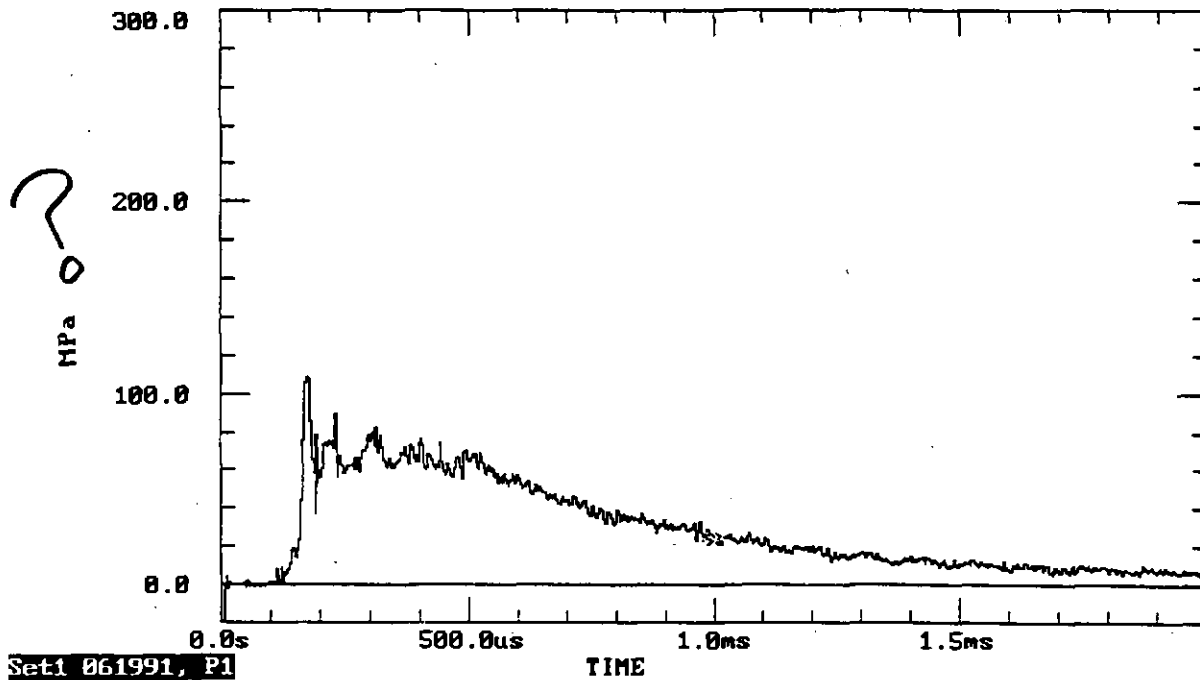
P1      P2  
kHz    kHz

(3.1)    (2.2)  
18.4    4.2  
19.5    (15.9)  
20.9  
(23.2)

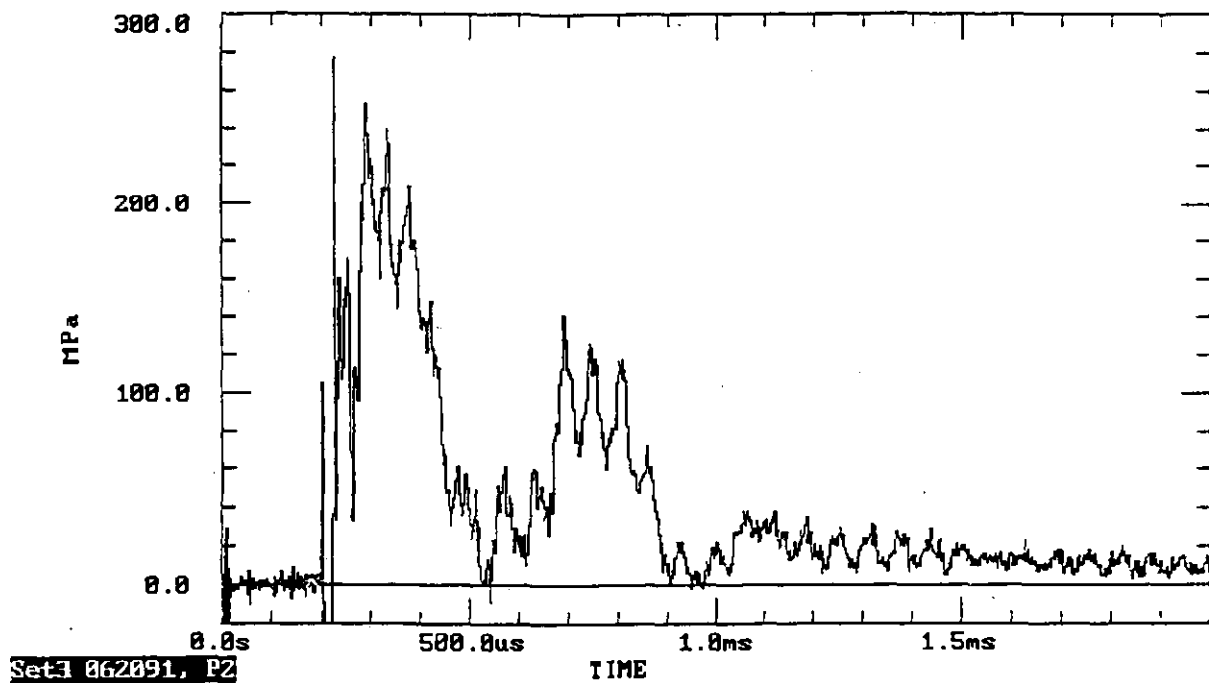
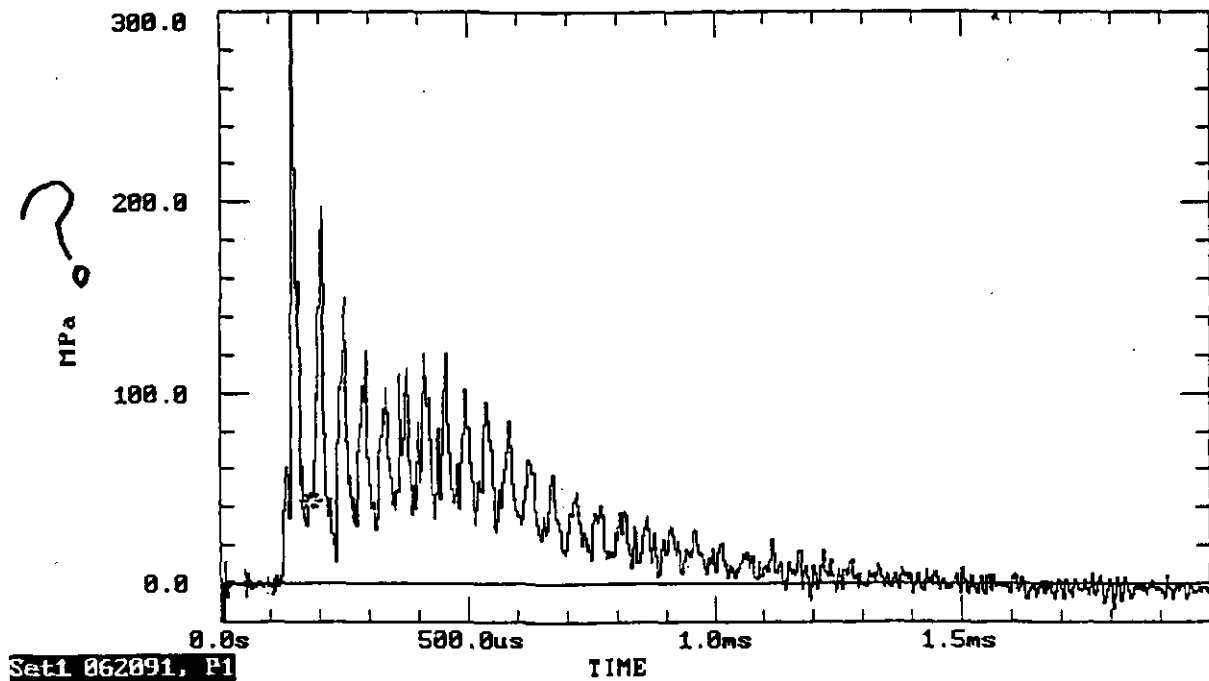
# ***RADIAL INJECTION WITHOUT LINER***



# AXIAL INJECTION WITH LINER

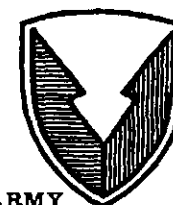


# AXIAL INJECTION WITHOUT LINER





# FOURIER ANALYSIS



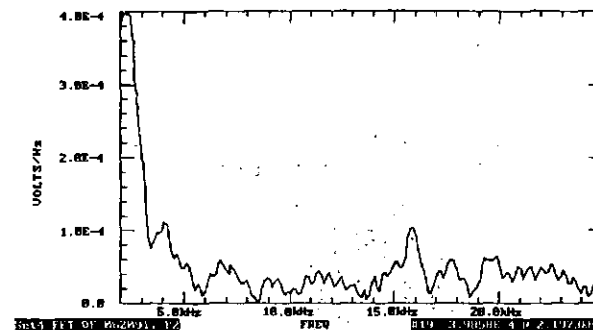
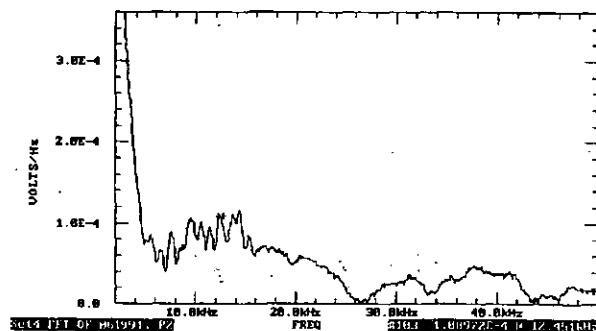
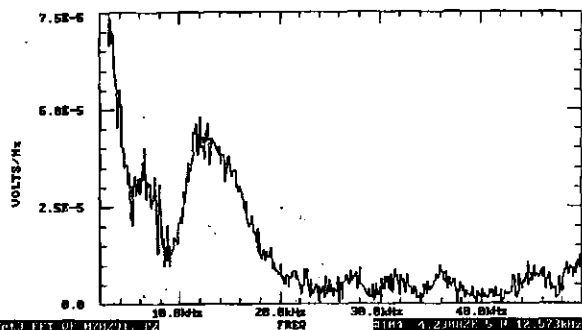
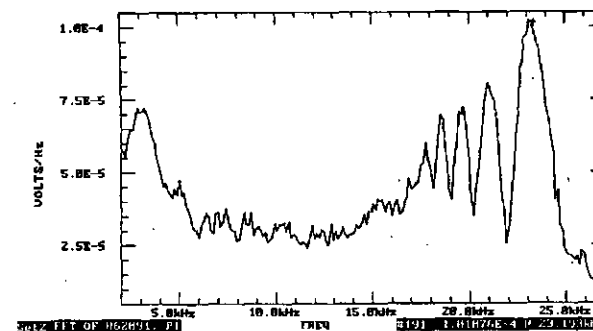
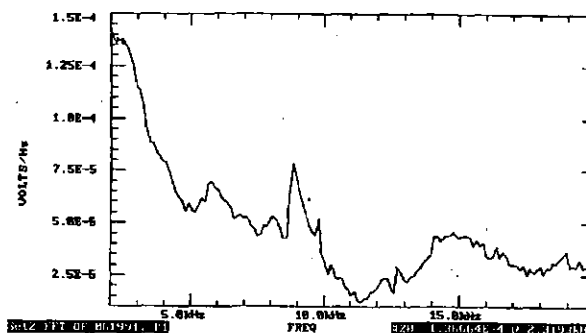
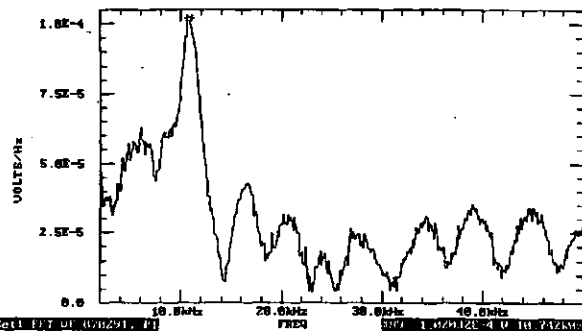
US ARMY  
LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY

Radial  
W/O Liner  
070291

Axial  
W Liner  
061991

Axial  
W/O Liner  
062091







## RESULTS



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### Radial Injection (Center Core)

| ID     | P2<br>MPa | Vol<br>cc | v<br>m/s | liner | ME<br>kJ | EE<br>kJ | Sam.<br>$\mu$ s | Disp<br>@1ms<br>mm | P<br>MW | Star<br>$\mu$ s |
|--------|-----------|-----------|----------|-------|----------|----------|-----------------|--------------------|---------|-----------------|
| 053091 | 50        | 154       | 73       | Y     | 0.48     | -        | 10              | 10                 | -       | 400             |
| 061791 | 70        | 131       | 79       | Y     | 0.56     | 67       | 10              | 12                 | 300     | 400             |
| 062591 | 150       | 423       | 65       | N     | 0.38     | 67       | 2               | 33.5               | 300     | 500             |
| 070291 | 80        | 383       | 0        | N     | 0        | 64       | 2               | -                  | 270     | -               |

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### Axial Injection

|        |     |     |     |   |      |    |   |    |     |     |
|--------|-----|-----|-----|---|------|----|---|----|-----|-----|
| 061991 | 150 | 136 | 202 | Y | 3.63 | 69 | 2 | 85 | 300 | 310 |
| 062091 | 200 | 500 | 182 | N | 2.95 | 68 | 2 | -  | 300 | -   |

Note: Water leakage around projectile in test ID 062591.



## CONCLUSIONS



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### Radial (Center Core) vs. Axial Injection

#### Radial

- more gradual pressure rise at projectile,
- lower pressures and velocities,
- pressure drops off more rapidly.

#### Issues:

- The water/plasma energy system does not behave as a well stirred system.
- P1 levels suspect,
- Chamber liner may attenuate high frequency waves  
acoustic attenuation,  
longer distance from pressure to gage,  
(10-15 mm).
- Pressures contain substantial high frequency components,  
not combustion driven,

### PROPELLANT SURFACE AREA IMPLICATIONS.



## ***FUTURE PLANS***



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LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY

**Develop data base of ETC firings for model validation:**

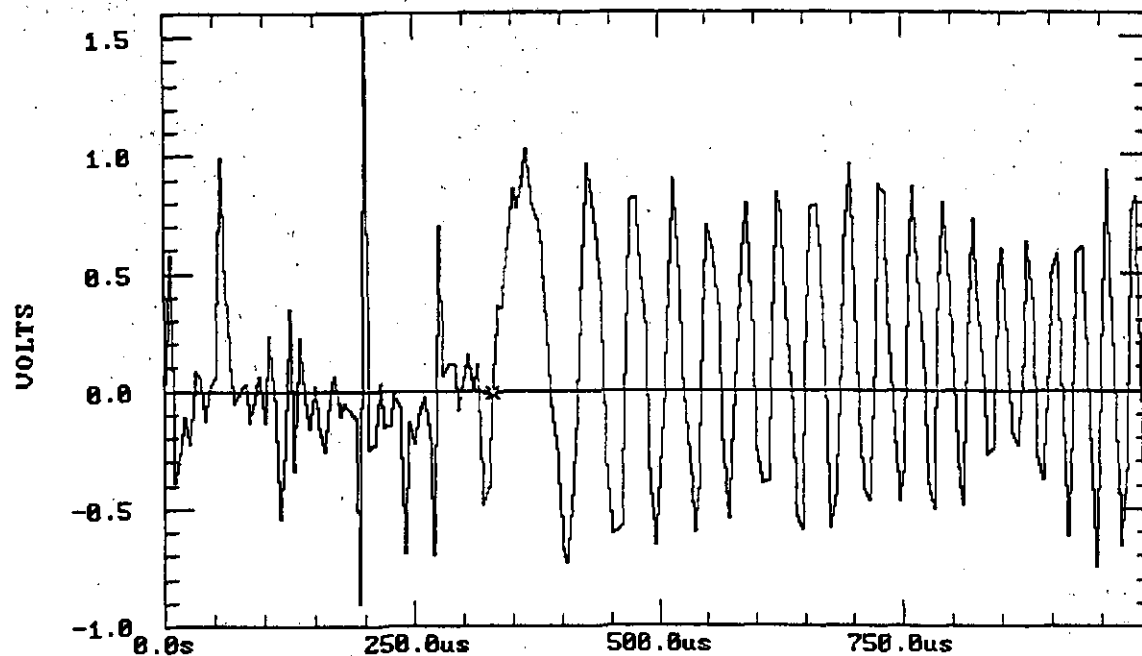
- Axial and radial plasma injection configurations,
- Inert and reactive working fluids,
- Moving boundary layer (projectile) & static,
- Short & long electrical pulse
- Optically/x-ray transparent chamber.

**Reactive working fluid:**

13-molar HAN,  
low energy,  
safe & available,  
some ballistic data.

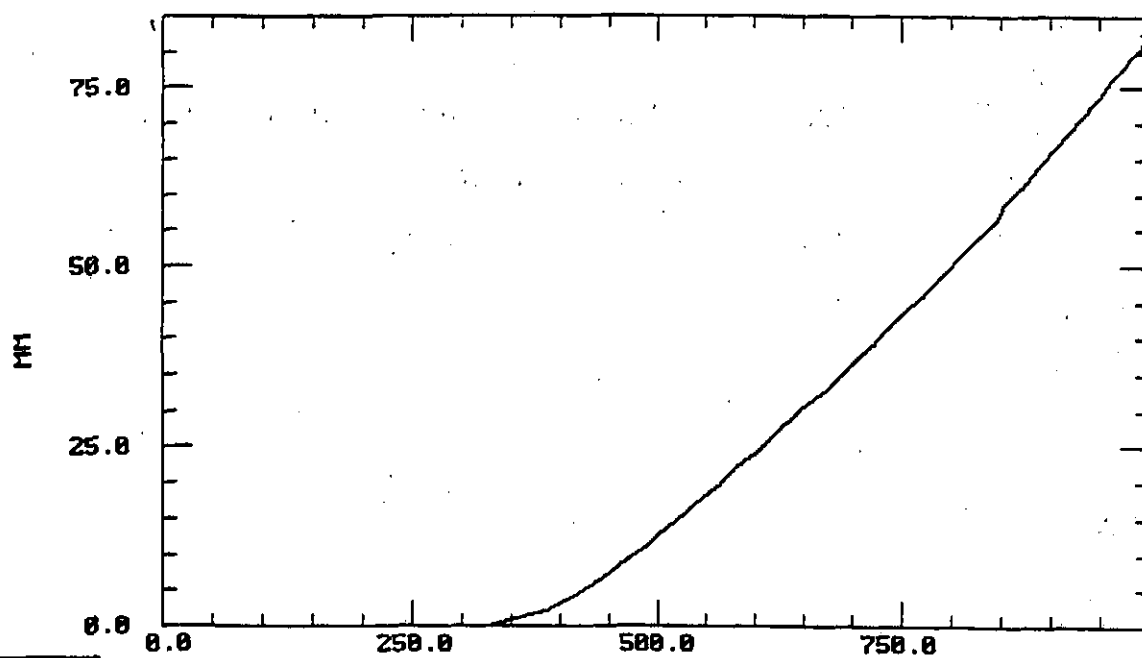
NOS-365, HAN + IPAN +H<sub>2</sub>O,  
safe & available,  
difficult to ignite,  
bulk loaded firing data,  
mono-propellant.

# INTERFEROMETER DATA & DISPLACEMENT



Set1 061991, INTERFEROMETER

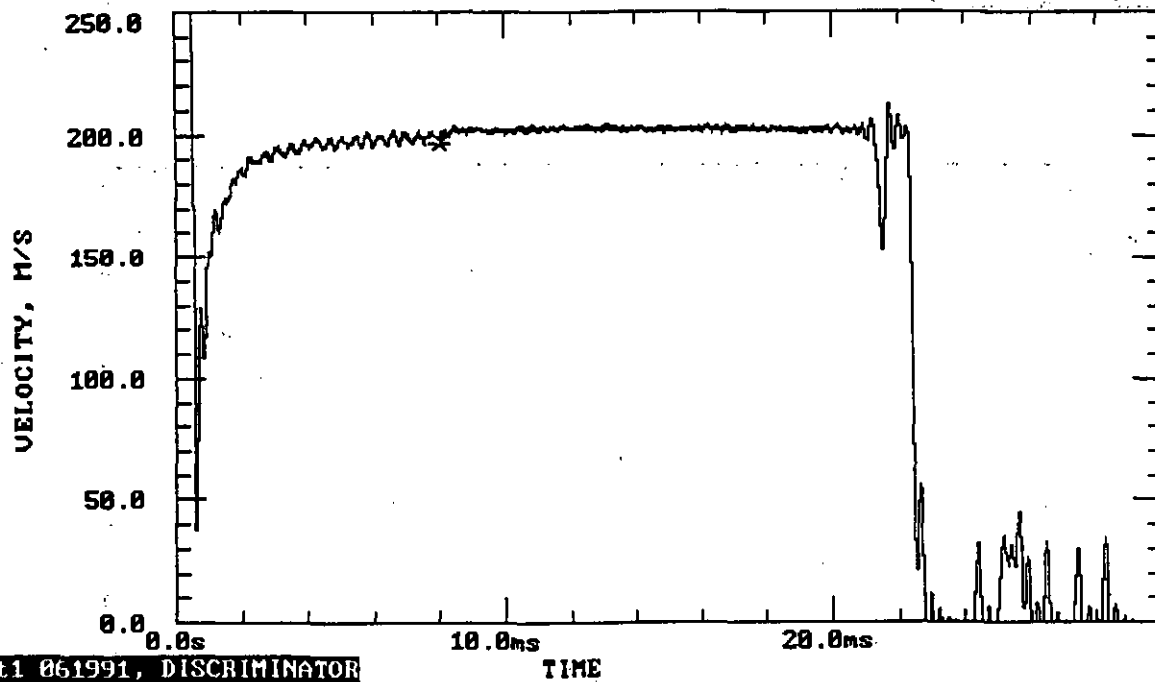
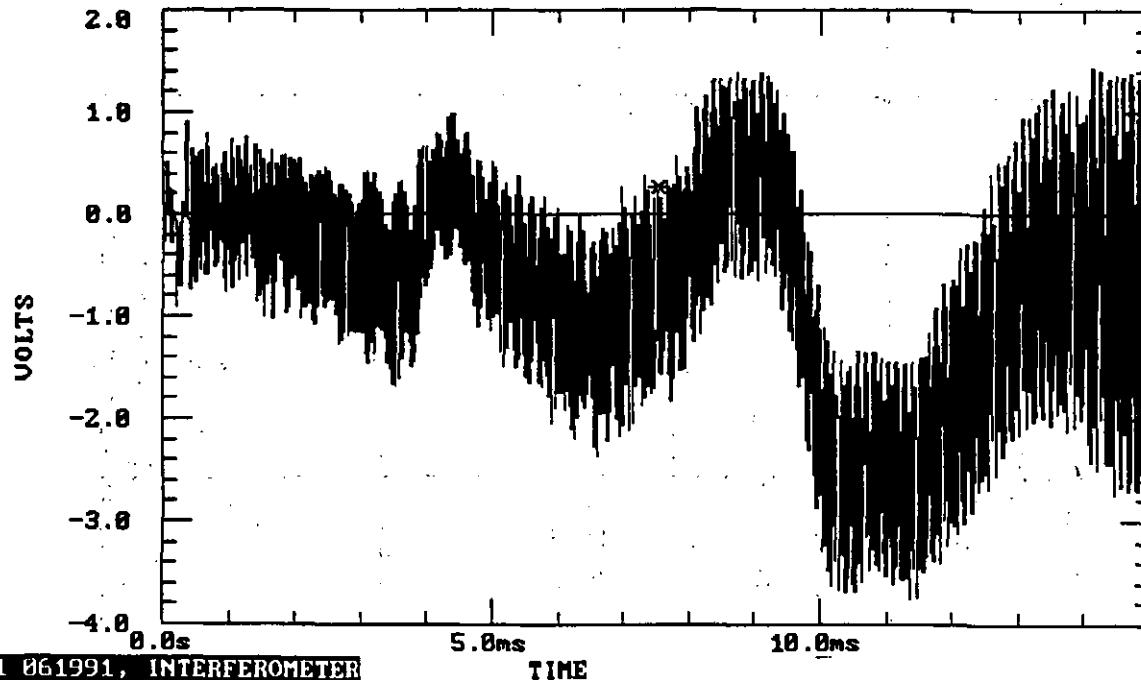
TIME



Set3 Set 3

TIME, u

# INTERFEROMETER & DISCRIMINATOR DATA



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# NUMERICAL SIMULATION OF THE INTERIOR BALLISTIC PROCESSES IN AN ETC GUN

J. L. Chen, F. B. Cheung and K. K. Kuo  
The Pennsylvania State University  
University Park, PA 16802

## ABSTRACT

A comprehensive theoretical model has been developed to study the interior ballistic processes in an ETC gun. Phenomena occurring in five separate regions are considered in the model. These regions consist of the gas phase (i.e., Taylor cavity), working fluid (i.e., liquid propellant), dispersed droplets in the Taylor cavity, projectile, and plasma generating cartridge (PGC). Dispersed droplets are generated through the entrainment process as a result of the relative motions between the gas and liquid phases. Governing equations are formulated from the first principles of physics, accounting for the plasma/working fluid interactions and the projectile dynamics. Two different sets of PFN discharge curves have been employed to identify the effects of PFN discharge characteristics on gun performance. Various energy ratios (chemical energy/electrical energy) have been used to investigate how the propulsive energy is influenced by plasma generation and combustion of liquid propellant in different stages of the ETC gun event. The model has been partially validated by comparing the computed breech pressure-time traces with the measured data provided by FMC.

**NUMERICAL SIMULATION OF THE INTERIOR BALLISTIC PROCESSES  
IN AN ETC GUN**

**J. L. Chen, K. K. Kuo, and F. B. Cheung**

**Department of Mechanical Engineering**

**The Pennsylvania State University**

**University Park, PA 16802**

**Presented at a JANNAF Workshop on  
Electrothermal-Chemical Modeling and Diagnostics**

**July 9-11, 1991**

**Ballistic Research Laboratory  
Aberdeen Proving Ground, MD**



## OBJECTIVE

- \* Develop a Comprehensive Theoretical Model to Investigate the Interior Ballistic Processes of an Electrothermal (ET) Gun
- \* Predict the Interior Ballistic Processes of an ET Gun
- \* Seek a Better Understanding of the Mechanisms Controlling the Performance of an ET gun

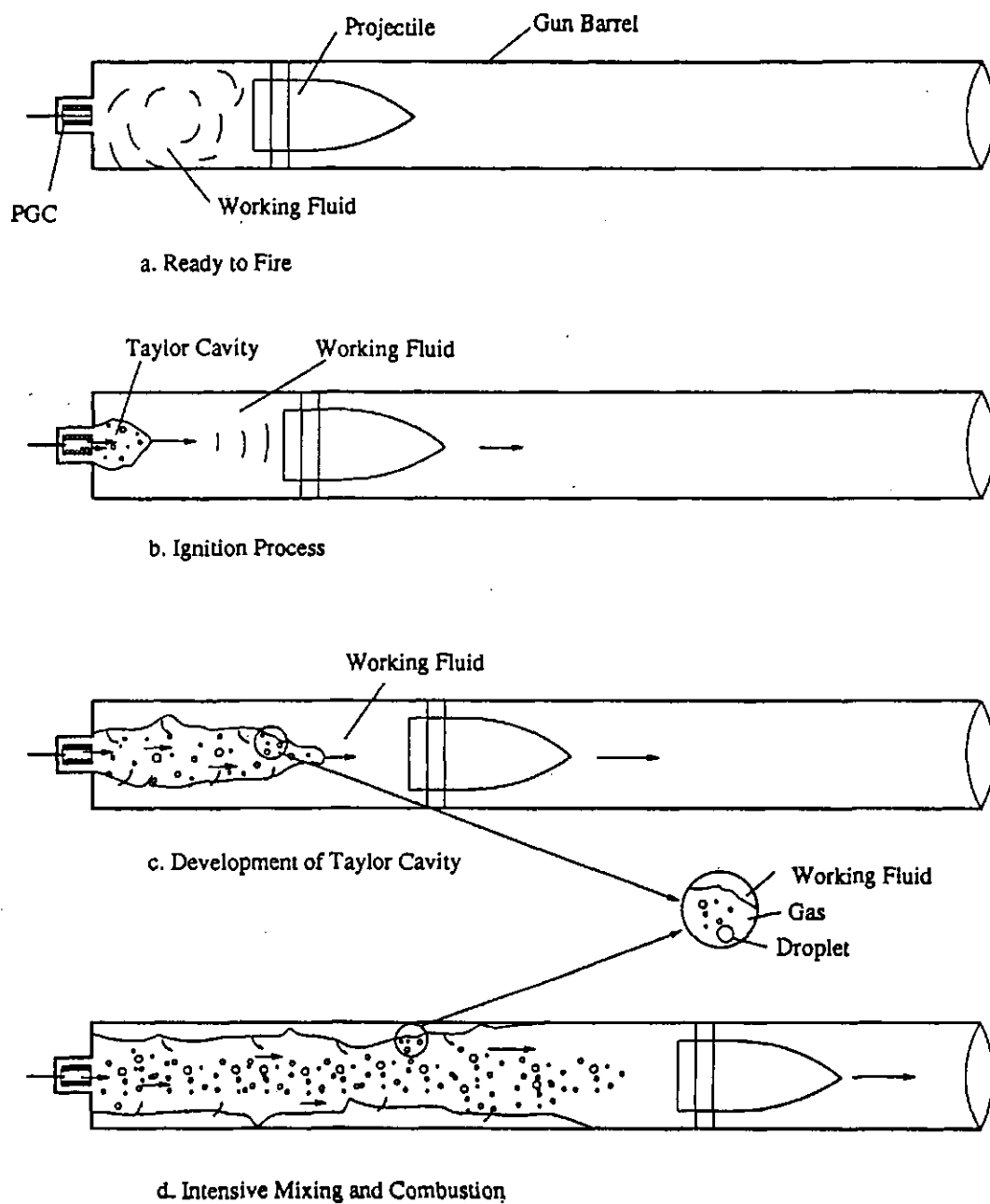
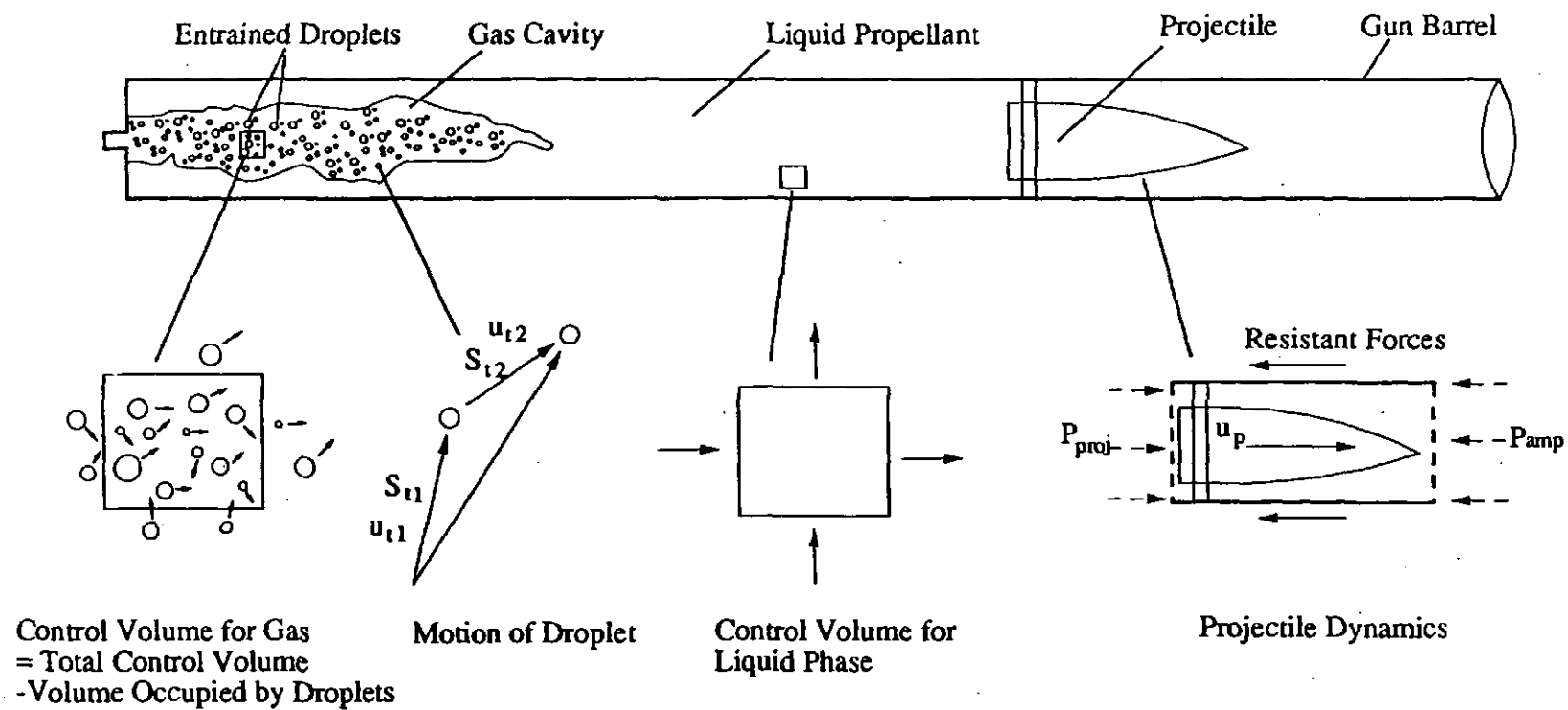


Fig. 1-2 Schematic of a Typical ET Gun Firing Cycle



Control Volumes for Different Phases in an ET Gun

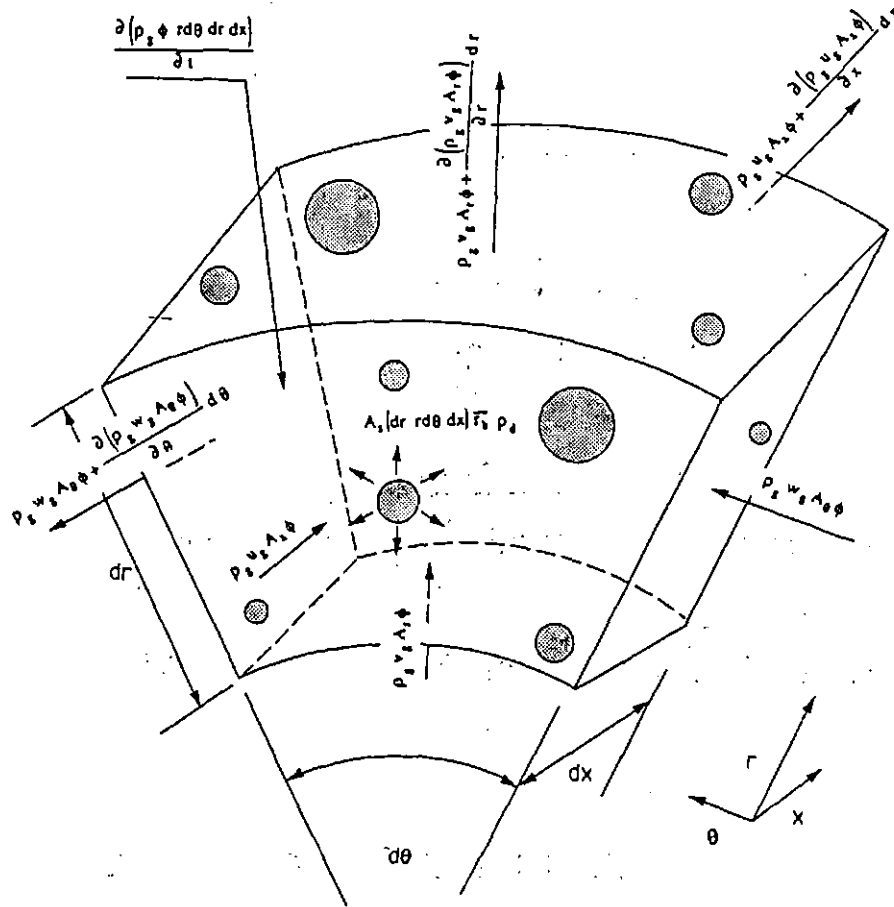
## THEORETICAL FORMULATION

### Assumptions

1. Gas, Liquid, and Solid Phases:  
Transient Axisymmetric Cylindrical Eulerian Coordinate
2. Motions of the Droplets :  
Small Droplets:
  - \* Following Gas Flow Motion
  - \* Number Density Equation
3. Combustion of Liquid Propellant :  
Oxidizer Droplets Burning in the Gaseous Fuel Environment  
(Heat of Vaporization of the Oxidizer is Much Higher than that of the Fuel at Standard State)
4. Combustion Mechanisms of Liquid Propellant :  
Simple Chemical Reacting System (SCRS)
  - \* Oxidizer, Fuel, and Product
  - \* One Step Chemical Reaction
5. Body Force Effect : Negligible

## Governing Equations for Gas Phase

- \* Deriving from First Principles of Physics
- \* Continuity, x-, r-Momentums, and Energy Equations



- \* Turbulence Closure
  1. Favre Averaged
  2. K,  $\epsilon$  Two Equation Model

## Gas Phase

### Continuity Equation

$$\frac{\partial (\bar{\rho}_g \tilde{\phi})}{\partial t} + \frac{\partial (\bar{\rho}_g \tilde{\phi} \tilde{u}_g)}{\partial x} + \frac{\partial (\bar{\rho}_g \tilde{\phi} \tilde{v}_g r)}{r \partial r} = \bar{S}_{gm}$$

### x-Momentum Equation

$$\begin{aligned} & \frac{\partial (\bar{\rho}_g \tilde{\phi} \tilde{u}_g)}{\partial t} + \frac{\partial (\bar{\rho}_g \tilde{\phi} \tilde{u}_g \tilde{u}_g)}{\partial x} + \frac{\partial (\bar{\rho}_g \tilde{\phi} \tilde{u}_g \tilde{v}_g r)}{r \partial r} \\ &= - \frac{\partial (\bar{P} \phi)}{\partial x} + \frac{\partial}{\partial x} \left[ \tilde{\phi} \mu_{eff} \left( \frac{4}{3} \frac{\partial \tilde{u}_g}{\partial x} - \frac{2}{3} \frac{\partial \tilde{v}_g}{\partial r} - \frac{2}{3} \frac{\tilde{v}_g}{r} \right) \right] \\ &+ \frac{\partial}{r \partial r} \left[ \tilde{\phi} \mu_{eff} r \left( \frac{\partial \tilde{u}_g}{\partial r} + \frac{\partial \tilde{v}_g}{\partial x} \right) \right] - \bar{S}_{dx} + \bar{S}_{gx} \end{aligned}$$

### r-Momentum Equation

$$\begin{aligned} & \frac{\partial (\bar{\rho}_g \tilde{\phi} \tilde{v}_g)}{\partial t} + \frac{\partial (\bar{\rho}_g \tilde{\phi} \tilde{v}_g \tilde{u}_g)}{\partial x} + \frac{\partial (\bar{\rho}_g \tilde{\phi} \tilde{v}_g \tilde{v}_g r)}{r \partial r} \\ &= - \frac{\partial (\bar{P} \phi)}{\partial r} + \frac{\partial}{\partial x} \left[ \tilde{\phi} \mu_{eff} \left( \frac{\partial \tilde{u}_g}{\partial r} + \frac{\partial \tilde{v}_g}{\partial x} \right) \right] \\ &+ \frac{\partial}{r \partial r} \left[ \tilde{\phi} \mu_{eff} r \left( \frac{4}{3} \frac{\partial \tilde{v}_g}{\partial r} - \frac{2}{3} \frac{\tilde{v}_g}{r} - \frac{2}{3} \frac{\partial \tilde{u}_g}{\partial x} \right) \right] \frac{\mu_{eff}}{r} \left( \frac{4}{3} \frac{\tilde{v}_g}{r} - \frac{2}{3} \frac{\partial \tilde{v}_g}{\partial r} - \frac{2}{3} \frac{\partial \tilde{u}_g}{\partial x} \right) \\ &- \bar{S}_{dr} + \bar{S}_{gr} \end{aligned}$$

## Gas Phase

### Energy Equation

$$\begin{aligned}
 & \frac{\partial (\bar{\rho}_g \tilde{\phi} \tilde{H})}{\partial t} + \frac{\partial (\bar{\rho}_g \tilde{\phi} \tilde{H} \tilde{u}_g)}{\partial x} + \frac{\partial (\bar{\rho}_g \tilde{\phi} \tilde{H} \tilde{v}_g r)}{r \partial r} \\
 &= \frac{\partial}{\partial x} \left[ \tilde{\phi} \lambda_{\text{eff}} \left( \frac{\partial \tilde{T}_g}{\partial x} \right) \right] + \frac{\partial}{r \partial r} \left[ r \tilde{\phi} \lambda_{\text{eff}} \left( \frac{\partial \tilde{T}_g}{\partial r} \right) \right] \\
 &+ \bar{q}_d - \bar{q}_{hx} - \bar{S}_p - \bar{S}_t - \bar{S}_d - \overline{P \frac{\partial \phi}{\partial t}}
 \end{aligned}$$

### Equation of State

$$\bar{P} = b \bar{\rho}_g \tilde{P} + R \bar{\rho}_g \tilde{T}_g$$

## Gas Phase

### \* Turbulence Model

#### k Equation

$$\begin{aligned}
 & \frac{\partial (\bar{\rho}_g k)}{\partial t} + \frac{\partial (\bar{\rho}_g \tilde{u}_g k)}{\partial x} + \frac{\partial (\bar{\rho}_g \tilde{v}_g k r)}{r \partial r} \\
 &= \frac{\partial}{\partial x} \left[ \left( \frac{\mu_T}{\sigma_k} + \mu_g \right) \frac{\partial k}{\partial x} \right] + \frac{\partial}{r \partial r} \left[ r \left( \frac{\mu_T}{\sigma_k} + \mu_g \right) \frac{\partial k}{\partial r} \right] + G_k \\
 & - \frac{\mu_T}{\rho_g} \frac{\partial \bar{\rho}_g}{\partial r} \frac{\partial \bar{P}}{\partial r} - \frac{\mu_T}{\rho_g} \frac{\partial \bar{\rho}_g}{\partial x} \frac{\partial \bar{P}}{\partial x} - \bar{\rho}_g \epsilon + \overline{A_s r_b \rho_d k}
 \end{aligned}$$

#### $\epsilon$ Equation

$$\begin{aligned}
 & \frac{\partial (\bar{\rho}_g \epsilon)}{\partial t} + \frac{\partial (\bar{\rho}_g \tilde{u}_g \epsilon)}{\partial x} + \frac{\partial (\bar{\rho}_g \tilde{v}_g \epsilon r)}{r \partial r} \\
 &= \frac{\partial}{\partial x} \left[ \left( \frac{\mu_T}{\sigma_\epsilon} + \mu_g \right) \frac{\partial \epsilon}{\partial x} \right] + \frac{\partial}{r \partial r} \left[ r \left( \frac{\mu_T}{\sigma_\epsilon} + \mu_g \right) \frac{\partial \epsilon}{\partial r} \right] \\
 & + C_{\epsilon 1} \frac{\epsilon}{k} \left( G_k + \frac{\mu_T}{\rho_g} \frac{\partial \bar{\rho}_g}{\partial r} \frac{\partial \bar{P}}{\partial r} - \frac{\mu_T}{\rho_g} \frac{\partial \bar{\rho}_g}{\partial x} \frac{\partial \bar{P}}{\partial x} \right) - C_{\epsilon 2} \bar{\rho}_g \frac{\epsilon^2}{k} + \overline{A_s r_b \rho_d \epsilon}
 \end{aligned}$$

with

$$\begin{aligned}
 G_k &\equiv \frac{4}{3} \mu_T \left[ \left( \frac{\partial \tilde{u}_g}{\partial x} \right)^2 - \frac{\partial \tilde{u}_g}{\partial x} \left( \frac{\partial \tilde{v}_g}{\partial r} + \frac{\tilde{v}_g}{r} \right) \right] + \left( \frac{\partial \tilde{v}_g}{\partial r} + \frac{\tilde{v}_g}{r} \right)^2 \\
 & + \mu_T \left( \frac{\partial \tilde{u}_g}{\partial r} + \frac{\partial \tilde{v}_g}{\partial x} \right)^2 - \frac{2}{3} \bar{\rho}_g k \left( \frac{\partial \tilde{u}_g}{\partial x} + \frac{\partial \tilde{v}_g}{\partial r} + \frac{\tilde{v}_g}{r} \right)
 \end{aligned}$$



## Droplet Phase

### Droplet Motion:

Small Droplets Follow Flow Motions

Number Density Equation for Group k

$$\frac{\partial (n_k)}{\partial t} + \frac{\partial (n_k u_g)}{\partial x} + \frac{\partial (n_k v_g r)}{r \partial r} = - C_{1,k} \dot{n}_k + \sum_{i=k+1} C_{2,i} \dot{n}_k + \dot{n}_{k, en}$$

(a)
(b)
(c)

(a): Due to Combustion of Group k

(b): Due to Combustion of Larger Droplets

(c): Due to Entrainment Mechanisms

### Droplet Combustion :

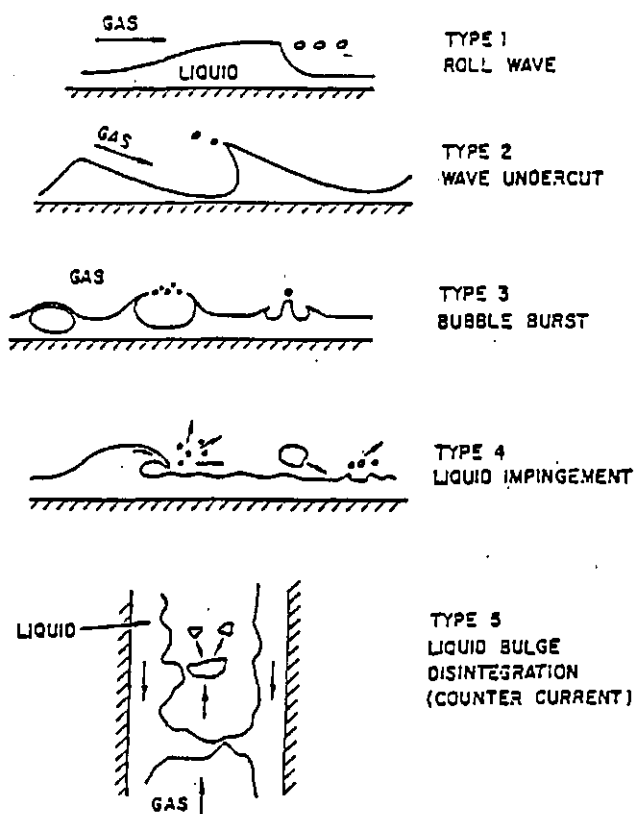
Boundary Condition at Droplet Surface

$P_{i,g} = P_{i,l}$  (at Ambient Pressure)

$f_{i,g} = f_{i,l}$  (at High Pressure), Equality of Fugacity

## Entrainment Mechanism

Roll Wave, Wave Undercut, Bubble Burst, Liquid Impingement, Liquid Bulge Disintegration



## Droplet Phase

### Entrainment Rate:

$$R_A = K_A \left[ \frac{W_{LF} - W_{LF,C}}{P_e} \right] u_g^2 \bar{\rho}_g^{1/2} \bar{\rho}_l^{1/2}$$

$R_A$ : entrainment rate

$K_A$ : entrainment coefficient

$P_e$ : wetted perimeter

$W_{LF}$ : liquid film flow rate

$W_{LF,C}$ : critical liquid film flow rate

### Entrainment Droplet Size

Average Droplet Size Based on a Log Normal Distribution for Annular Flow

$$\frac{d_{32}}{d_t} \left( \frac{\bar{\rho}_g u_g^0 f_s d_t}{2 \sigma} \right)^{1/2} = 2.3 * 10^{-2}$$

$d_{32}$ : Sauter mean diameter

$d_t$ : hydraulic diameter of tube

$f_s$ : friction factor for smooth pipe

$\sigma$ : surface tension

## Projectile Dynamic Motions

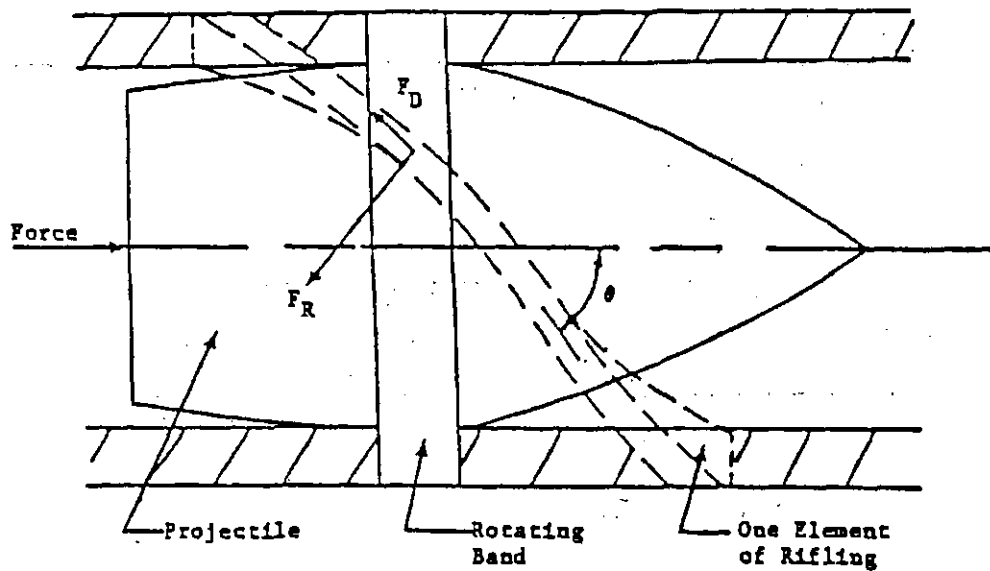
### Projectile Dynamic Motions :

Sliding, Rotating, and Engraving in the Gun Barrel

### Force Balance :

Driving Force : Pressure Acting on Projectile Base

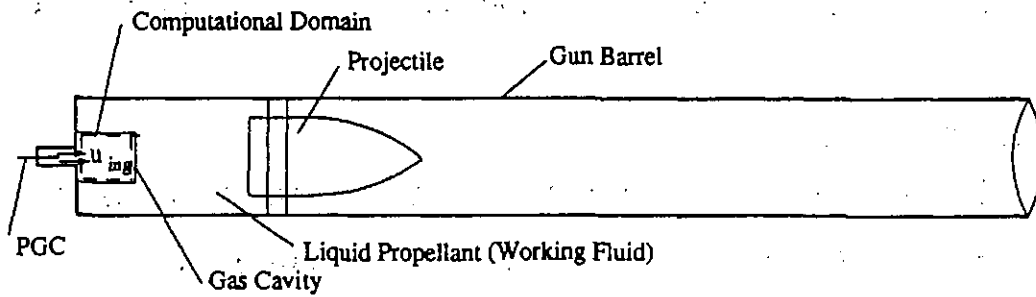
Resistant Forces : Due to Sliding, Rotating, and  
Engraving Motions



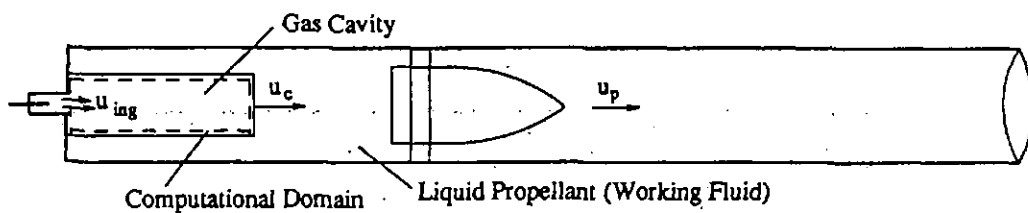
$$a_p = \frac{R_p^* \left[ (P_B - P_\infty) A_{CS} (\cos \theta - C_f \sin \theta) - F_D \right]}{W_p R_p^* (\cos \theta - C_f \sin \theta) + I_p K_p (\cos \theta + C_f \sin \theta)}$$

## Numerical Solutions

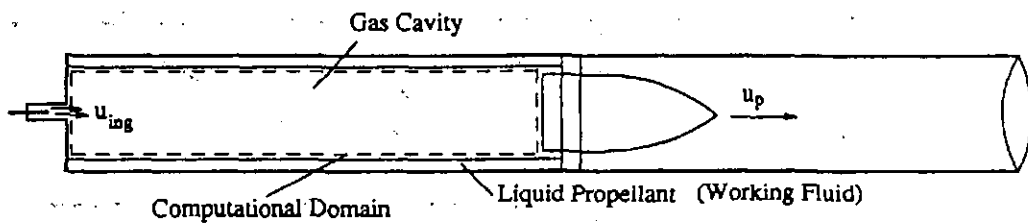
### \* Computational Domain



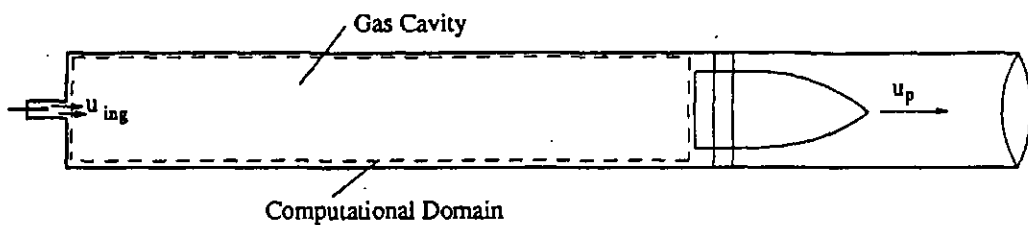
(a) Initial Stage of Firing Cycle



(b) Development of Taylor Cavity



(c) Annual Liquid Film Stage



(d) Free Expansion stage

## Coordinate Transformation

Original Coordinate :  $t, x, r$

New Coordinate :  $\tau, \eta, \zeta$

$$\tau = t, \quad \eta = x + u_c(t - t_0), \quad \zeta = r + v_w(t - t_0)$$

$$\frac{\partial(\Phi\psi\rho_g)}{\partial t} = \frac{\partial(\Phi\psi\rho_g)}{\partial \tau} + u_c \frac{\partial(\Phi\psi\rho_g)}{\partial \eta} + v_w \frac{\partial(\Phi\psi\rho_g)}{\partial \zeta}$$

## Algorithm

\* SIMPLE (Semi-Implicit Method for Pressure-Linked Equations)

\* Highly Compressible Flows :

a. Density Variation Effects on Pressure

Correction Equations

b. Equation of State - Noble Abel Equation

\*Pressure Correction Equation

$$a_p P_p = a_E P_E + a_W P_W + a_N P_N + a_S P_S$$

$$a_E = (\rho_e^* d_e - K u_e^*) A_\eta$$

$$a_W = (\rho_w^* d_w - K u_w^*) A_\eta$$

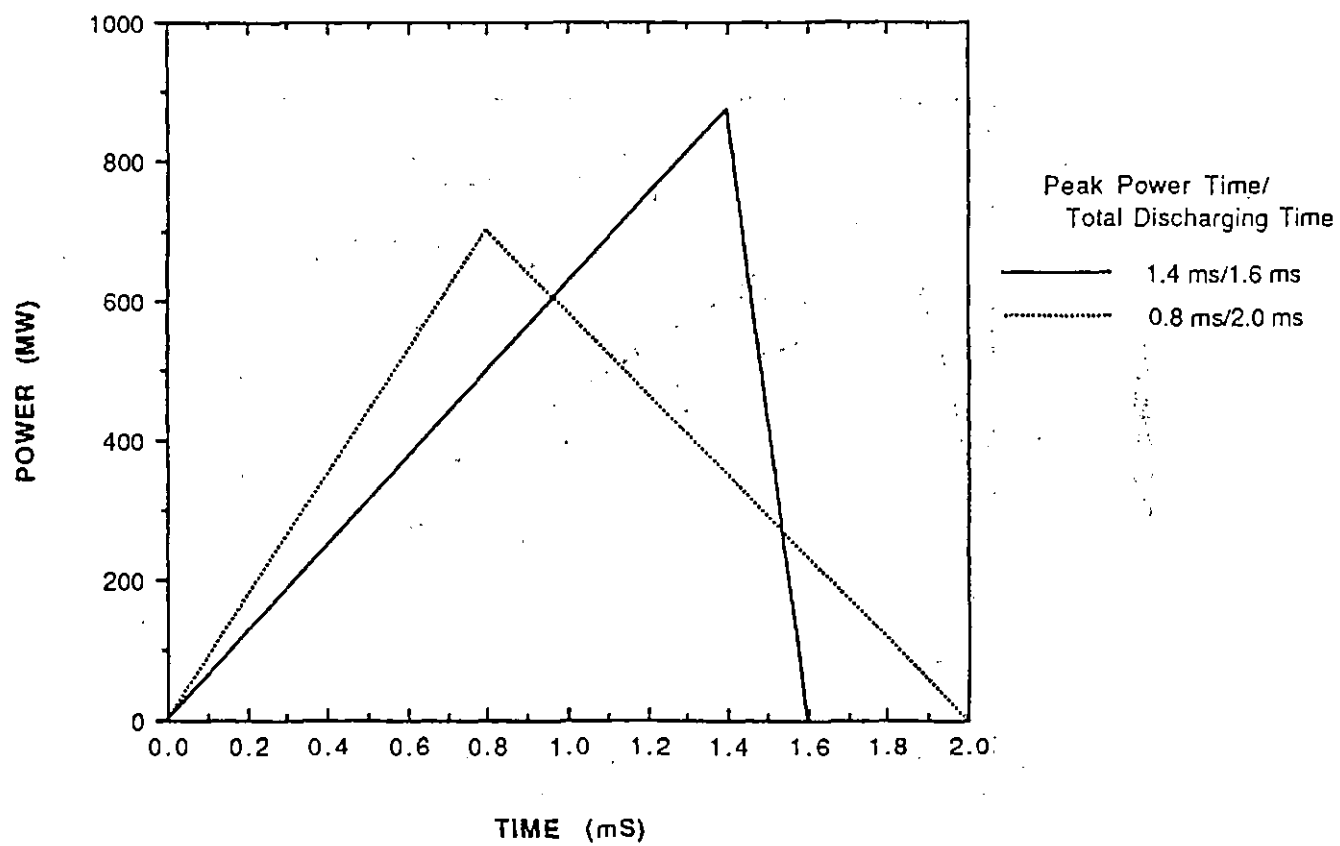
$$a_S = (\rho_s^* d_s - K u_s^*) A_\zeta$$

$$a_N = (\rho_n^* d_n - K u_n^*) A_\zeta$$

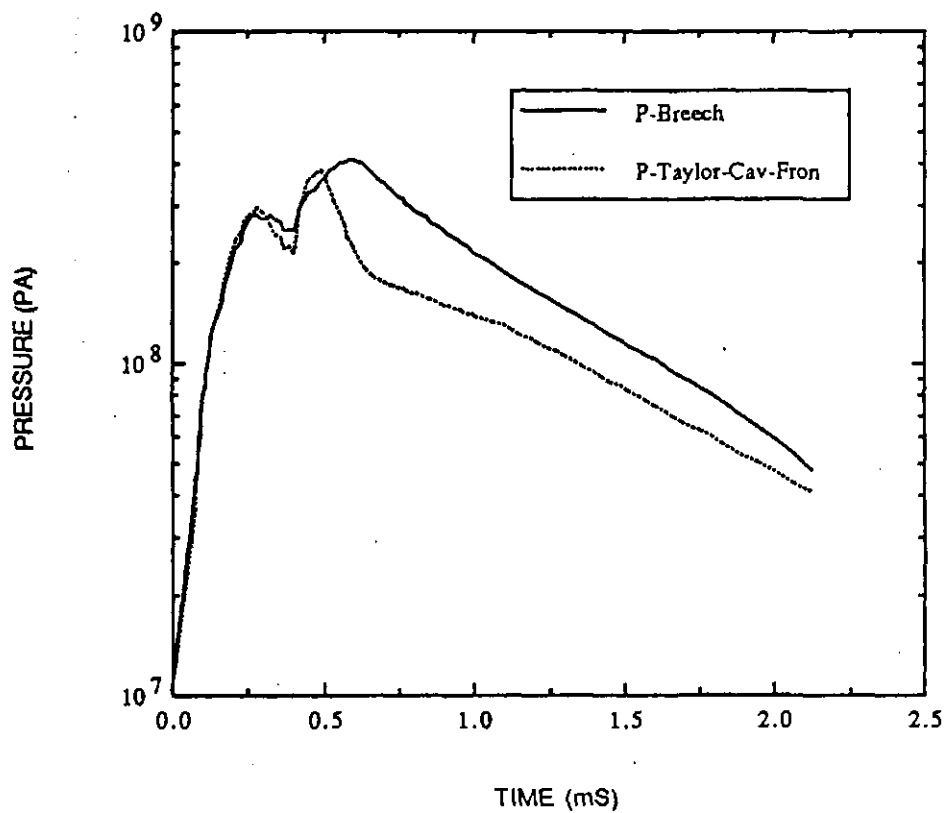
$$a_P = (\rho_n^* d_n + \rho_s^* d_s) A_\zeta + (\rho_e^* d_e + \rho_w^* d_w) A_\eta + \frac{K \Delta V}{\Delta t}$$

$$d_j = \frac{A_j}{a_j} \quad j = e, w, s, n$$

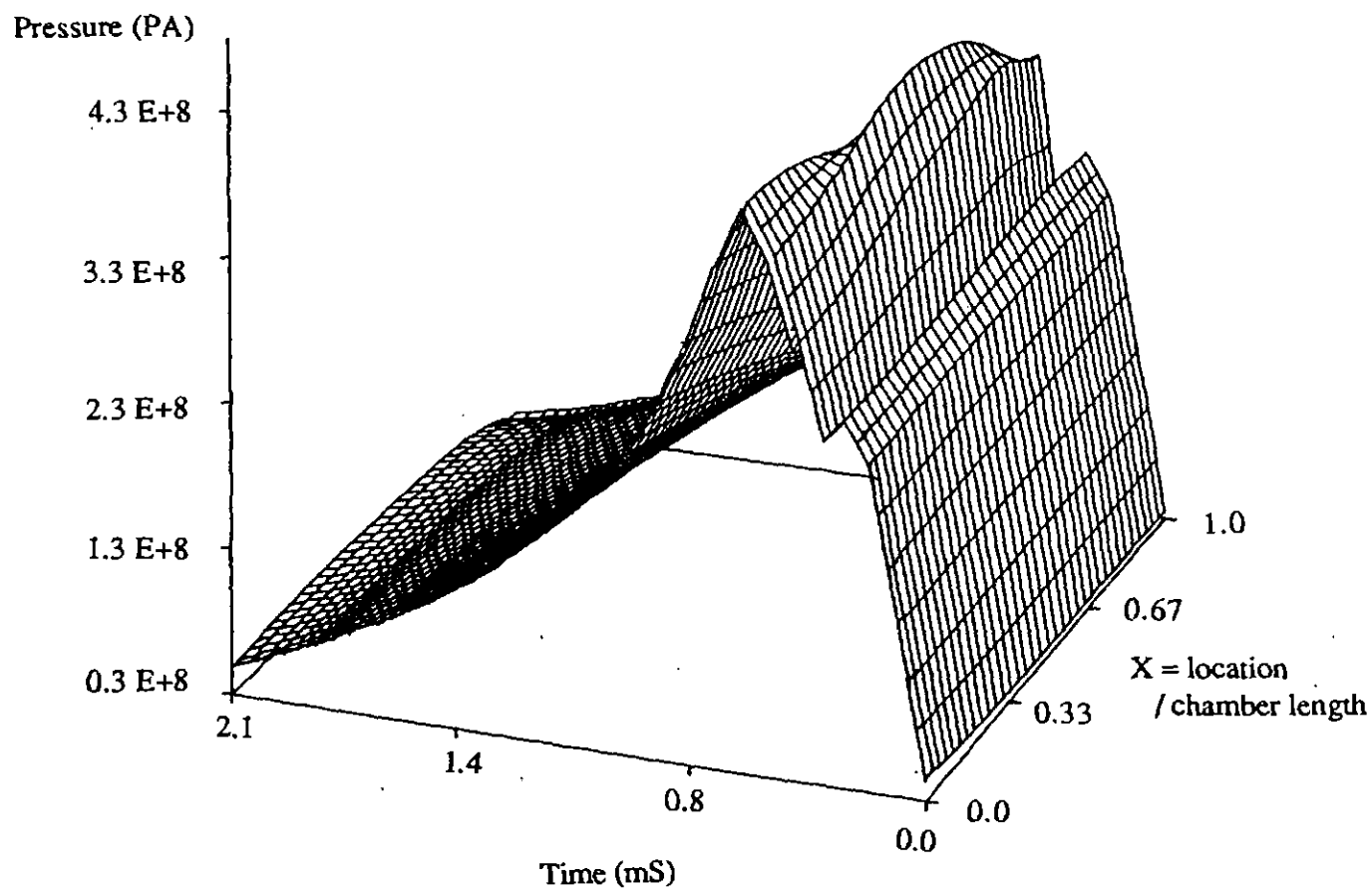
$$K = \frac{R T_g}{(P_b + R T_g)^2}$$



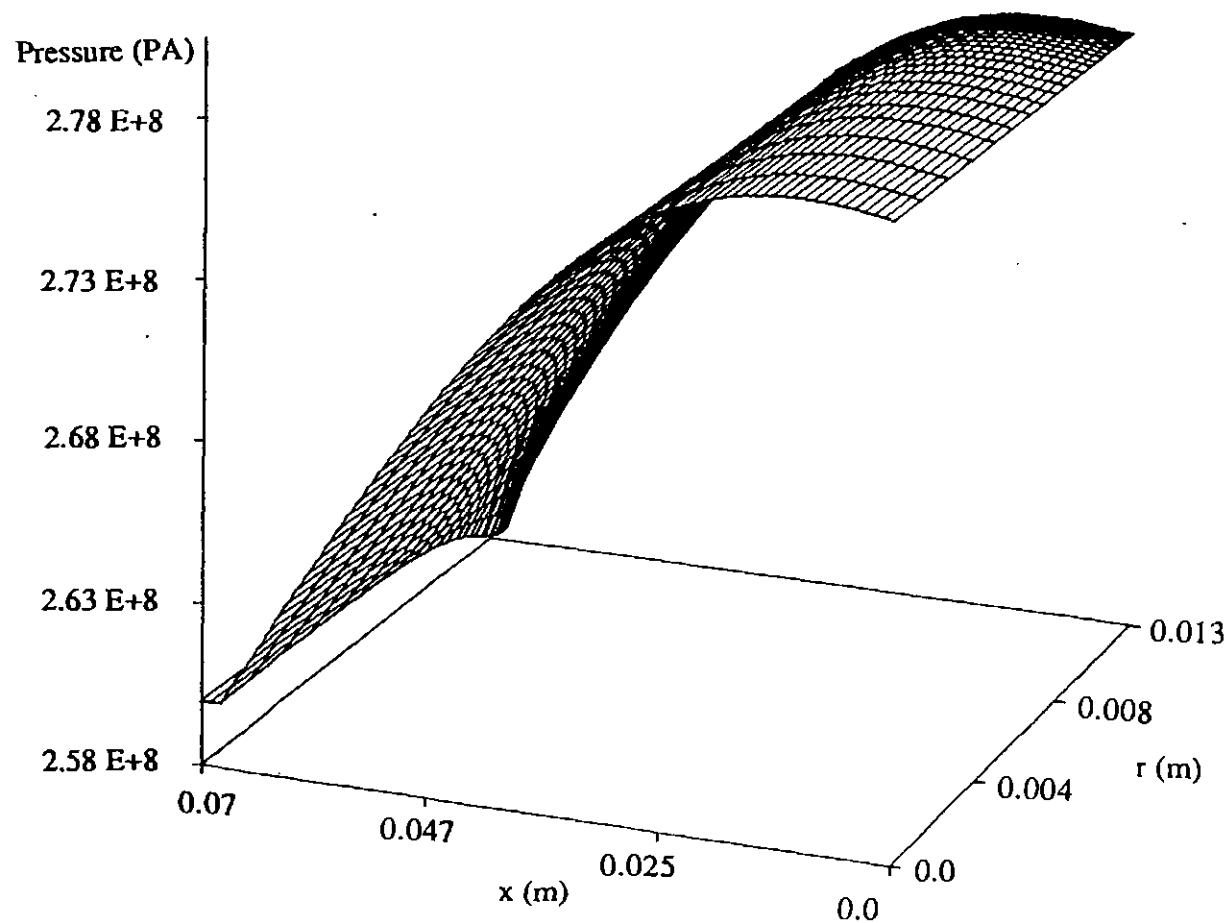




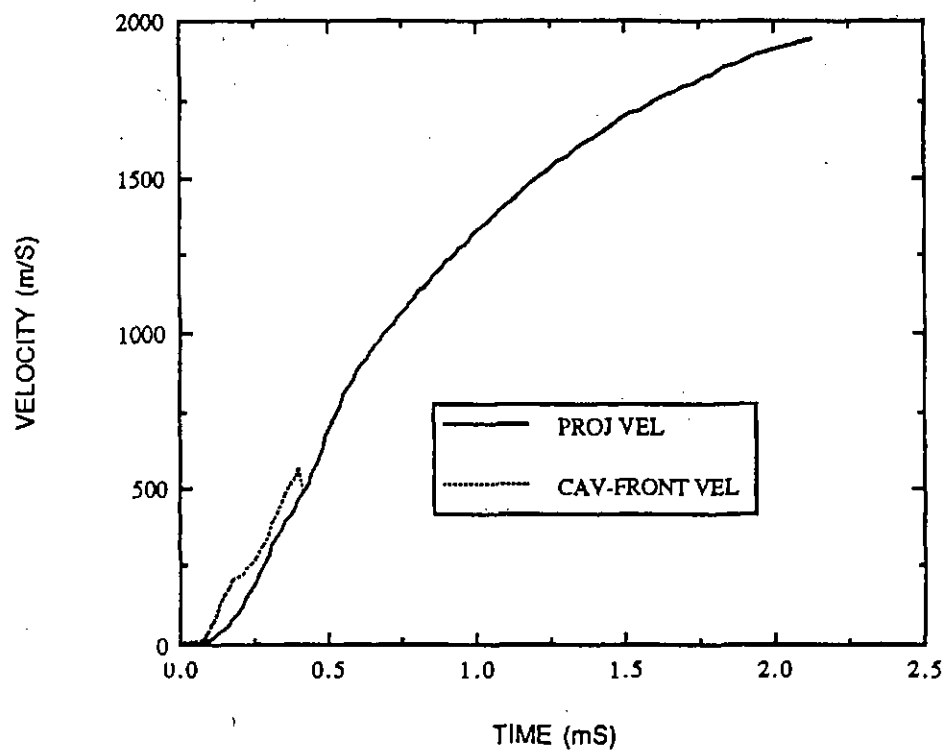
Breech and Taylor Cavity Front Pressure-Time Traces with PFN  
Discharging Time of 2.0 ms and Peak Power Time at 0.8 ms



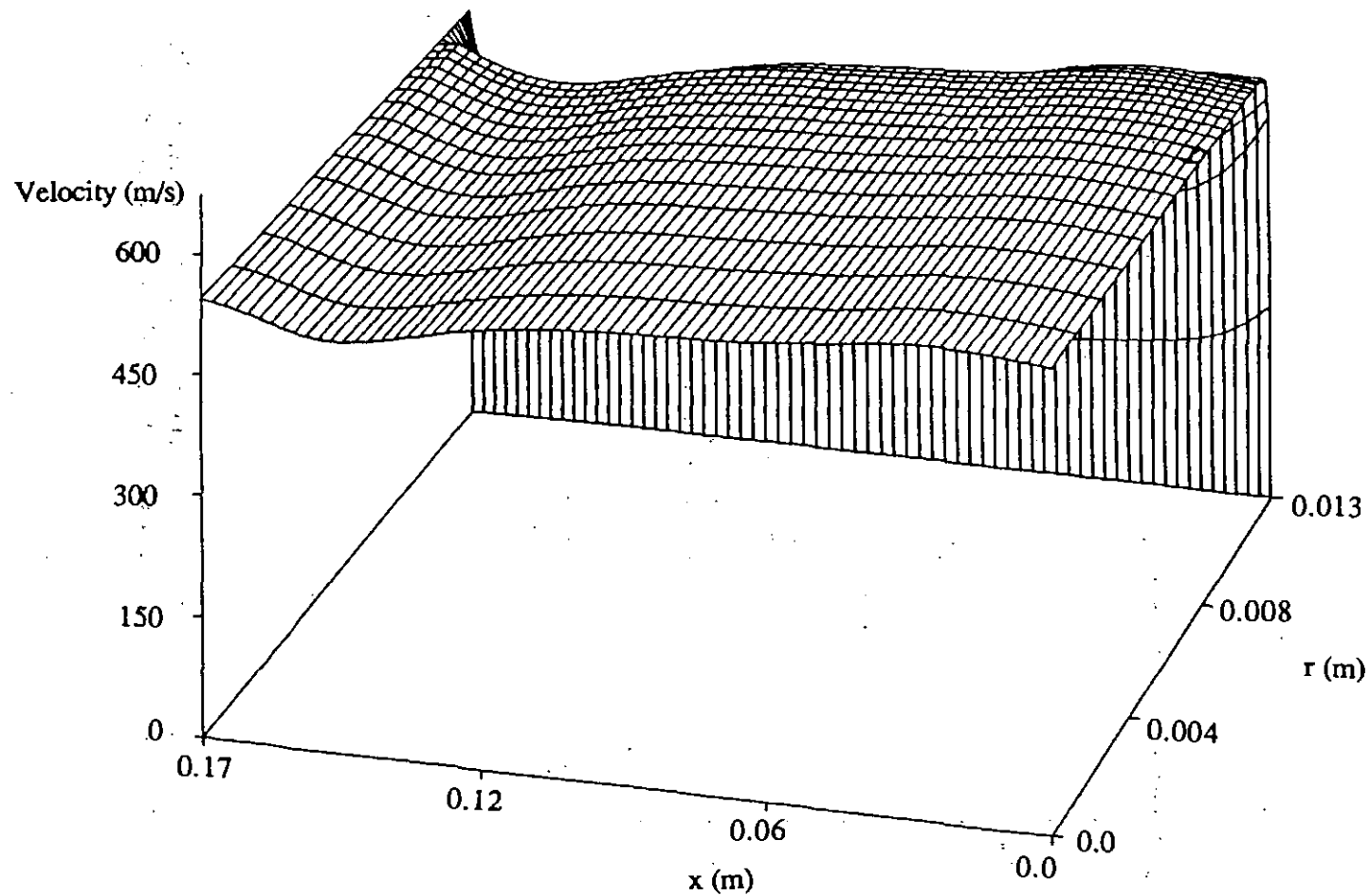
Time History of Averaged Axial Pressure in the ET Gun Chamber with PFN  
Discharging Time of 2.0 ms and Peak Power Time at 0.8 ms



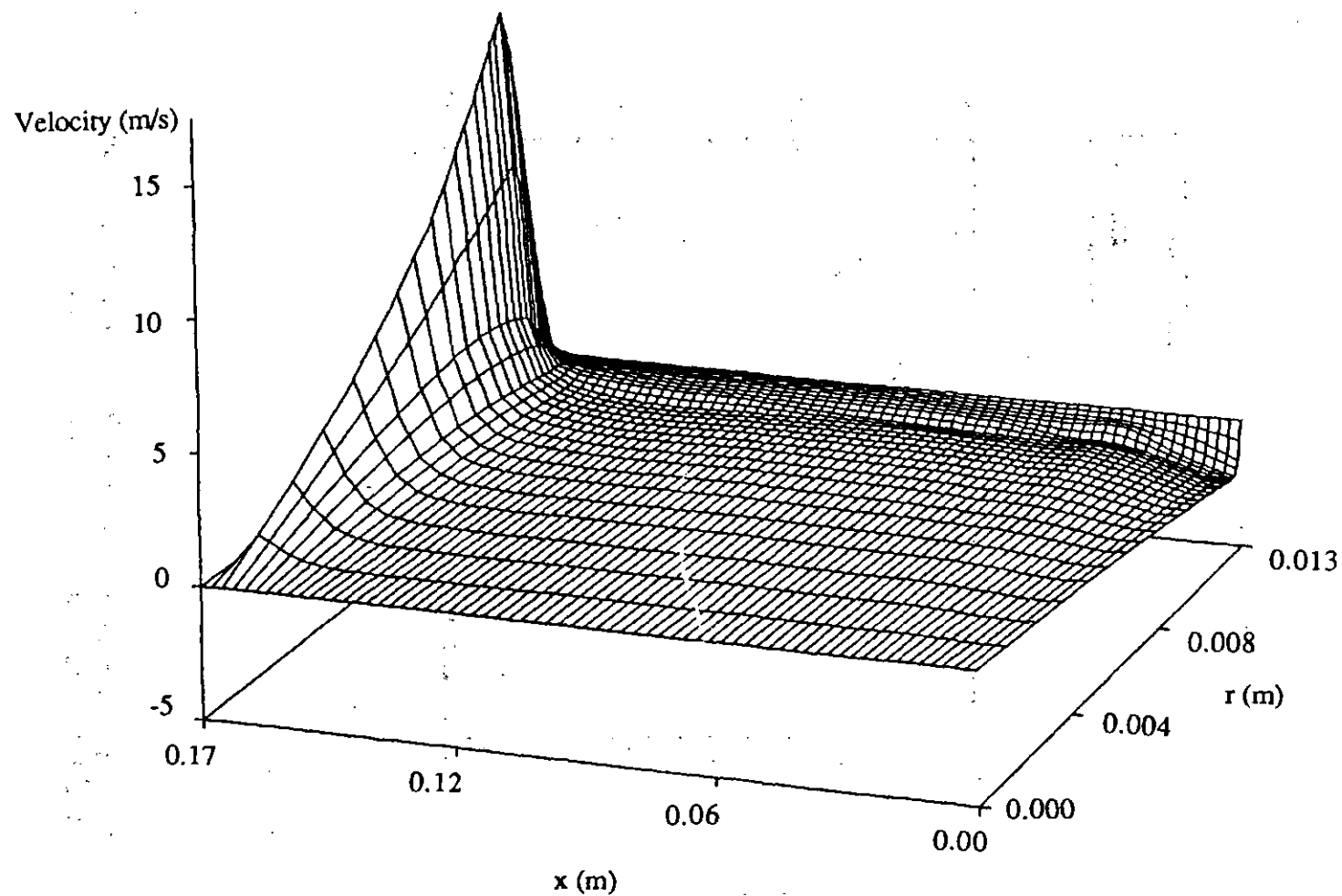
Spatial Pressure Distribution in the ET Gun Chamber at 0.33 ms with PFN  
Discharging Time of 2.0 ms and Peak Power Time at 0.8 ms



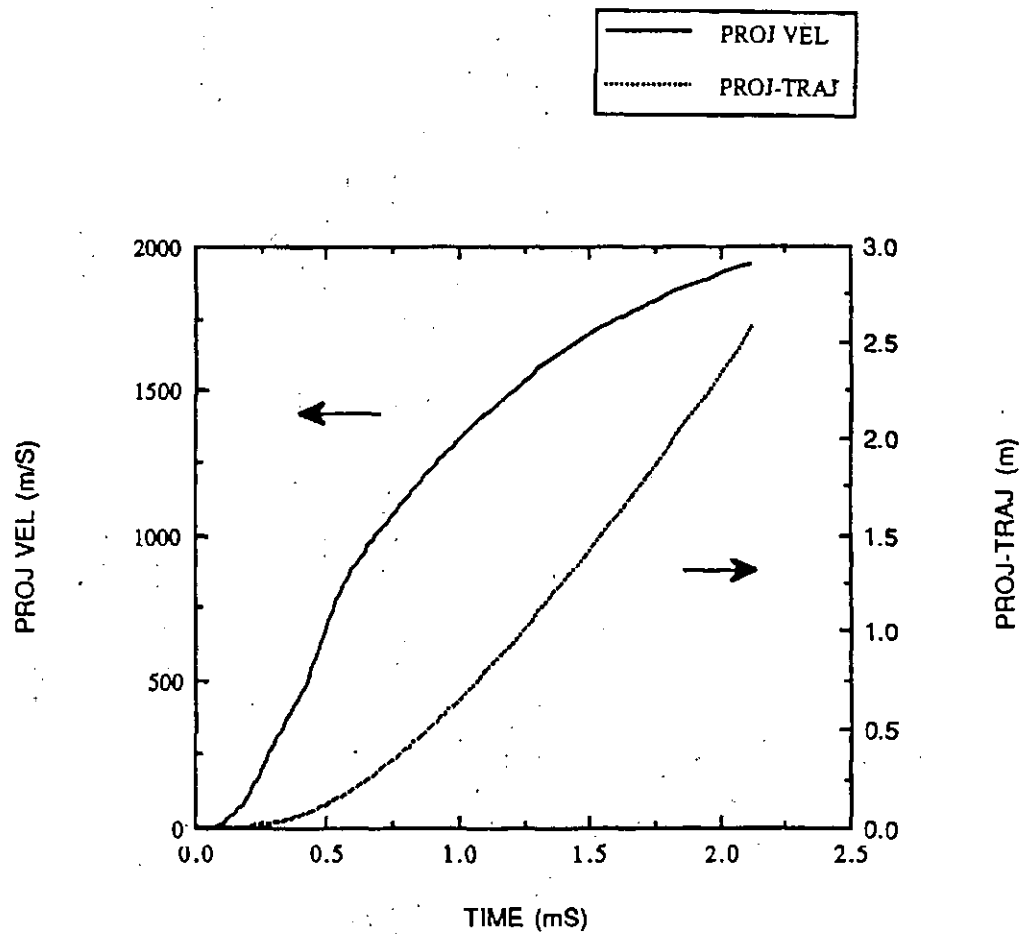
Projectile and Taylor Cavity Frontal Velocity-Time Traces with PFN  
Discharging Time of 2.0 ms and Peak Power Time at 0.8 ms



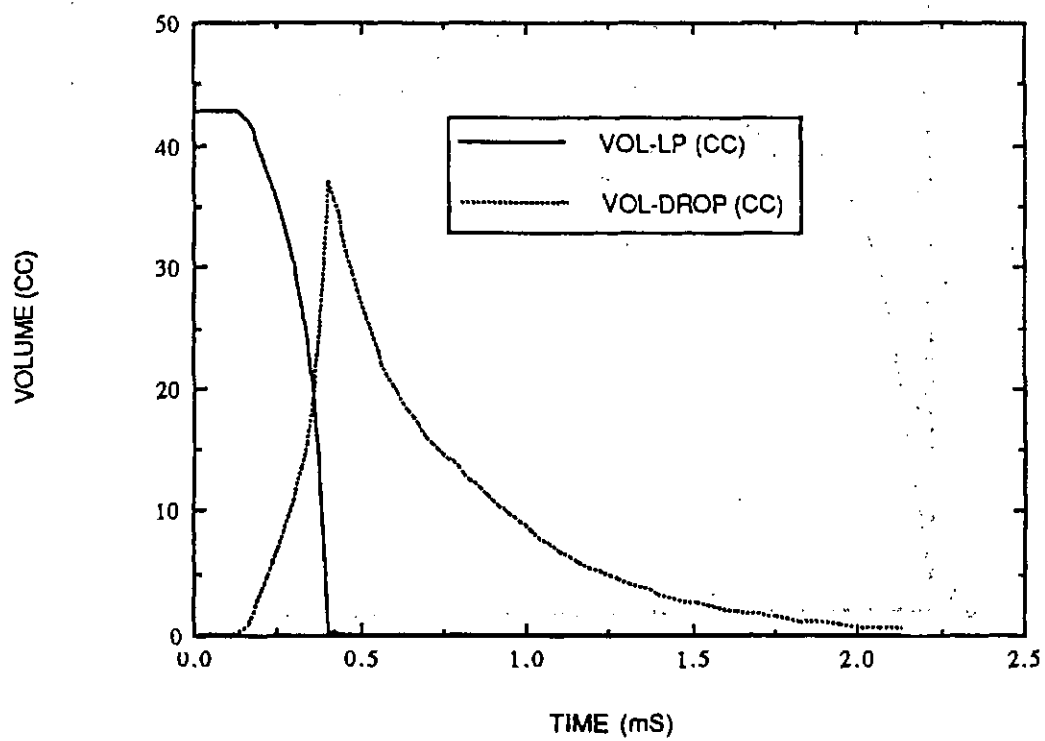
Spatial Distribution of Axial Gas Velocity in the ET Gun Chamber at 0.45 ms with PFN Discharging Time of 2.0 ms and Peak Power Time at 0.8 ms



Spatial Distribution of Radial Gas Velocity in the ET Gun Chamber at 0.45 ms with PFN Discharging Time of 2.0 ms and Peak Power Time at 0.8 ms

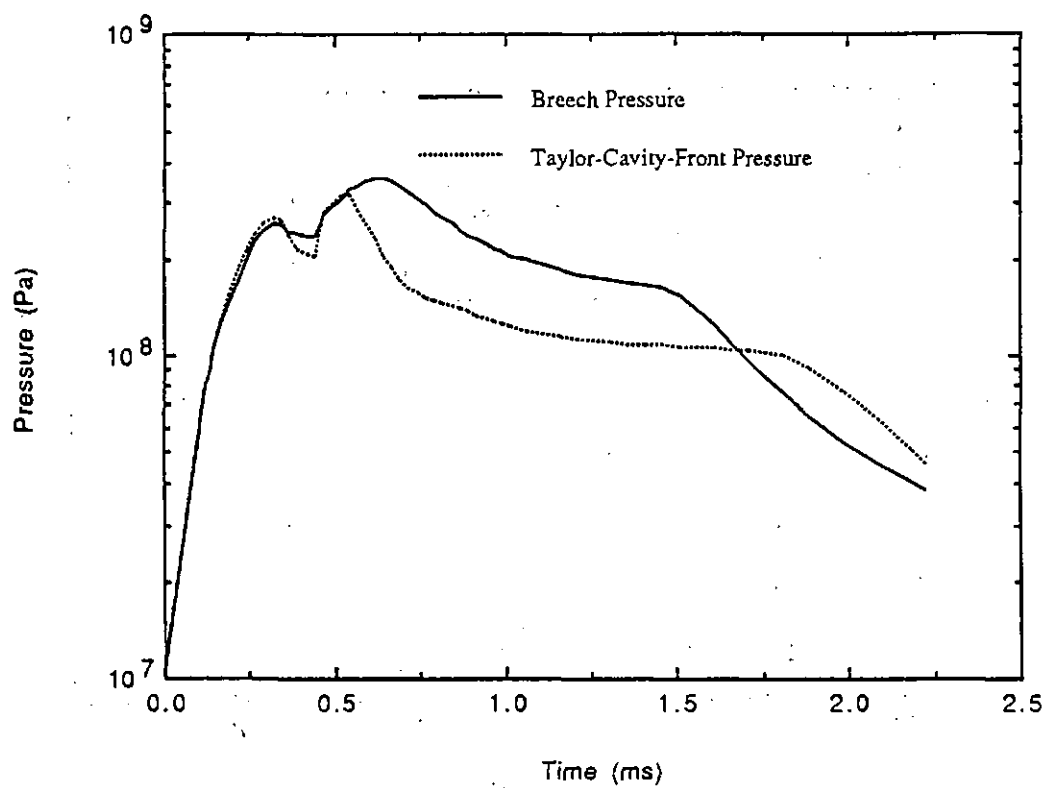


Projectile Trajectory and Velocity-Time History with PFN Discharging Time of 2.0 ms and Peak Power Time at 0.8 ms



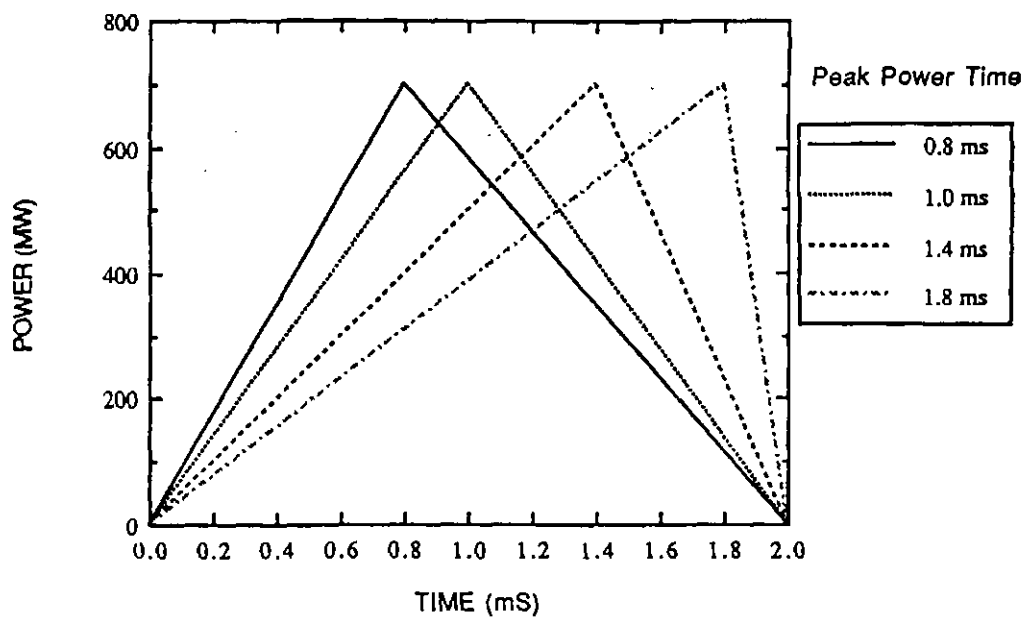
Liquid Propellant and Droplet Volume-Time Traces with PFN Discharging Time of 2.0 ms and Peak Power Time at 0.8 ms



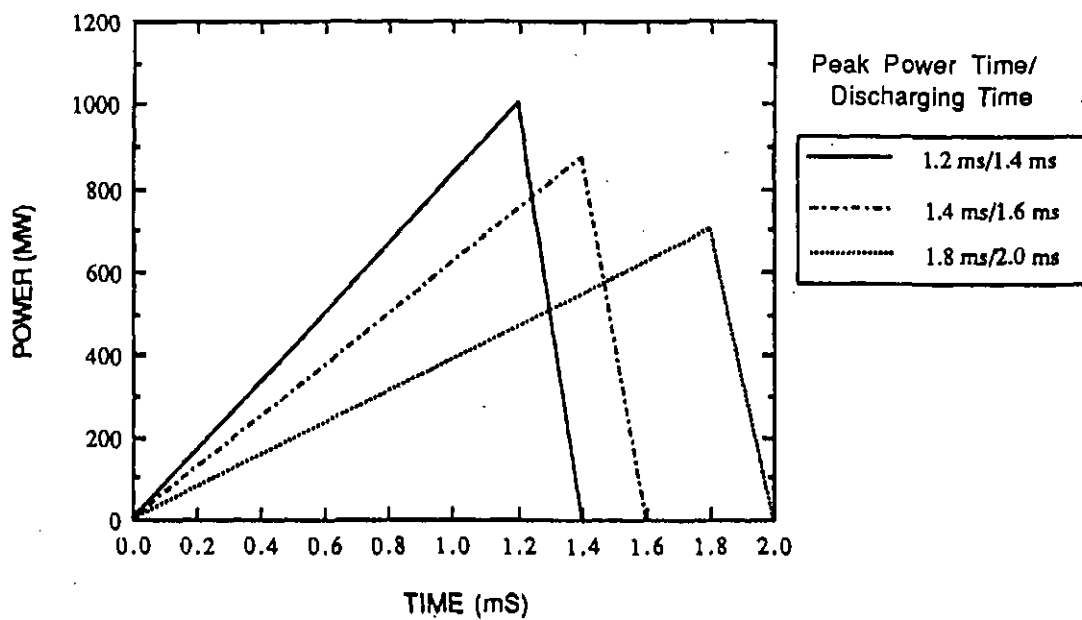


Breech and Taylor Cavity Front Pressure-Time Traces with PFN Peak Power Time at 1.4 ms and Discharging Time of 1.6 ms

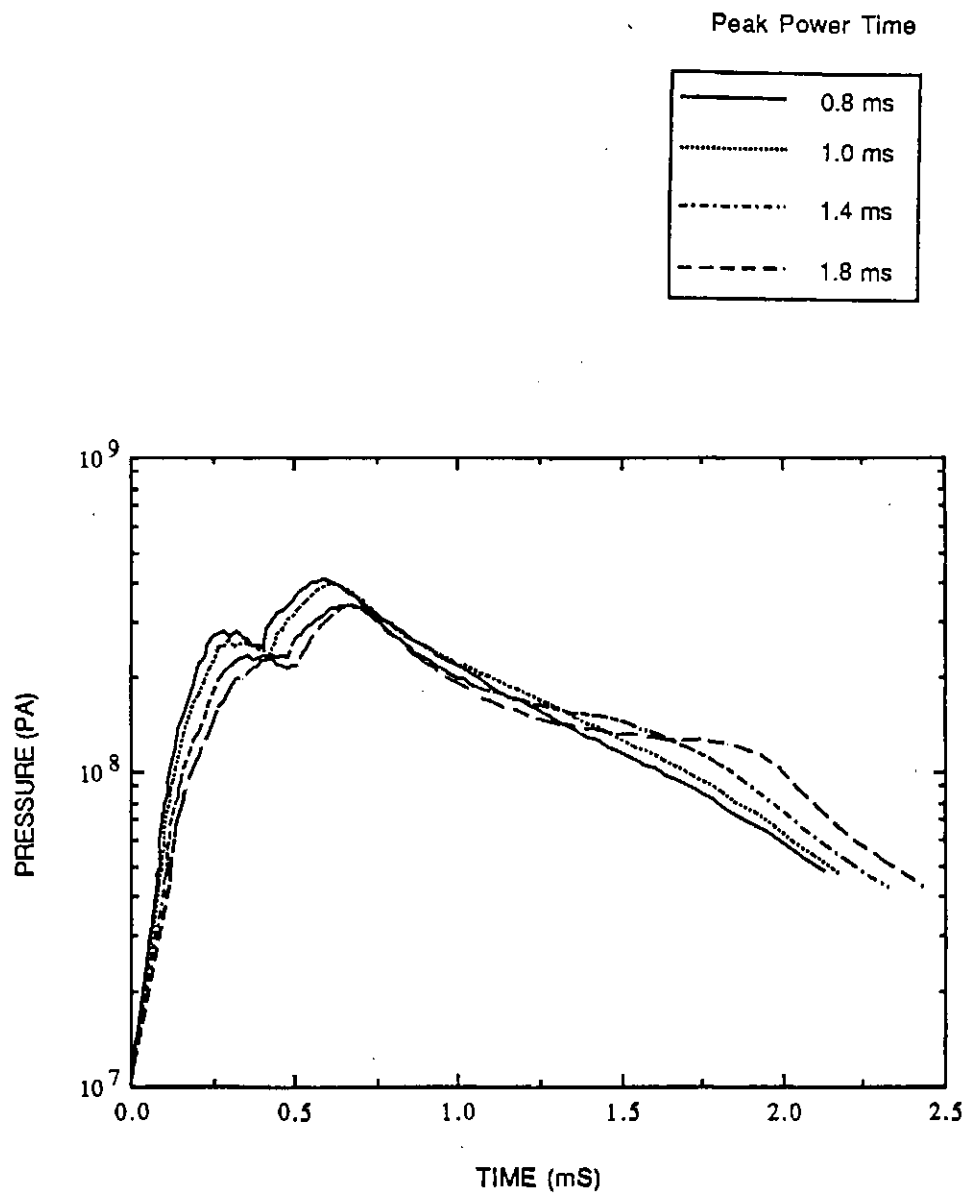
(a) Various Peak Power Times



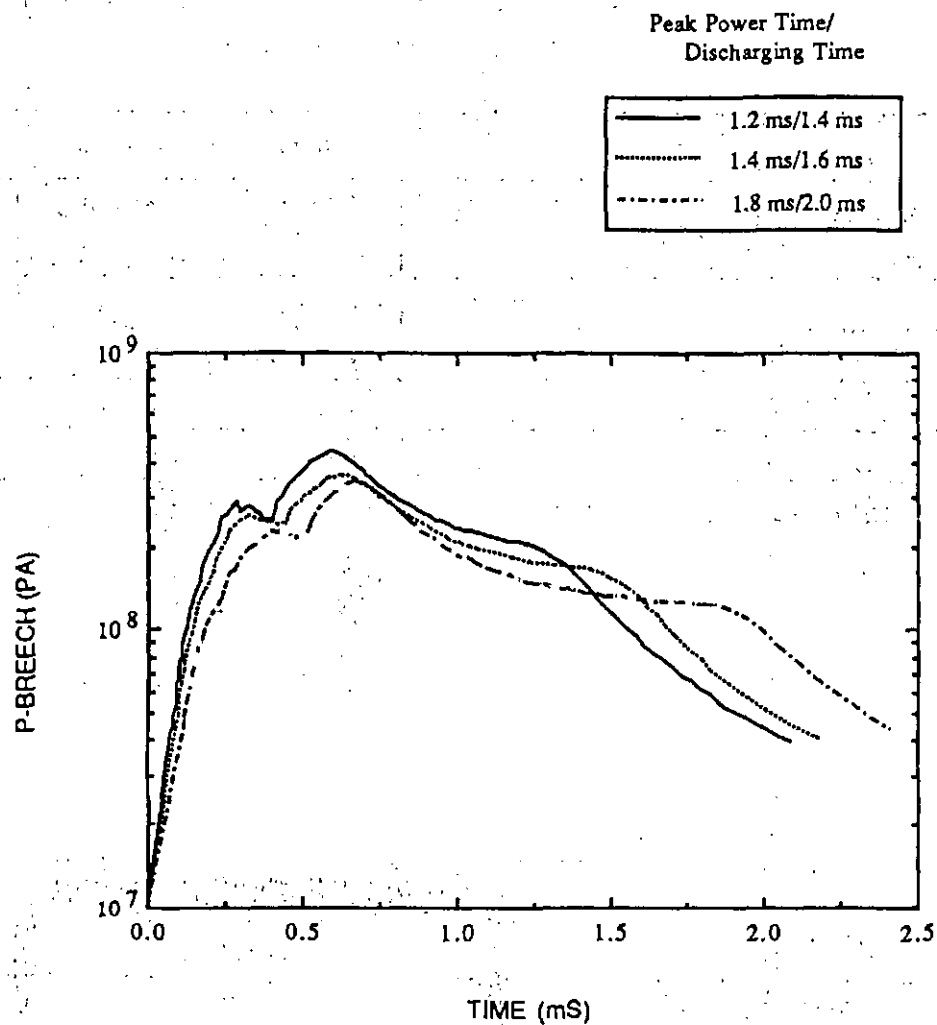
(b) Various Total Discharging Times



PFN Discharging Power Curves with (a) Various Peak Power Times and (b) Various Total Discharging Times



Breech Pressure-Time History Traces with PFN Discharging Time of 2.0 ms and Various Peak Power Times



Breech Pressure-Time Traces for Various PFN Total Discharging Times and Peak Power Times

Results from Numerical Analysis for Cases with  
Various Peak Power Times

| PFN Discharging Characteristics |                             | Interior Ballistic Data |                              |                       |                      |
|---------------------------------|-----------------------------|-------------------------|------------------------------|-----------------------|----------------------|
| Peak Power Time (ms)            | Total Discharging Time (ms) | Event Time (ms)         | Maximum Breech Pressure (PA) | Muzzle Velocity (m/s) | Ballistic Efficiency |
| 0.8                             | 2.0                         | 2.11                    | $4.10 \times 10^8$           | 1936                  | 12.0 %               |
| 1.0                             | 2.0                         | 2.18                    | $3.95 \times 10^8$           | 1924                  | 11.8 %               |
| 1.4                             | 2.0                         | 2.32                    | $3.40 \times 10^8$           | 1882                  | 11.0 %               |
| 1.8                             | 2.0                         | 2.43                    | $3.39 \times 10^8$           | 1822                  | 10.6 %               |

\*Electrical Energy 0.7 MJ, Chemical Energy 0.4 MJ

Results from Numerical Analysis for Cases with  
Total Discharging Times

| PFN Discharging Characteristics |                             | Interior Ballistic Data |                              |                       |                      |
|---------------------------------|-----------------------------|-------------------------|------------------------------|-----------------------|----------------------|
| Peak Power Time (ms)            | Total Discharging Time (ms) | Event Time (ms)         | Maximum Breech Pressure (PA) | Muzzle Velocity (m/s) | Ballistic Efficiency |
| 1.2                             | 1.4                         | 2.08                    | $3.60 \times 10^8$           | 2048                  | 13.3 %               |
| 1.4                             | 1.6                         | 2.22                    | $3.40 \times 10^8$           | 1972                  | 12.4 %               |
| 1.8                             | 2.0                         | 2.43                    | $3.39 \times 10^8$           | 1822                  | 10.6 %               |

\*Electrical Energy 0.7 MJ, Chemical Energy 0.4 MJ

# Interior Ballistic Results from Present Work and Literature

## (a) Measured Results

| Source              | Gun (mm) | Barrel (caliber) | Projectile Mass (gm) | Muzzle Vel (km/S) | Electrical Eng (kJ) | Working Fluid         | Electrical+ Efficiency | Ballistic+ Efficiency | Max Breech P (psi) |
|---------------------|----------|------------------|----------------------|-------------------|---------------------|-----------------------|------------------------|-----------------------|--------------------|
| Greig et al (1988)  | 20       | 100              | 8                    | 3.5               | 700                 | *                     | 7%                     | *                     | *                  |
| Greig et al (1988)  | 20       | 100              | 21                   | 2.8               | 700                 | *                     | 11.8%                  | *                     | 55,000 - 74,000    |
| Greig et al (1988)  | 20       | 100              | 50                   | 2.1               | 700                 | *                     | 15.7%                  | *                     | *                  |
| Greig et al (1988)  | 30       | 100              | 102                  | 1.43              | 2000                | *                     | 5.2%                   | *                     | *                  |
| Chrysomallis (1988) | 10       | *                | 1 - 6.5              | 1.2 - 1.7         | 190 - 325           | exothermic propellant | 25 - 40%               | *                     | 30,000 - 40,000    |
| Chrysomallis (1988) | 30       | 85               | 50 - 380             | 1.1 - 2.75        | 240 - 850           | exothermic propellant | 25 - 90%               | *                     | 45,000 - 75,000    |
| Chrysomallis (1988) | 90       | *                | 1100 - 1200          | 1.0 - 1.3         | 800 - 1100          | exothermic propellant | 75 - 95%               | *                     | 20,000 - 35,000    |
| Chrysomallis (1988) | 105      | *                | 2000 - 6000          | 0.7 - 1.5         | 1000 - 4000         | exothermic propellant | 90 - 130%              | *                     | 20,000 - 40,000    |

\* Data Unavailable

+Electrical Efficiency = Projectile Kinetic Energy / Input Electrical Energy

Ballistic Efficiency = Projectile Kinetic Energy / Total Input Energy

## (b) Predicted Results

| Source        | Gun (mm) | Barrel (caliber) | Projectile Mass (gm) | Muzzle Vel (km/s) | Working Fluid                                                 | Electrical Engy (kJ) | Total Engy (kJ) | Electrical Efficiency | Ballistic Efficiency |
|---------------|----------|------------------|----------------------|-------------------|---------------------------------------------------------------|----------------------|-----------------|-----------------------|----------------------|
| Oberle (1988) | 14       | 100              | 18                   | 2.17              | H <sub>2</sub> O                                              | 447.8                | 368.6           | 9%                    | 10.9%                |
| Oberle (1988) | 14       | 100              | 18                   | 2.34              | LiBH <sub>4</sub>                                             | 449.8                | 406.4           | 10.9%                 | 12.1%                |
| Oberle (1988) | 14       | 100              | 18                   | 1.75              | TiH <sub>2</sub> /Al                                          | 77.9                 | 222.2           | 35.6%                 | 12.5%                |
| Oberle (1988) | 14       | 100              | 18                   | 2.13              | C <sub>8</sub> H <sub>18</sub> /H <sub>2</sub> O <sub>2</sub> | 43.3                 | 322.6           | 94.2%                 | 12.6%                |
| Present Work+ | 25       | 100              | 70                   | 1.94 - 2.05       | C <sub>8</sub> H <sub>18</sub> /H <sub>2</sub> O <sub>2</sub> | 700                  | 1100            | 18.7 - 21.0%          | 10.6 - 13.3%         |

+ Max Breech Pressure = 52,900 - 60,200 psi,

Gun System Information: Projectile Mass = 70 gm, Residual Air = 5%, Chamber Length/Diameter = 3.5, Electrical Energy = 0.7 MJ, Total Energy = 1.1 MJ, Working Fluid = C<sub>8</sub>H<sub>18</sub>/H<sub>2</sub>O<sub>2</sub>

## Conclusions

1. A comprehensive theoretical model describing the interior ballistic processes of an ET gun has been formulated.
2. The effects of PFN discharging characteristics on gun performance have been identified.
3. Muzzle velocity can be optimized by tailoring the PFN discharging time and peak power time while holding a moderate maximum breech pressure.

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# **FINITE-ELEMENT MODELING OF ELECTROTHERMAL-CHEMICAL GUNS**

N. K. Winsor and S. A. Goldstein  
GT-Devices, Inc.  
Alexandria, VA 22312

## **ABSTRACT**

Two-dimensional modeling of reactive flow dynamics in an electrothermal cartridge is described and illustrated. Special emphasis will be placed on the effects of ullage and rate-dependent chemistry on large-scale wave dynamics.

**1991 JANNAF ETC Modeling Workshop**  
**FINITE-ELEMENT MODELING OF**  
**ELECTROTHERMAL-CHEMICAL GUNS**

**N. K. WINSOR & S. A. GOLDSTEIN**

**GT-DEVICES, INC.**

*A subsidiary of General Dynamics Land Systems*

**5705A General Washington Drive**

**Alexandria, VA 22312-2408**

**703-642-8150**

# **SPECIAL THANKS TO:**

**Simon Wang**

**Bob Greig**

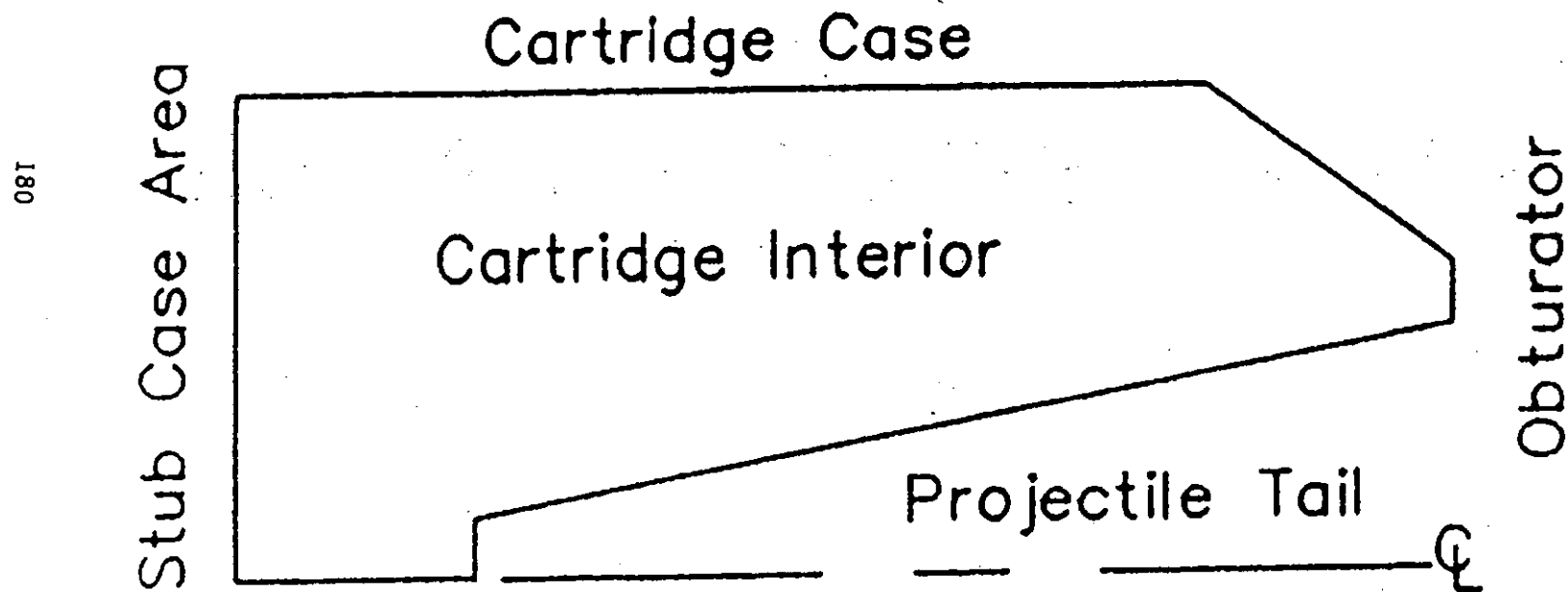
**Hugh McElroy**

**Steven Bunte**

**William Oberle**

# CARTRIDGE GEOMETRY

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# **OUTLINE**

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**FINITE-ELEMENT MODEL**

**WATER HAMMER TESTS**

**CLOSED BOMB EXPTS.**

**IBHVG2 #6 SIMULATION**

# **SUMMARY**

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- 1. WATER HAMMER: SOUND SPEED  
DEPENDENCE ON PRESSURE IS KEY  
TO DYNAMICS OF ELECTROTHERMAL  
AND LIQUID PROPELLANT GUNS.**
- 2. CLOSED BOMB: AN IDEAL METHOD  
FOR VALIDATING BURN MODELS.**
- 3. IBHVG2 TEST: UNSTRUCTURED  
FINITE-ELEMENT METHODS WORK  
SPECTACULARLY IN GUN GEOMETRY!**

# **FINITE-ELEMENT ETC MODEL (FETC)**

**NAVIER-STOKES EQ. OF MOTION**

**4th TIME, 2nd SPACE FCT ALG.**

**UNSTRUCTURED FINITE-ELT. GRID**

**DETAILED CARTRIDGE GEOMETRY**

**DETAILED PROPELLANT CHEMISTRY**

# NAVIER-STOKES

## TRANSPORT EQUATIONS

$$\frac{\partial U}{\partial t} + \frac{\partial F_a^x}{\partial x} + \frac{1}{r} \frac{\partial F_a^r}{\partial r} = \frac{S_a}{r} + \frac{\partial F_v^x}{\partial x} + \frac{1}{r} \frac{\partial F_v^r}{\partial r} + \frac{S_v}{r}$$

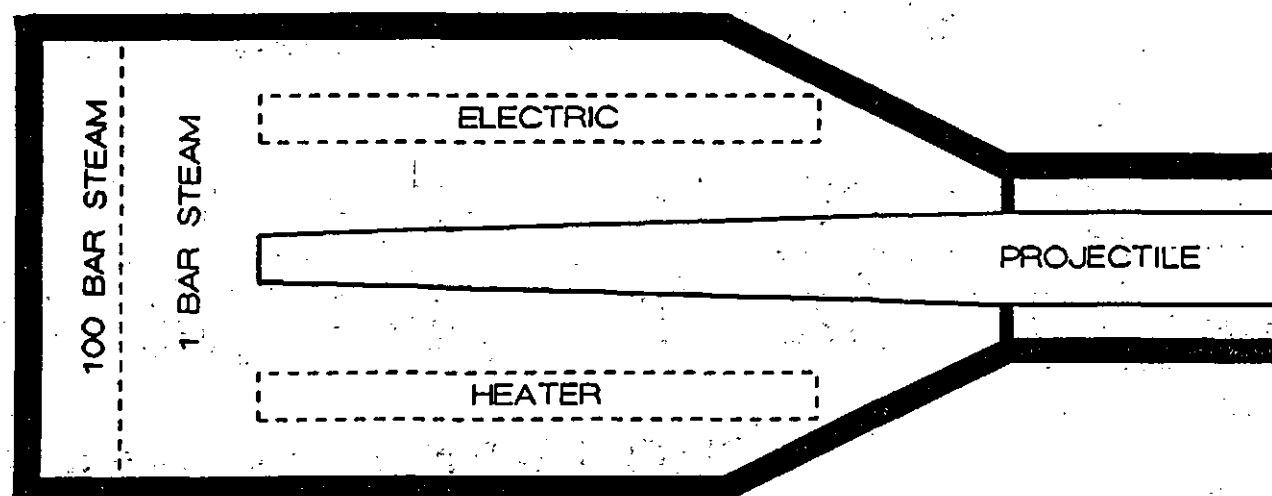
## STATE VECTOR AND FLUXES

$$U = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho e \end{bmatrix}, F_a^x = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ uH \end{bmatrix}, F_a^r = \begin{bmatrix} r\rho v \\ r\rho uv \\ r\rho v^2 + rp \\ rvH \end{bmatrix}, H = \rho e + p$$



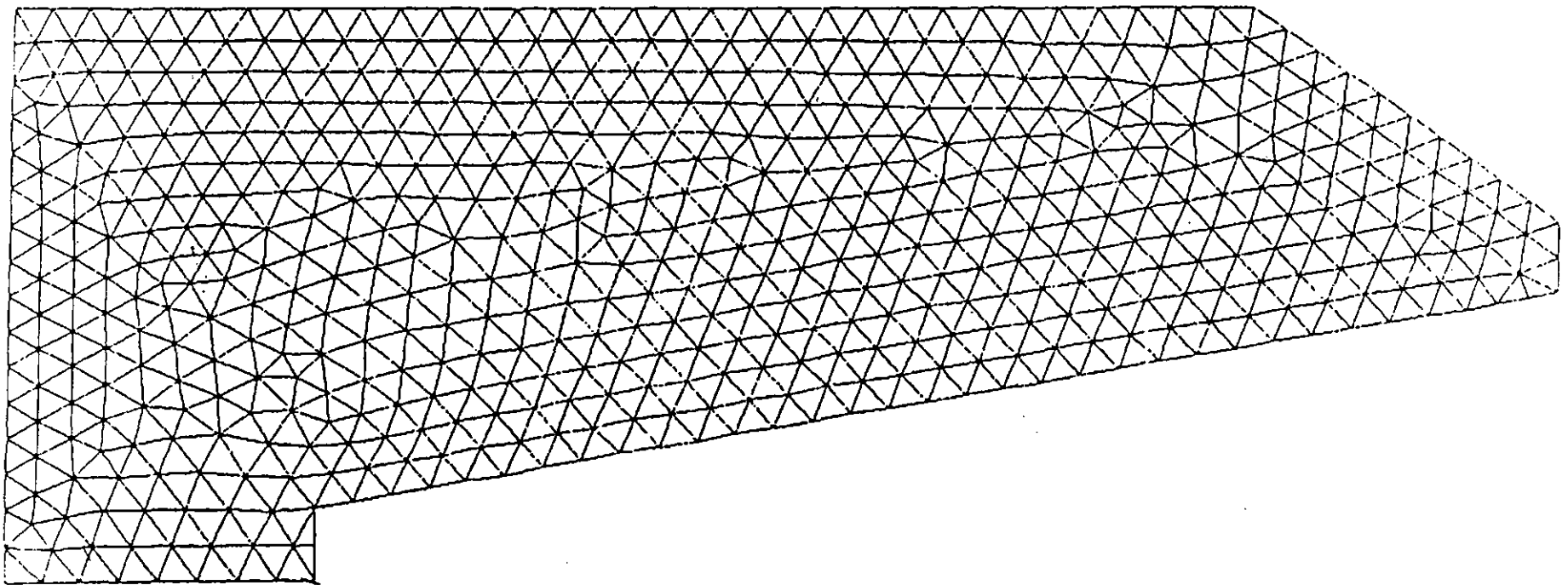


# SCHEMATIC GEOMETRY



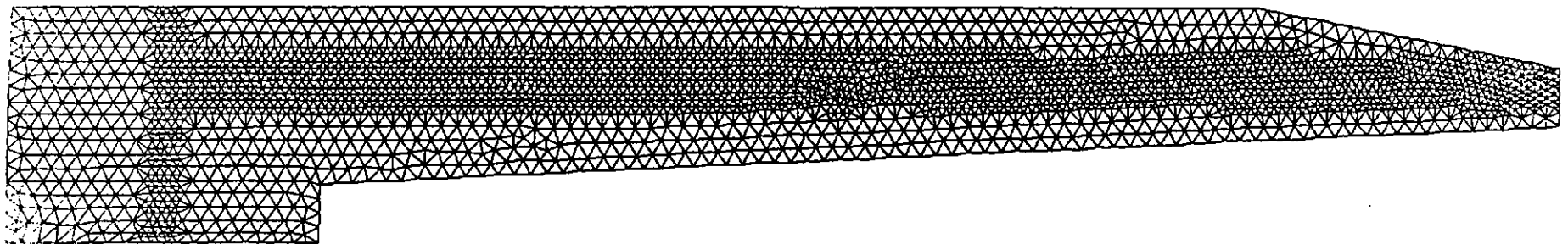
# BASIC GRID STRUCTURE

186



## SELECTIVELY-REFINED GRID

187



# **WATER HAMMER TESTS**

**WATER EQUATION OF STATE**

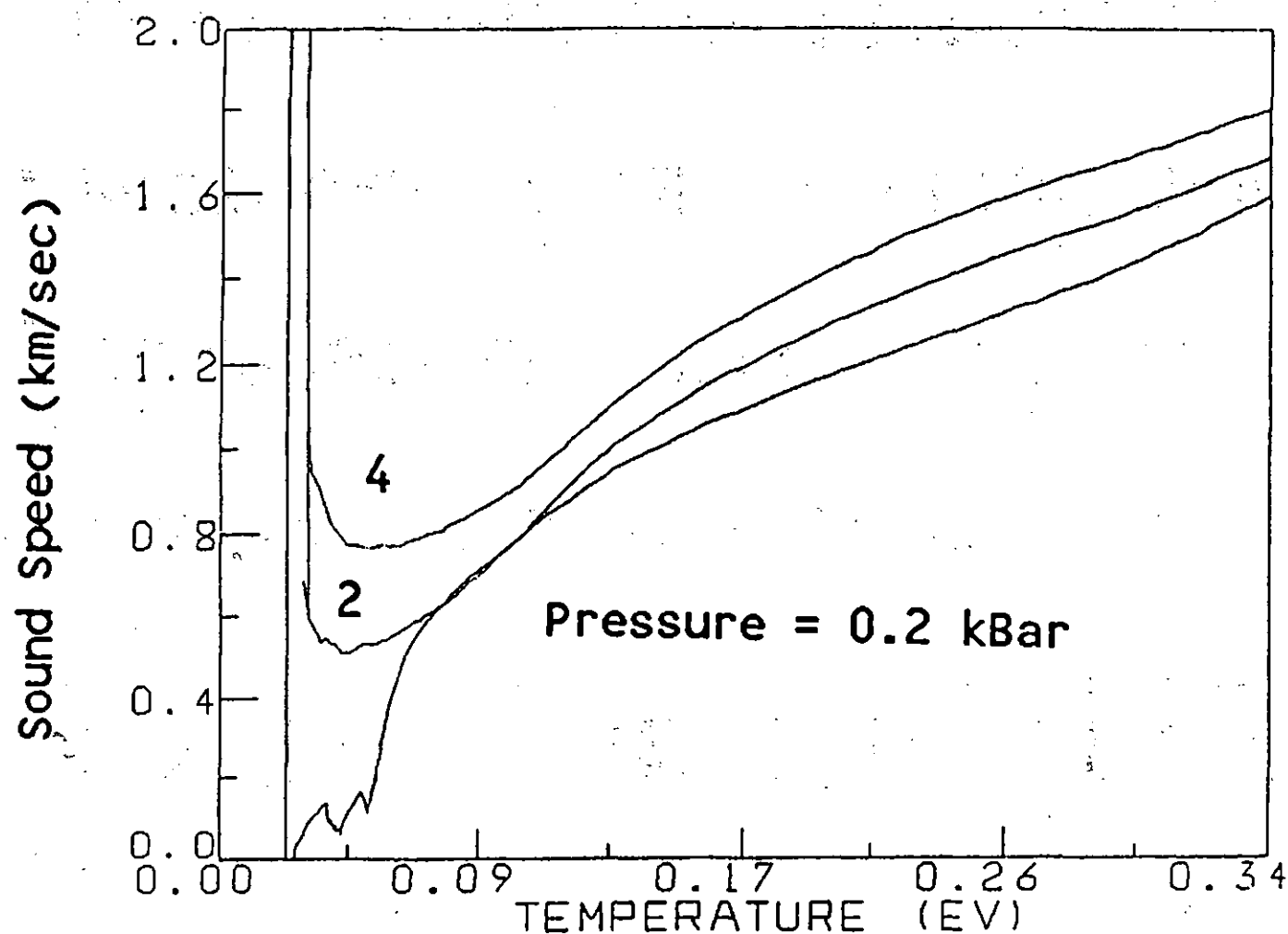
**COMBUSTIBLE STUB CASE "VOID"**

**PRESSURE WAVE -> SHOCK WAVE**

**LARGE AMPLITUDE TRANSIENTS**

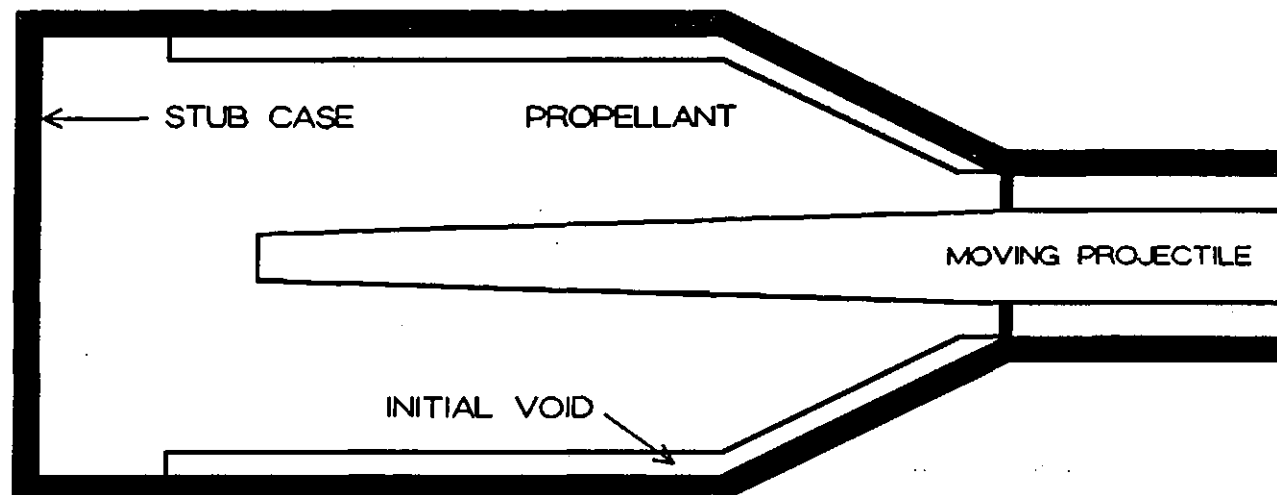
**HOW TO CONTROL THEM**

# SOUND SPEED VS. TEMPERATURE



# **120mm GEOMETRY**

**COMBUSTIBLE CASE, VIEWED AS**



**INITIAL VOID, LIMITING SOUND SPEED.**

# **SOUND SPEED**

---

**REDUCED BY:**

**LOW PRESSURE**

**BUBBLES**

**OTHER VOIDS**

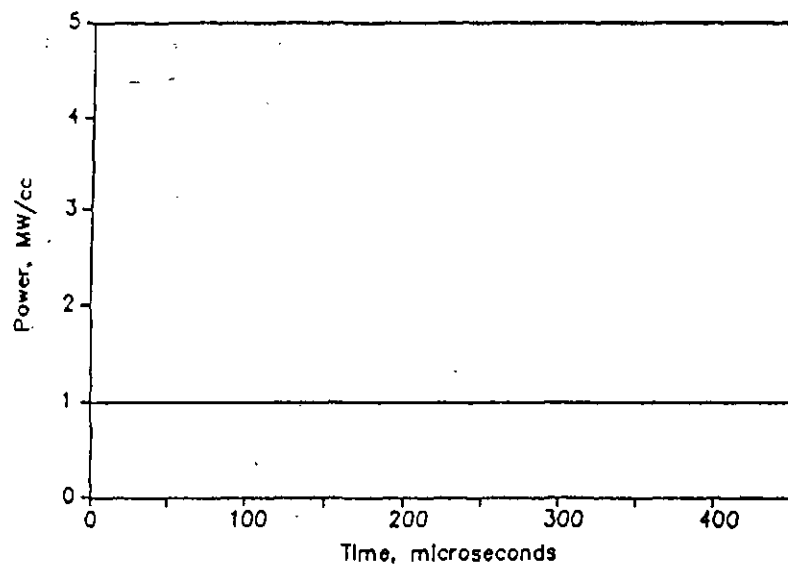
**EFFECTS:**

**SNOWPLOW SHOCK**

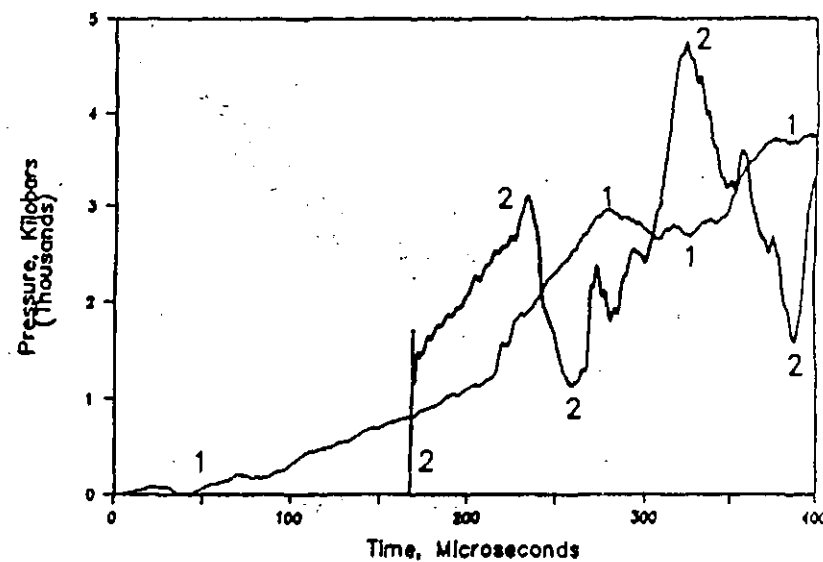
**WATER HAMMER**

## CASE 1. UNIFORM POWER INPUT

POWER VS. TIME



PRESSURE VS. TIME



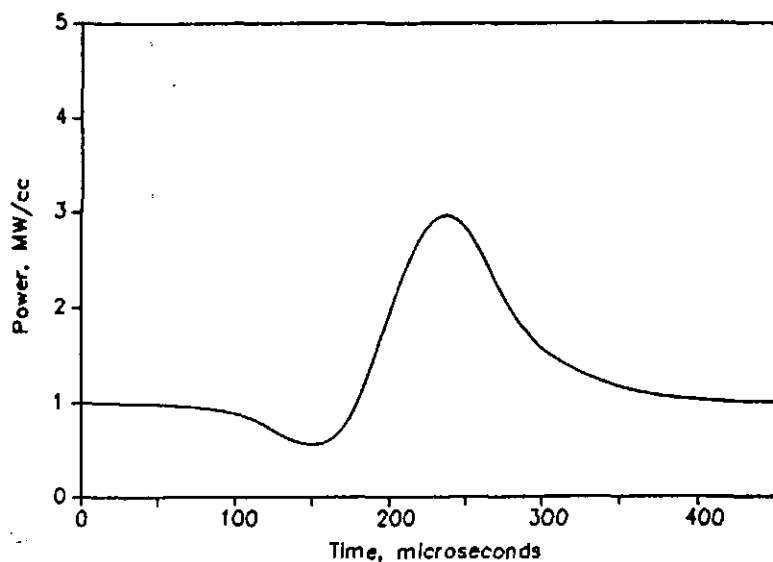
1 - IGNITER

2 - REFLECTOR

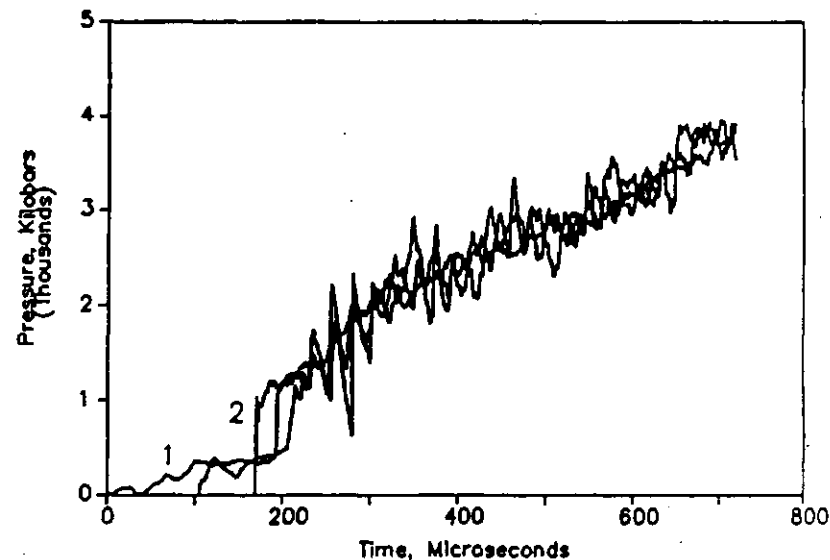


## CASE 2. TAILORED POWER DISTRIBUTION

POWER VS. TIME



PRESSURE VS. TIME



1 - IGNITER

2 - REFLECTOR

# **CONTROL OF TRANSIENTS**

**SEND A COMPRESSION WAVE**

**MINIMIZE THE SNOWPLOW**

**MEET THE REFLECTION**

**BE GENTLE!**

# **CLOSED-BOMB EXPTS.**

**FIXED-WALL GEOMETRY**

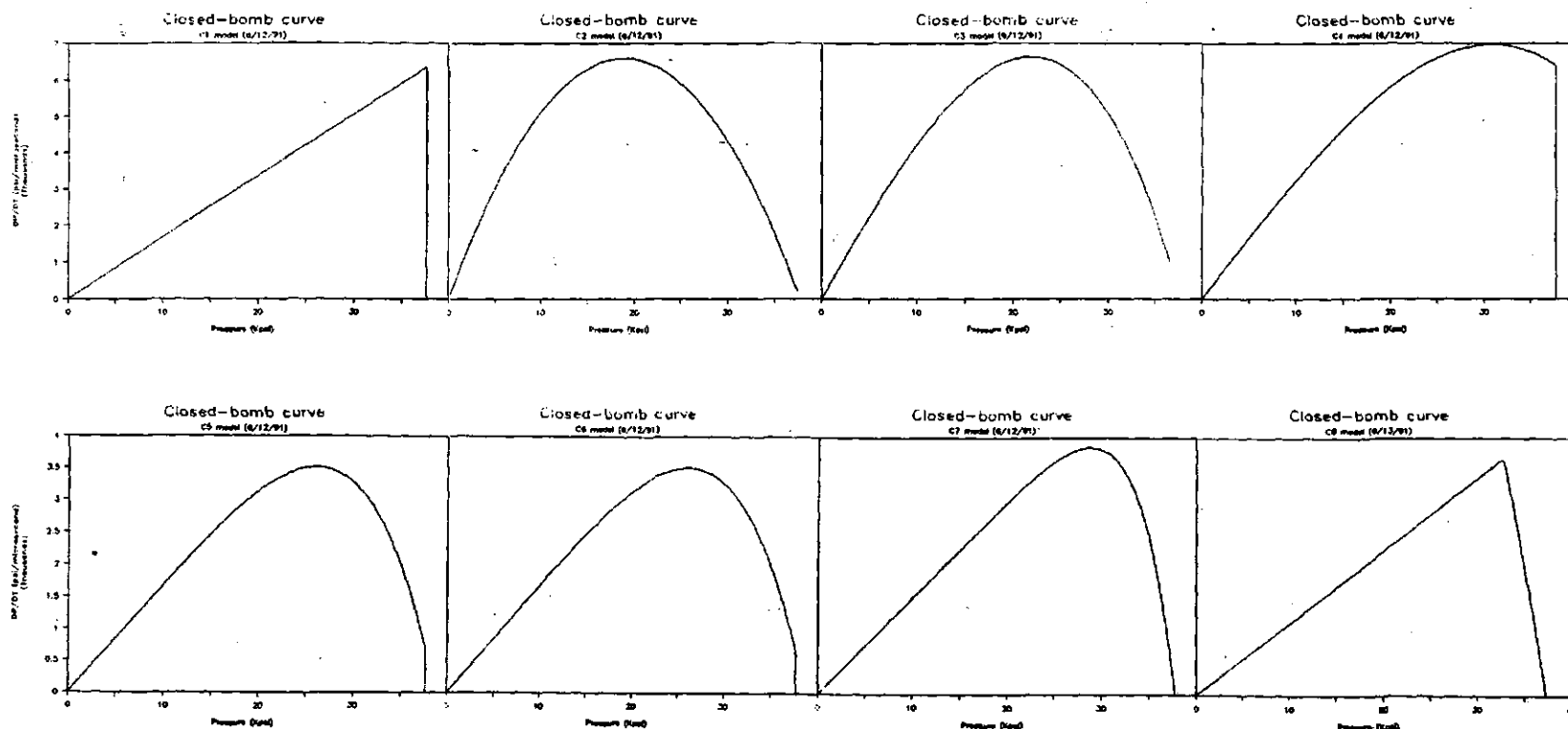
**FULL MODEL CHEMISTRY**

**TRANSIENT COMBUSTION**

**MOVING-WALL GENERALIZATION**

# VARIOUS CLOSED-BOMB CURVES

## $dP/dt$ VERSUS $P$



## **IBHVG2 TEST CASE #6**

### **FEATURES INCLUDED:**

**M829 LONG ROD PROJECTILE**

**M125 PRIMER TUBE FLAME SPREAD**

**JA2 COMBUSTION RATE**

### **FEATURES OMITTED:**

**PROPELLANT PERF GEOMETRY**

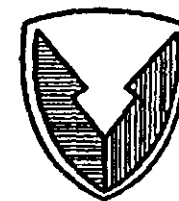
**JA2 COMPRESSIBILITY IN EOS**

### **RESULT:**

**RELATIVELY COMPLETE SIMULATION**



# Temperature Sensitivity



US ARMY  
LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY

## Solid Propellant JA2 Experimental closed chamber burn rates at Ambient, at 50°C, and -32°C

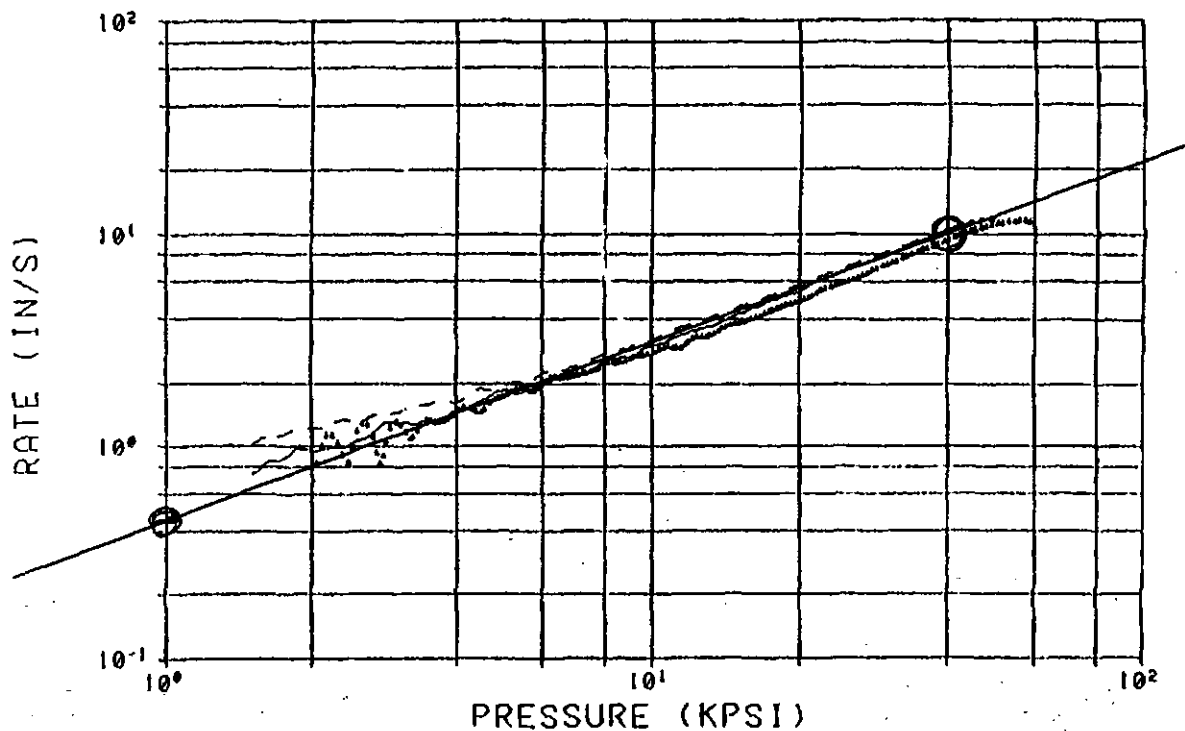
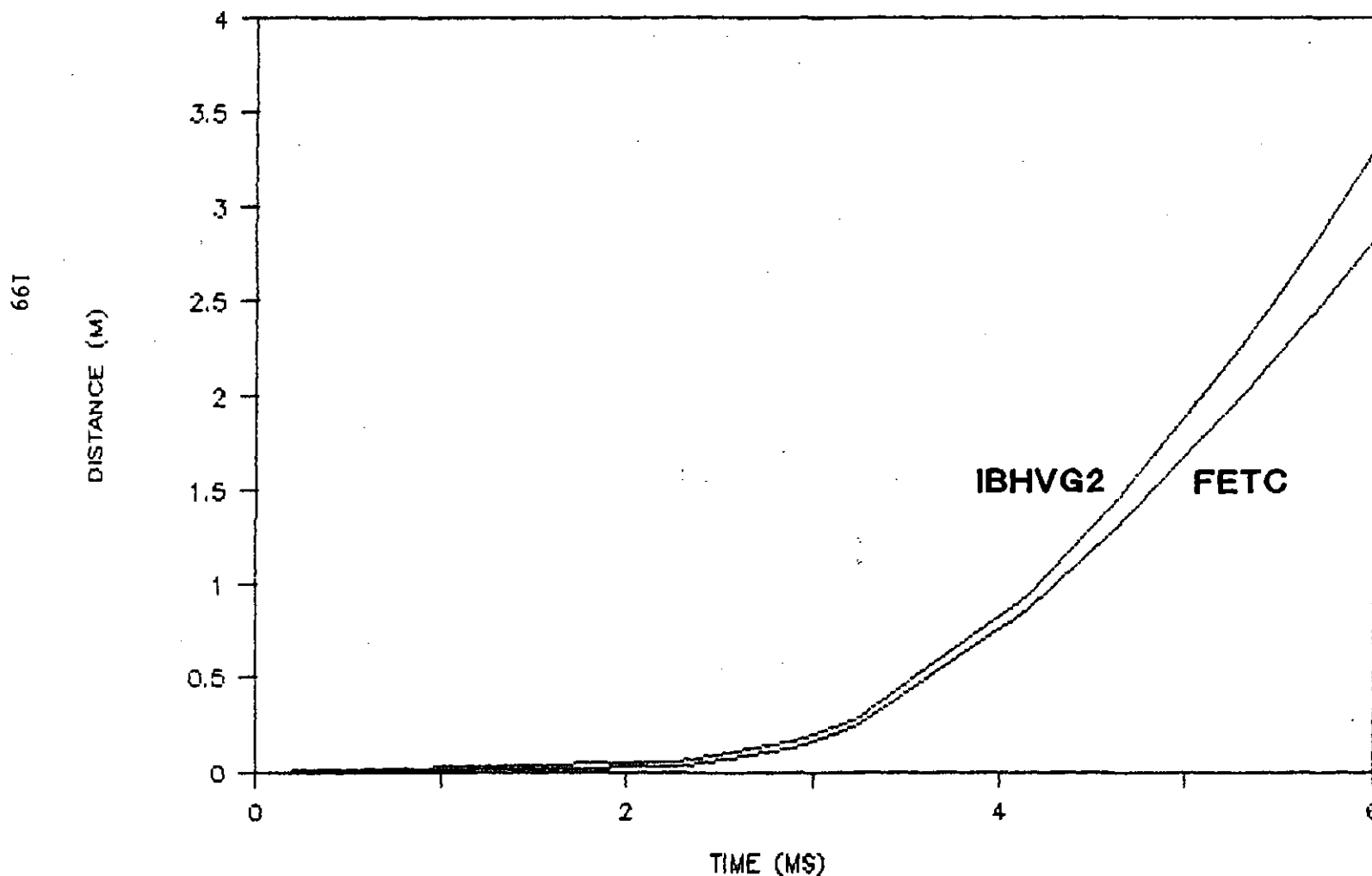


Figure 4. Comparison of Burning Rates at Ambient (—), at 50°C (---), and at -32°C (....).

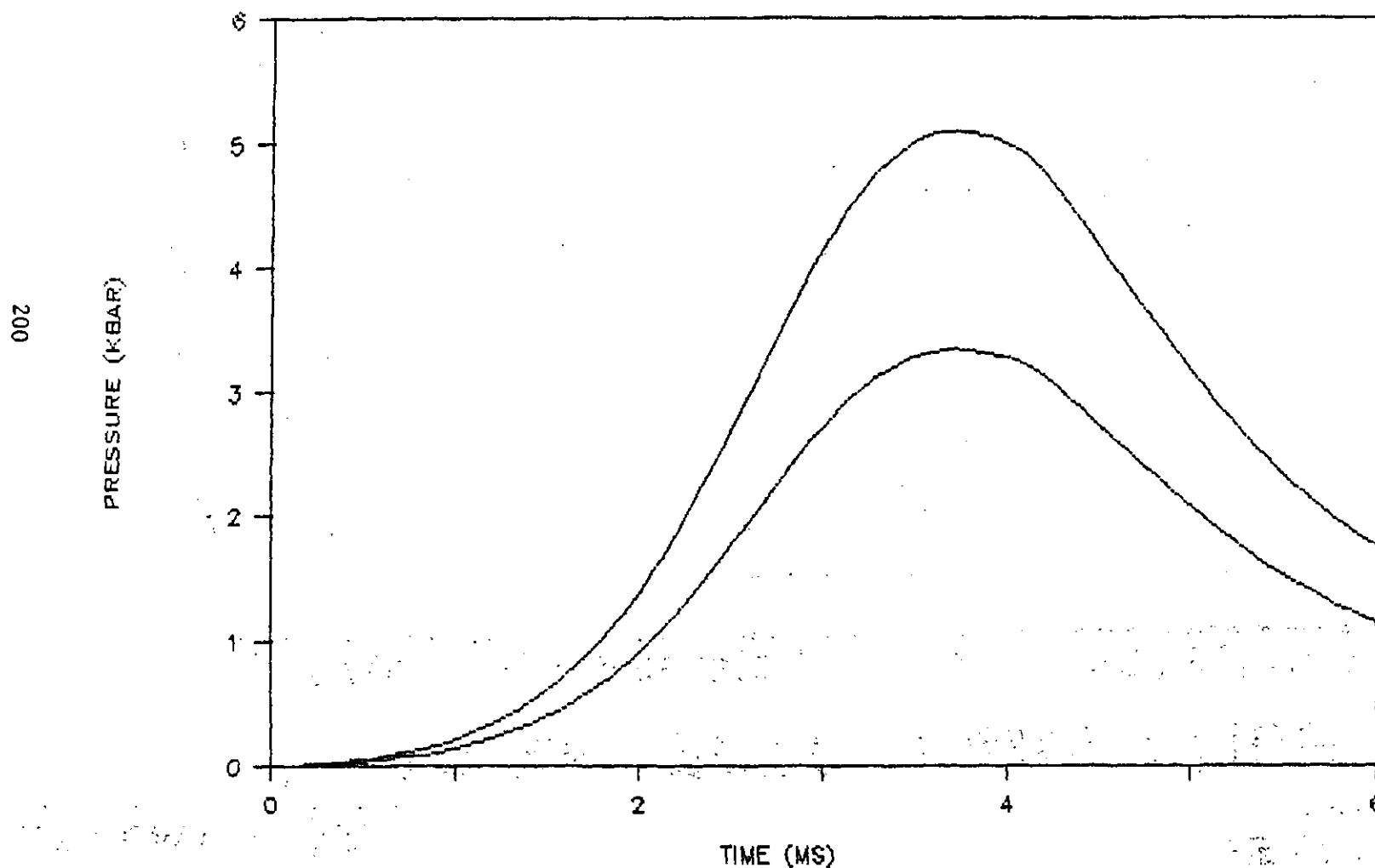
# 120 MM SIMULATIONS COMPARED

## IBHVG2 AND FETC PROJECTILE TRAVEL



# 120 MM IBHVG2 SIMULATION

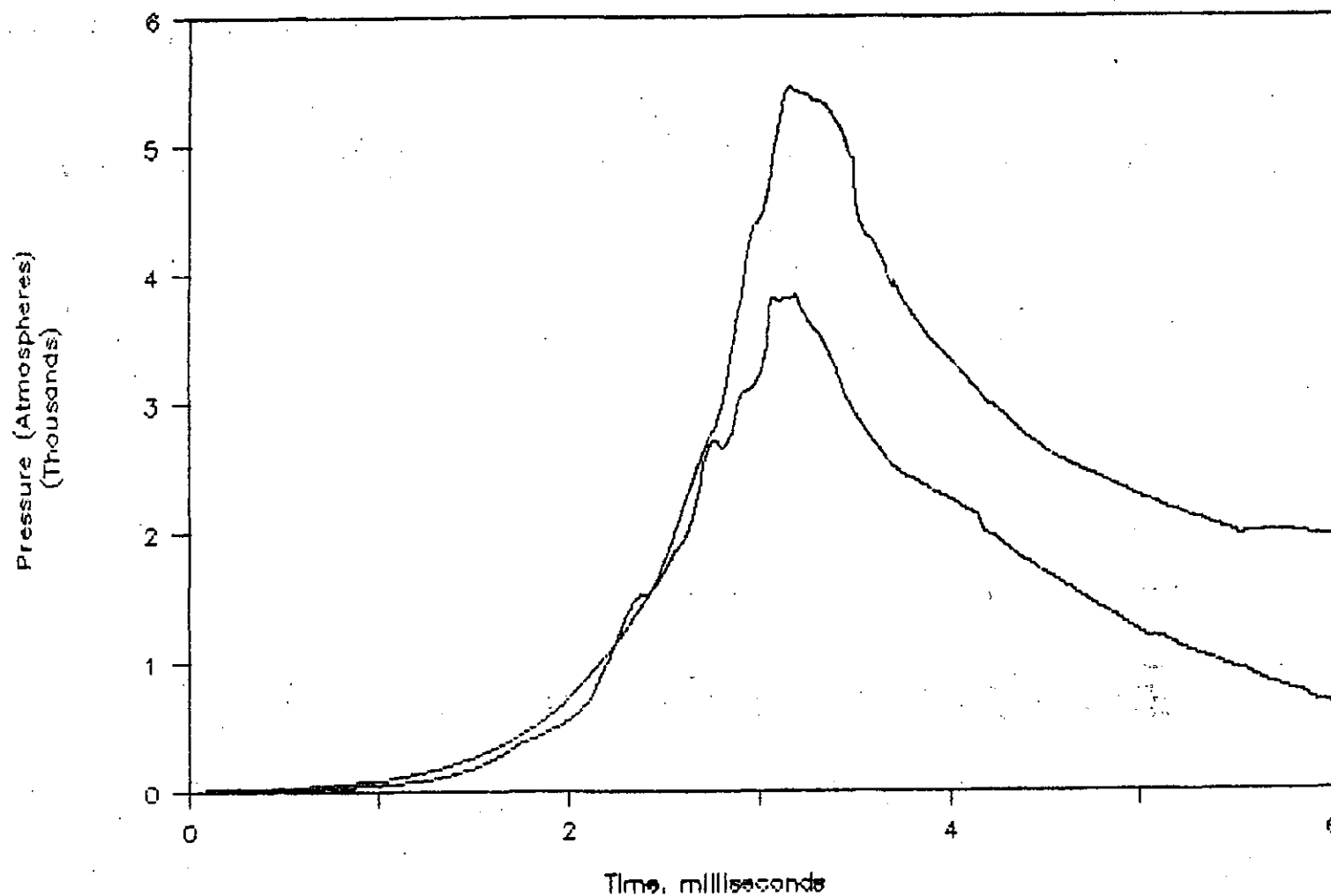
## STUB AND PROJECTILE BASE PRESSURES





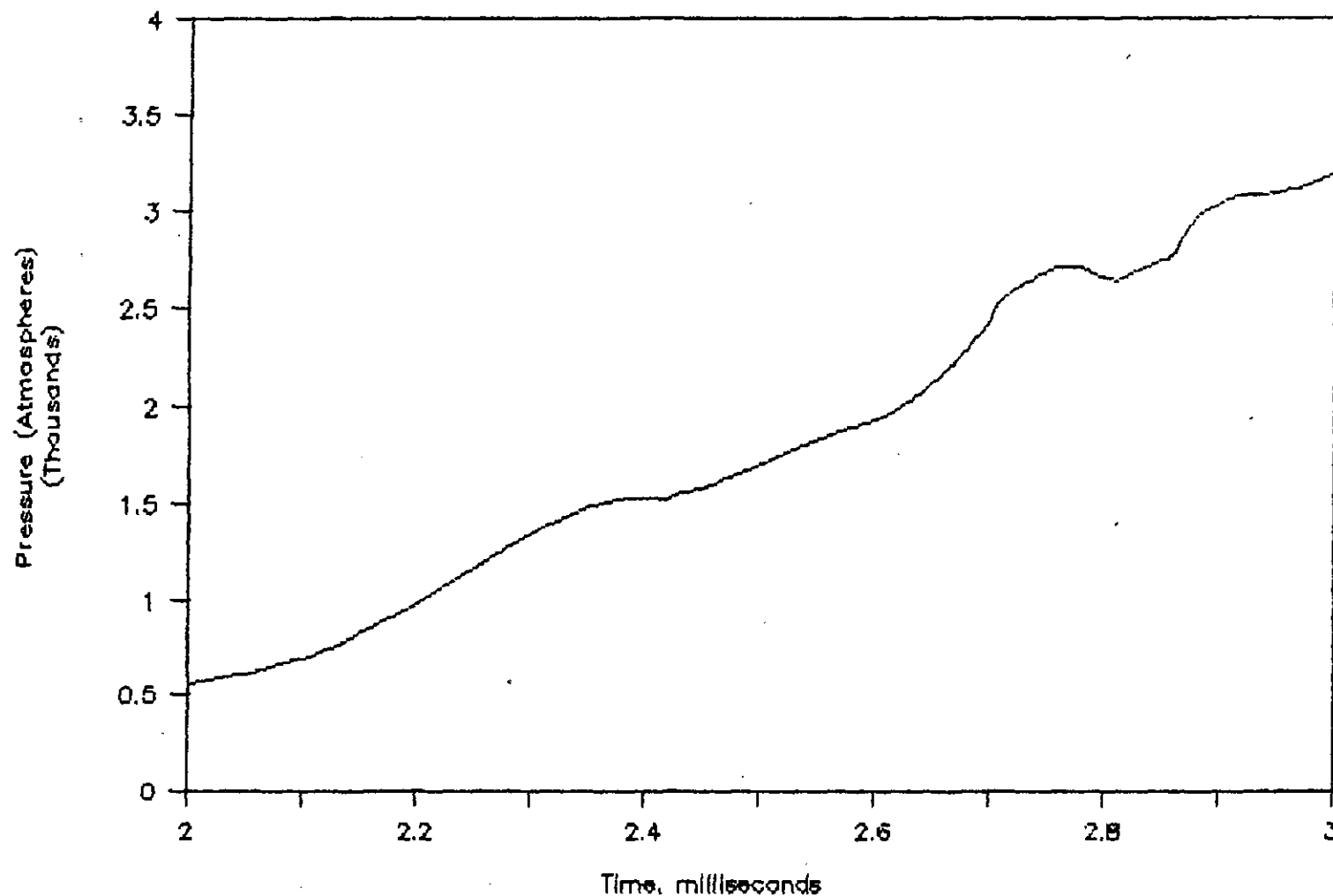
# 120 MM FETC SIMULATION

## STUB AND PROJECTILE BASE PRESSURES

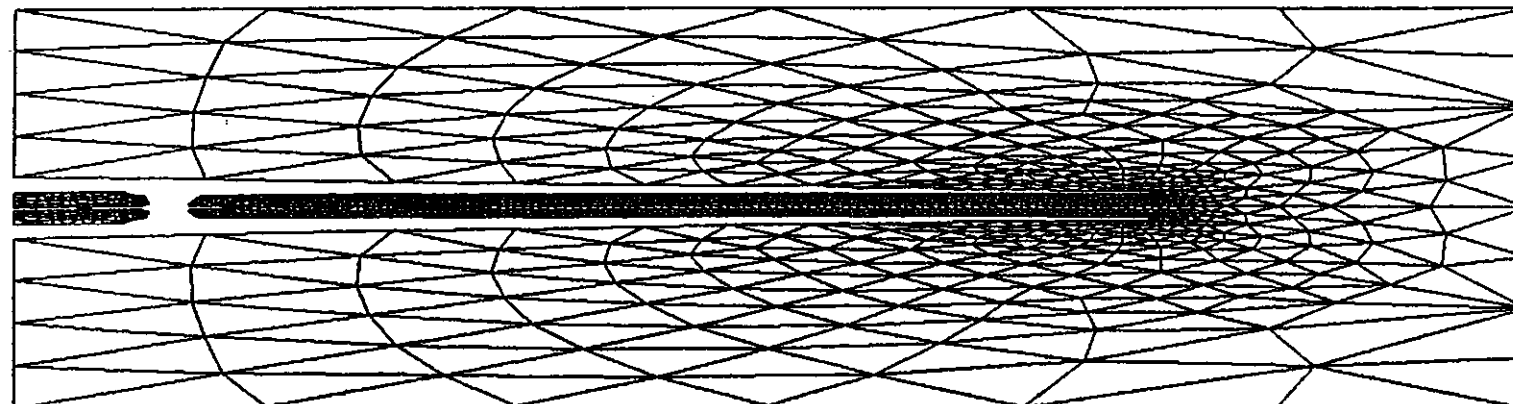
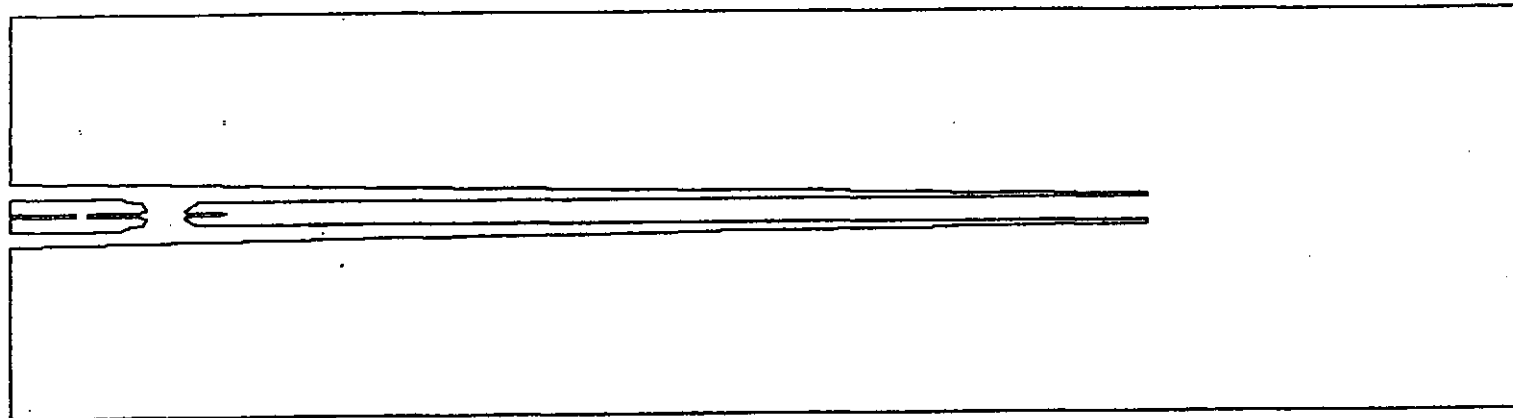


# 120 MM FETC SIMULATION

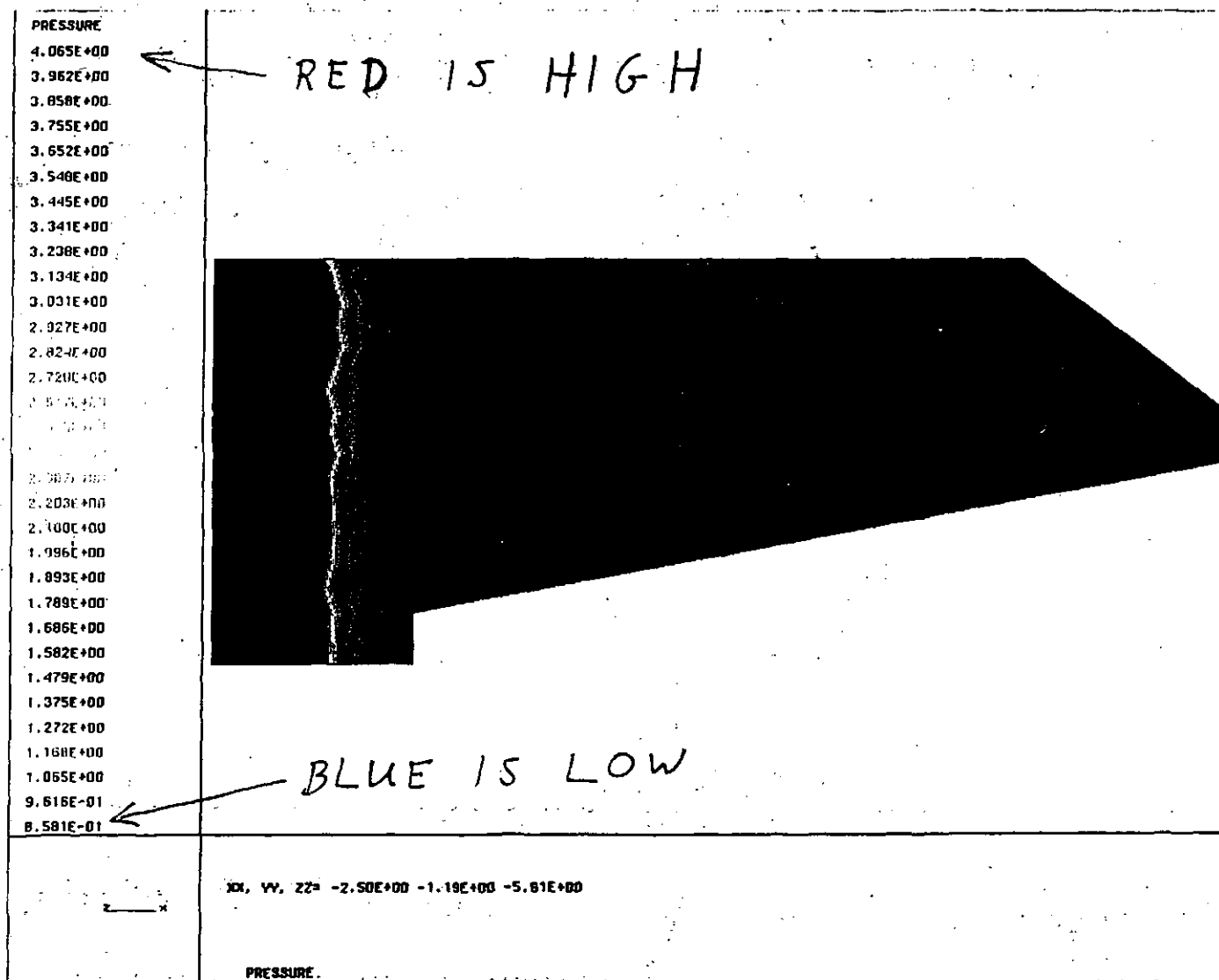
## DETAIL OF PROJECTILE BASE PRESSURE



# **120 MM FETC GRID**



# COLOR PLOT LAYOUT



## **SUMMARY**

---

1. WATER HAMMER: SOUND SPEED  
DEPENDENCE ON PRESSURE IS KEY  
TO DYNAMICS OF ELECTROTHERMAL  
AND LIQUID PROPELLANT GUNS.
2. CLOSED BOMB: AN IDEAL METHOD  
FOR VALIDATING BURN MODELS.
3. IBHVG2 TEST: UNSTRUCTURED  
FINITE-ELEMENT METHODS WORK  
SPECTACULARLY IN GUN GEOMETRY!

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## **SPECIAL DIAGNOSTICS AND INSTRUMENTATION**

**Rex D. Richardson and Michael D. Haworth  
Science Applications International Corporation  
Albuquerque, NM 87106**

### **ABSTRACT**

SAIC and FMC experimenters are currently planning to field two special diagnostics for application on the Defense Nuclear Agency's ETC Propulsion for Enhanced Gun System Effectiveness program. A three-frame flash x-ray radiographic system is being developed to observe dynamic mixing processes in the 30 mm FMC CAP<sub>tm</sub> test fixture. Results of x-ray transmission calculations along with cold model flash x-ray tests at 300 kV will be presented. Data analysis and image processing techniques will be described. The second diagnostic is a laser rangefinder system designed to track the position of a projectile in-bore from shot start to muzzle exit at a resolution of less than one centimeter and a data rate of 40 kHz. System design issues and the prototype test plan will be discussed.

**JANNAF Workshop on  
ETC Modeling and Diagnostics  
June 1991**



**SPECIAL DIAGNOSTICS AND  
INSTRUMENTATION\***

**Prepared by**

**Dr. Rex D. Richardson**

***Science Applications International Corporation  
Albuquerque, New Mexico***

**\* WORK SUPPORTED BY THE DEFENSE NUCLEAR AGENCY**

**FMC**

**SAIC**

**Science Applications  
International Corporation  
An Employee-Owned Company**

RR 91/860 hs/de



# INTRODUCTION

- **X-Ray radiography of fluid/plasma jets**

**Overview**

**Technical approach**

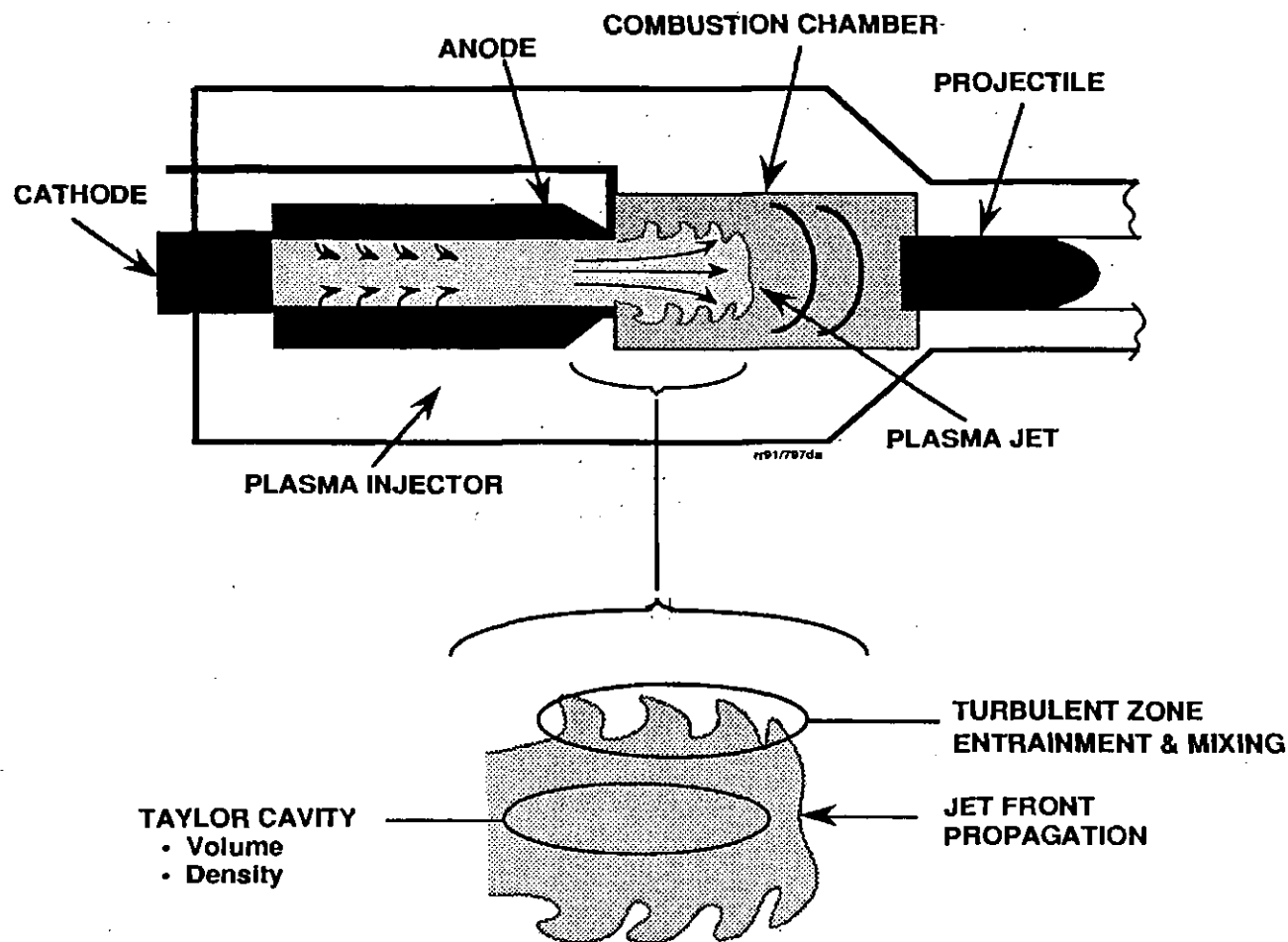
**FSCATT runs**

**300 kV FXR tests**

**Image analysis**

- **Laser rangefinder in-bore diagnostic**  
**Conceptual design, system issues**

# FLASH X-RAY OBSERVABLES CAP SYSTEMS



# TECHNICAL APPROACH

ADD X-RAY WINDOW  
TO BURN RATE FIXTURE

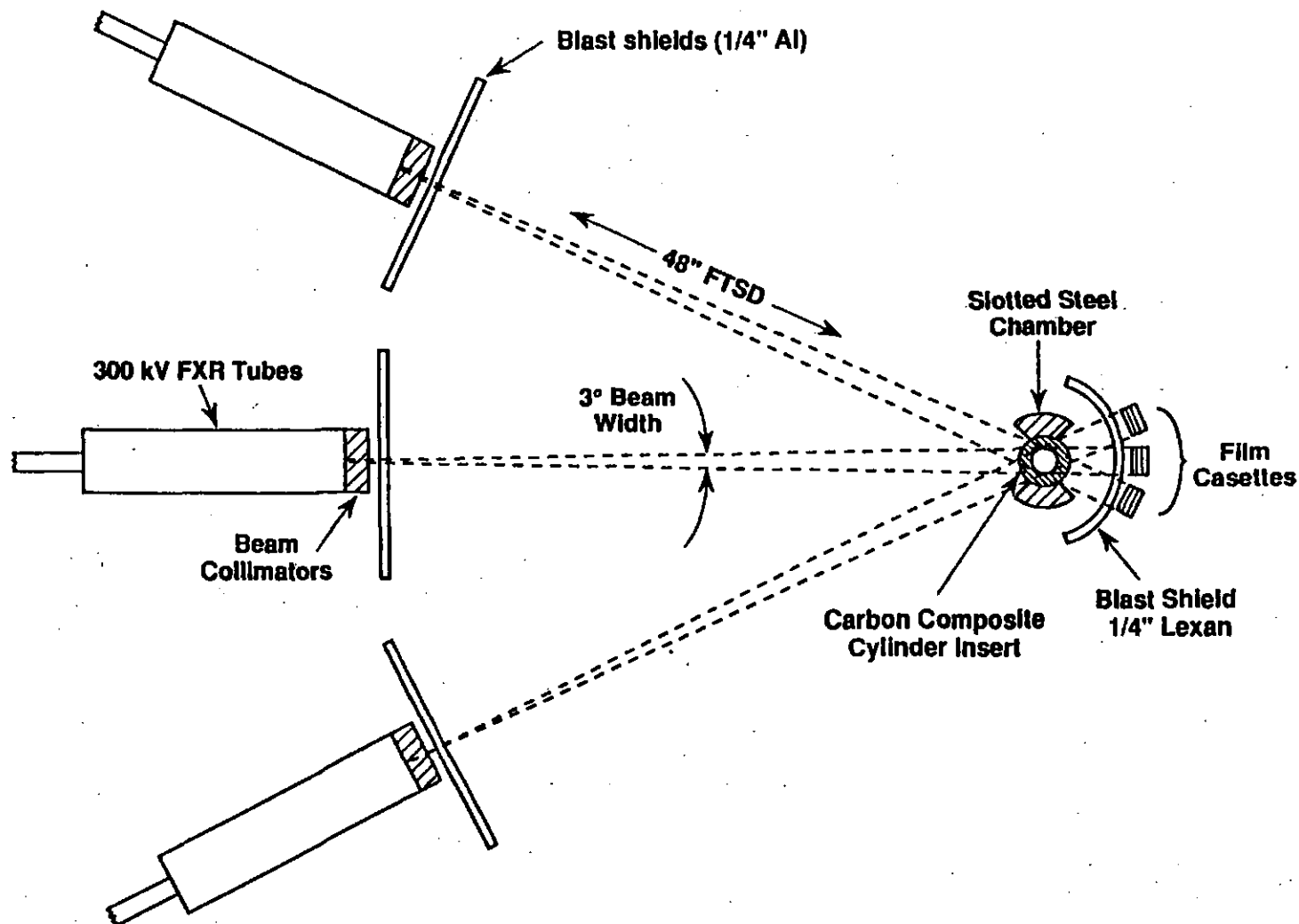
DEVELOP 3-FRAME  
FLASH X-RAY SYSTEM

OBTAIN THREE FILM  
RADIOGRAPHS AT SELECTED  
TIMES DURING THE 800 $\mu$ s CAP  
DISCHARGES

DIGITIZE FILM USING CCD  
VIDEO CAMERA AND FG-BOARD

USE COMPUTER IMAGE PROCESSOR TO  
EXTRACT AND ENHANCE DENSITOMETRIC DATA

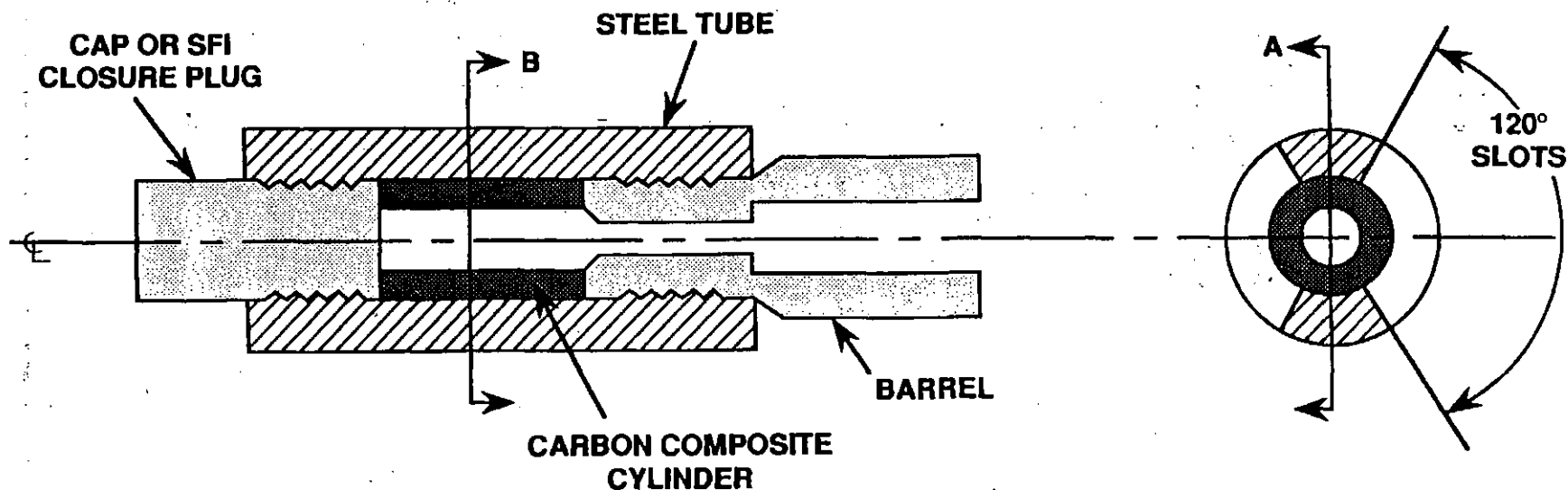
# LAYOUT OF 3 FRAME FXR SYSTEM



# BURN RATE FIXTURE MODIFICATION FOR X-RAY RADIOGRAPHY

SECTION A

SECTION B

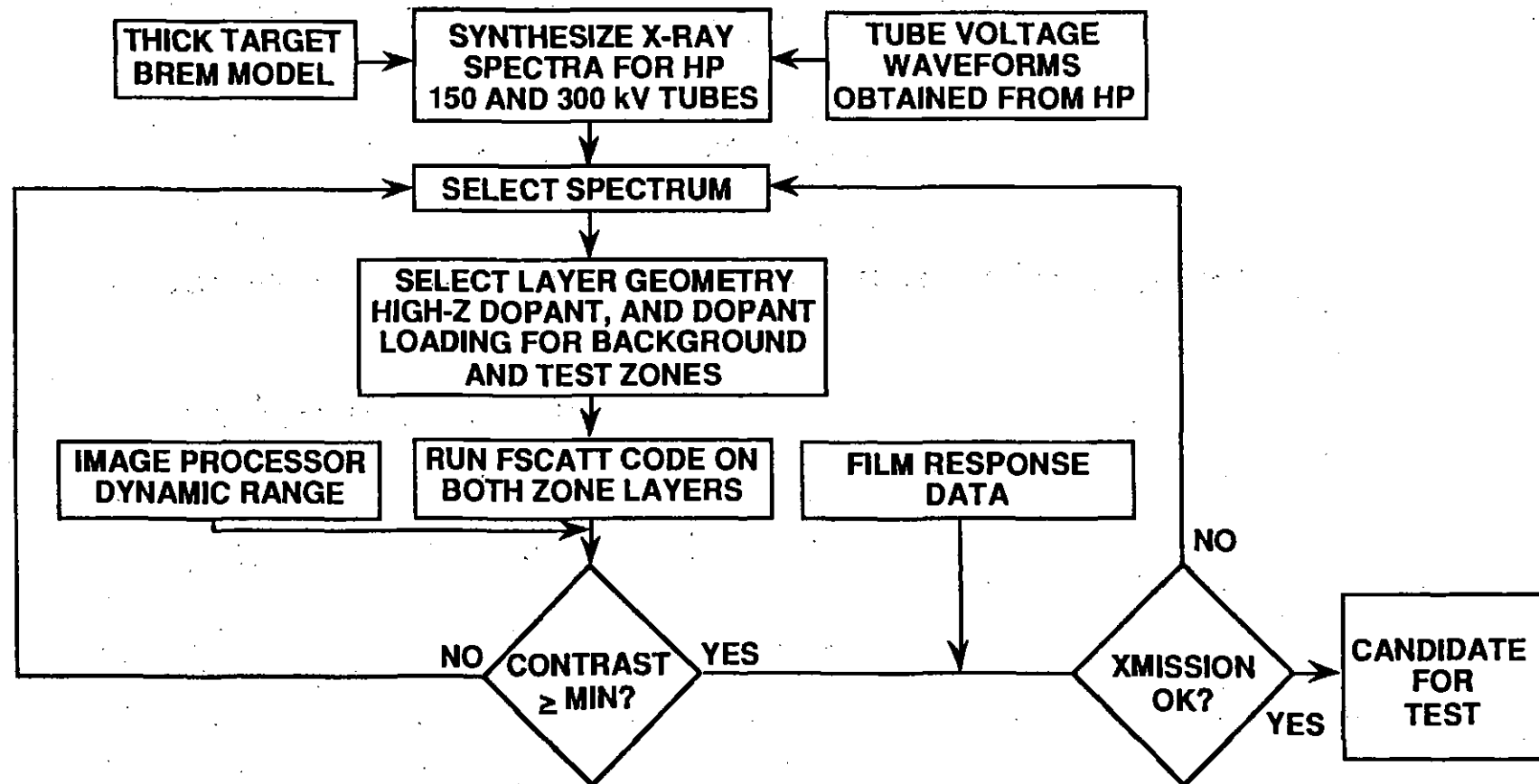


rr91/797 da

## FSCATT CODE RUNS

- **X-ray transport and energy deposition**
- **Discrete ordinate, ID**
- **PE absorption, Compton scattering and fluorescence**
- **Input/output energy flux and fluence**
- **Angular distribution of secondary radiation**

# X-RAY TRANSMISSION MODELING

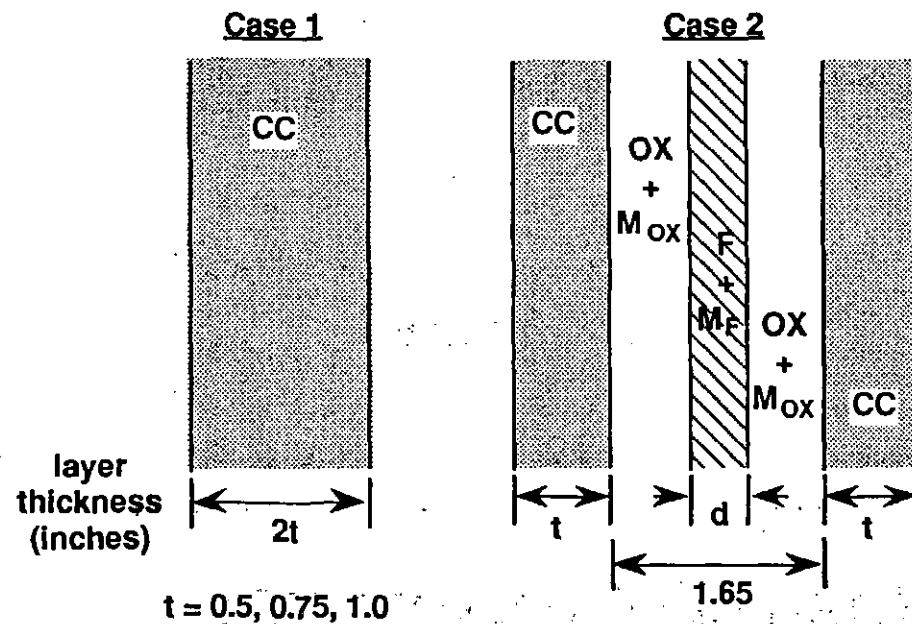


# FSCATT INPUT GEOMETRIES

## Abbreviations

CC Carbon composite  
 OX Oxidizer  
 F Fuel  
 $M_F$  Mass fraction of High Z dopant in Fuel

W Tungsten  
 Ba Barium  
 Au Gold  
 $M_{OX}$  Mass fraction of High Z dopant in Oxidizer



## For Case 2

- a)  $d = 0$ ,  $M_{OX} = 0$
- b)  $d = 0.2, 0.5$  cm
  - $M_F = 0, 0.1 W, 0.2 W$
  - $M_{OX} = 0$
  - $M_F = .07 W + .07 Ba + .07 Au$
  - $M_{OX} = 0$
- c)  $d = 0.2, 0.5$  cm
  - $M_F = 0$  (100% & 25% density)
  - $M_{OX} = 0.1 W, 0.2 W$



## CONCLUSIONS OF FSCATT CALCULATIONS

- FSCATT runs show 10 – 30 percent contrast is possible for a 5 mm jet doped with high-Z material, or for a 5 mm jet penetrating a doped fluid
- Total x-ray transmitted fluence is 1 – 7 percent of incident fluence depending upon doping fraction, geometry and spectrum
- Film response data indicated marginal exposure operation at 150 kV, acceptable exposure levels at 300 kV

## 300 kV EXPERIMENTS

- One day test series conducted at the Alliant Techsystems Proving Ground, Minneapolis
  - HP 43733A 300 kV FXR system
  - Kodak XAR film using TI-3 or NDT-9 front and back intensifying screens
  - Automatic and hand processing
- Two mock-ups used as x-ray test objects
  - Water filled graphite cylinder with tungsten carbide doped, gelled water on axis
  - Graphite cylinder filled with tungsten carbide doped, gelled water and empty glass tube on axis

# FLASH X-RAY RADIOGRAPHY SUMMARY AND STATUS

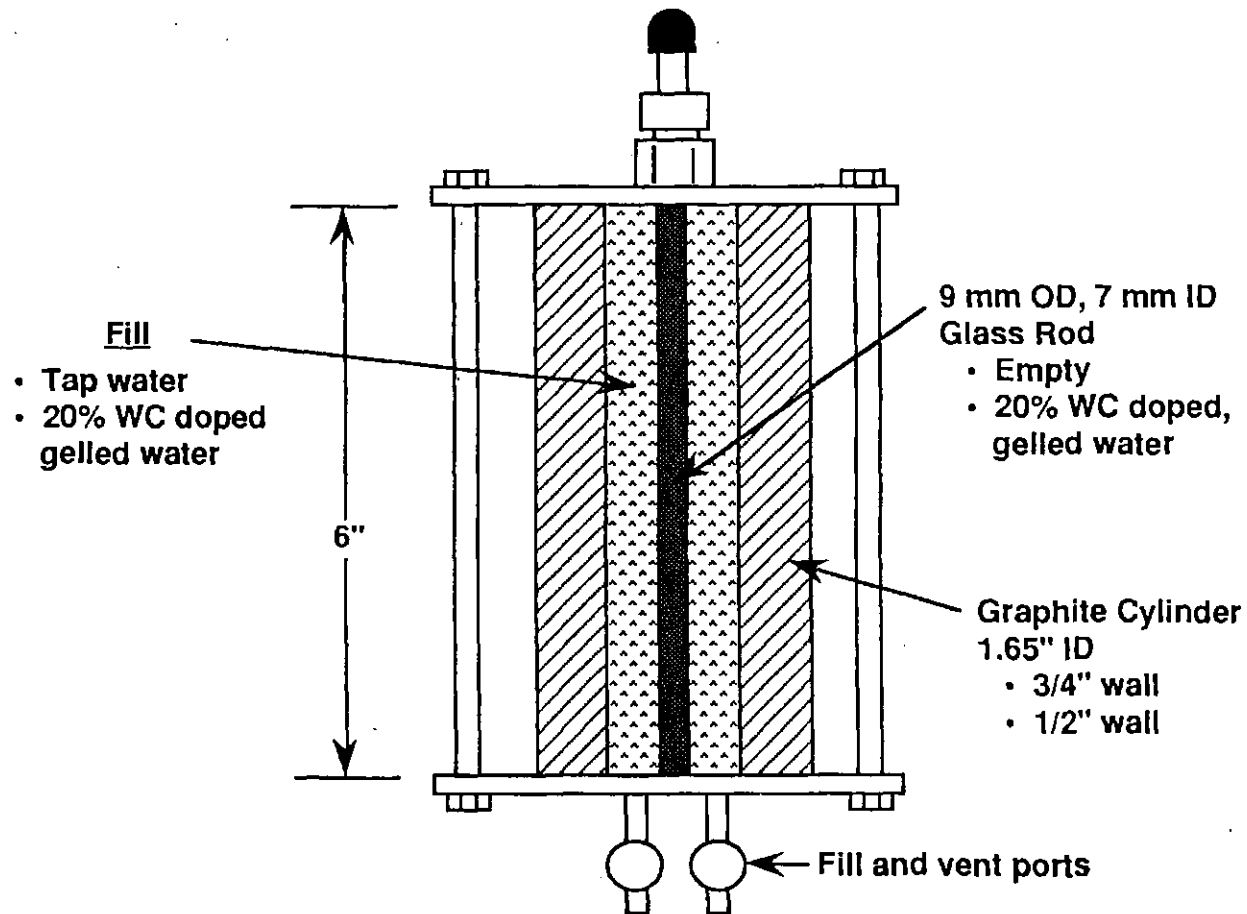
## SUMMARY:

- FSCATT x-ray photon transport calculations show good contrast in tungsten carbide doped SFI or CAP geometries
- Carbon composite cylinders with up to one inch wall thickness may be used as the x-ray transparent chamber
- 300kV FXR experiments confirm code predictions and serve as initial optimization study
- PC based image analysis system is more than adequate for the task

## STATUS:

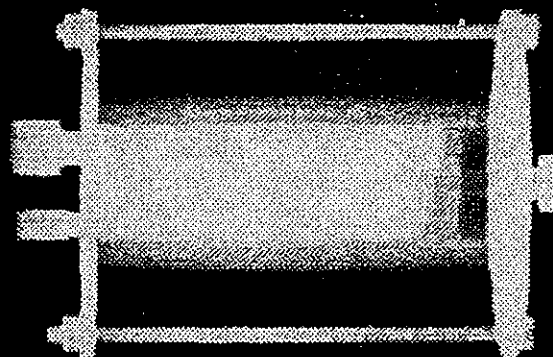
- Vendor identified for composites; FMC working on fabrication specs and prototypes
- Burn rate chamber to be ready in early July, 1991
- Alliant Techsystems will set up and operate the FXR system

# X-RAY TEST OBJECT



TEST OBJECT:  
GRAPHITE CYLINDER, 1.65" ID,  
0.5" WALLS. GELLED WATER FILL,  
20% WC DOPED, 7mm ID, 9mm OD  
EMPTY GLASS ROD ON AXIS.

FILM: KODAK XAR  
FTSD: 60"  
OTFD: 3.75"  
F-SCREEN T1-3  
B-SCREEN T1-3  
300 kV HP FXR  
25 kV CHARGE



**TEST OBJECT:**

GRAPHITE CYLINDER, 1.65" ID,  
0.5" WALLS. GELLED WATER FILL,  
20% WC DOPED. 7mm ID, 9mm OD  
EMPTY GLASS ROD ON AXIS.

**FILM: KODAK XAR**

**FTSD: 60"**

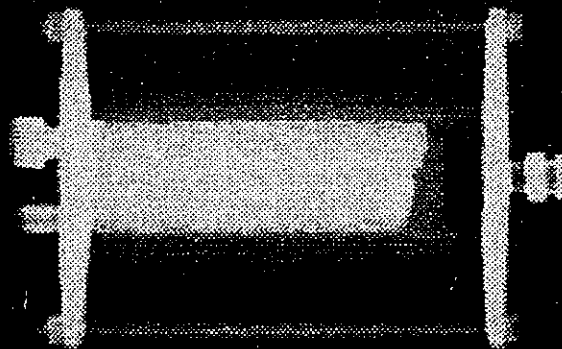
**OTFD: 3.75"**

**F-SCREEN NDT9**

**B-SCREEN NDT9**

**300 kV HP FXR**

**30 kV CHARGE**



**TEST OBJECT:**

**GRAPHITE CYLINDER, 1.65" ID,  
0.5" WALLS. GELLED WATER FILL,  
20% WC DOPED. 7mm ID, 9mm OD  
EMPTY GLASS ROD ON AXIS.**

**FILM: KODAK XAR\***

**FTSD: 48"**

**OTFD: 3.75"**

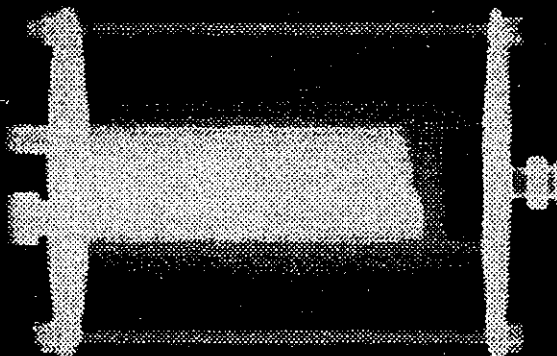
**F-SCREEN T1-3**

**B-SCREEN T1-3**

**300 kV HP FXR**

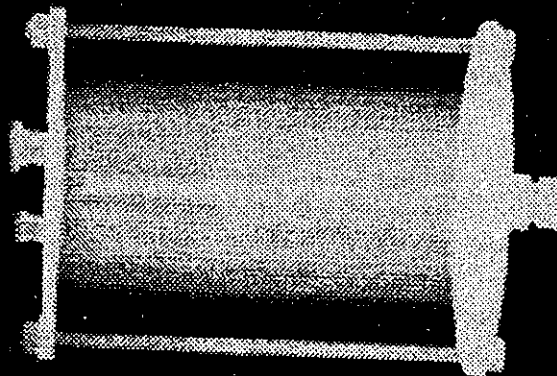
**25 kV CHARGE**

**\* HAND PROCESS**



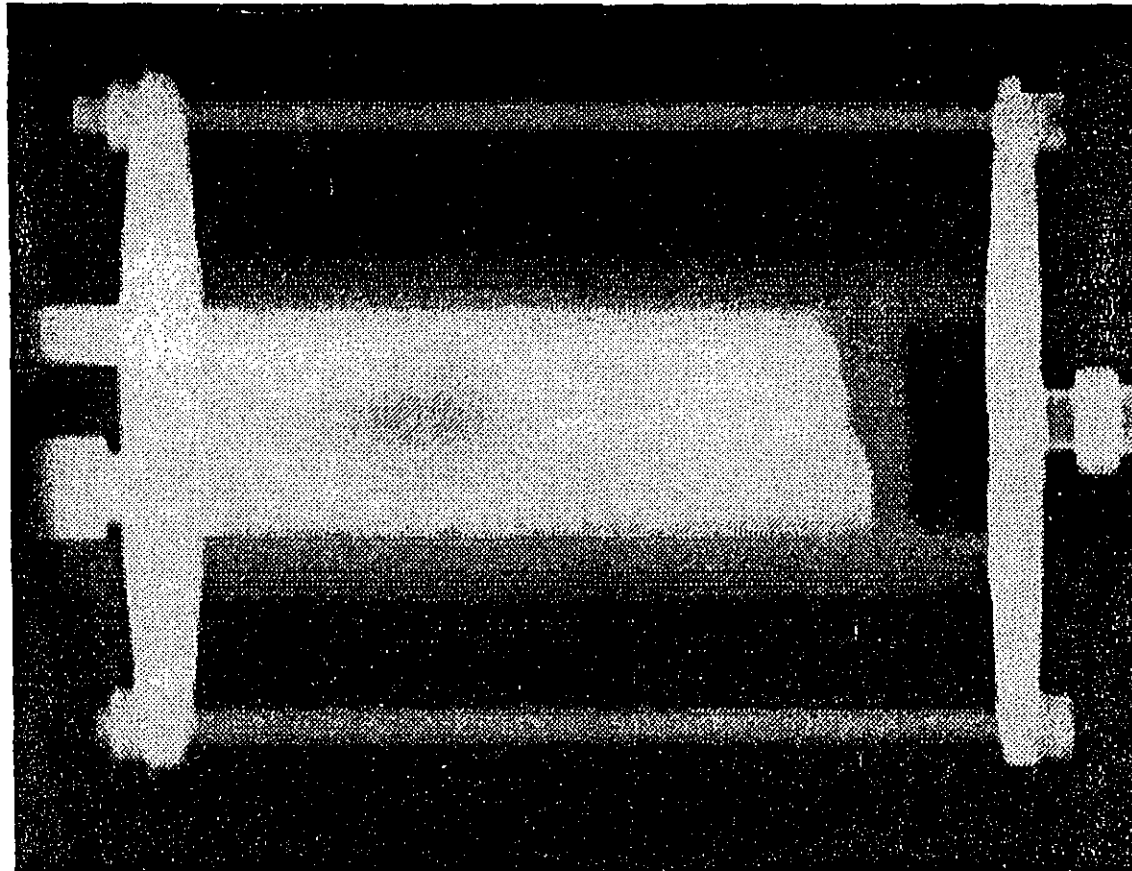
**TEST OBJECT:**  
GRAPHITE CYLINDER, 1.65" ID,  
0.75" WALLS. WATER FILL. 20% WC  
DOPED GELLED WATER IN 7mm ID,  
9mm OD GLASS ROD ON AXIS.

**FILM: KODAK XAR**  
**FTSD: 60"**  
**OTFD: 3.75"**  
**F-SCREEN T1-3**  
**B-SCREEN T1-3**  
**300 kV HP FXR**  
**25 kV CHARGE**

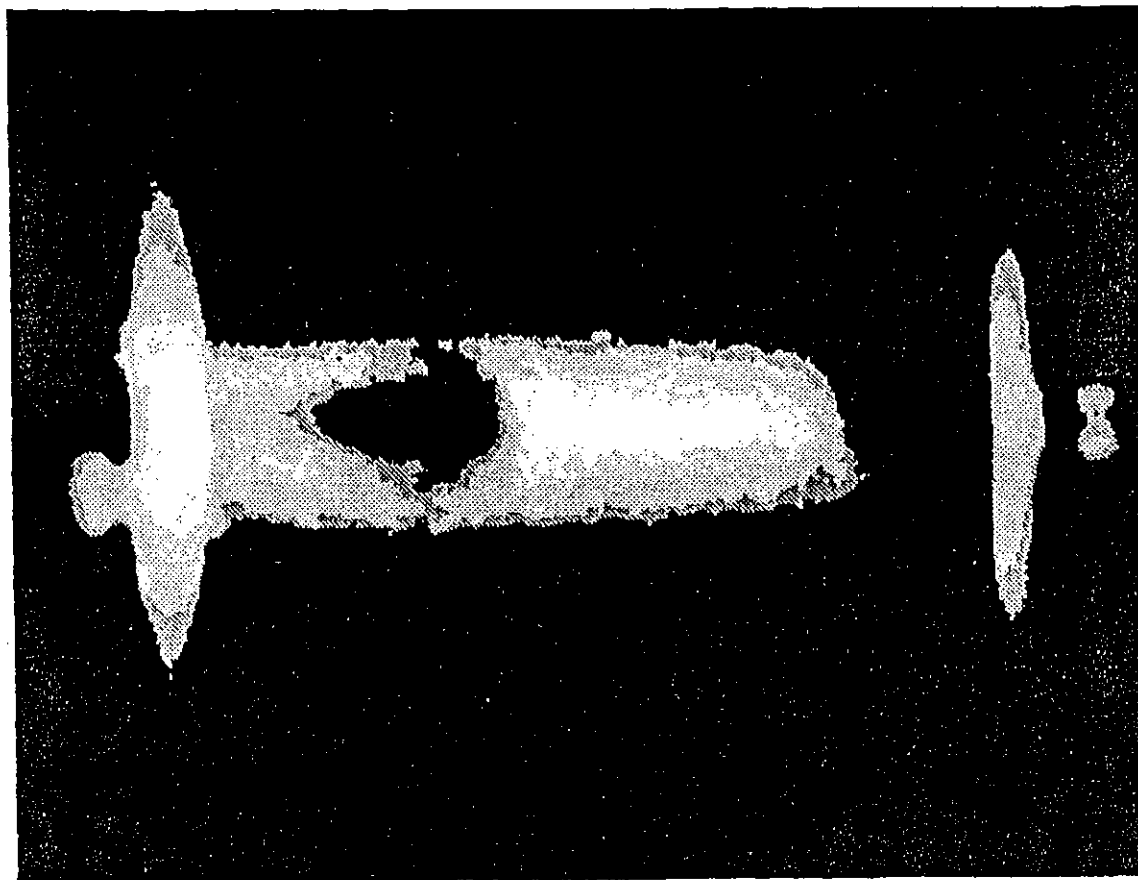




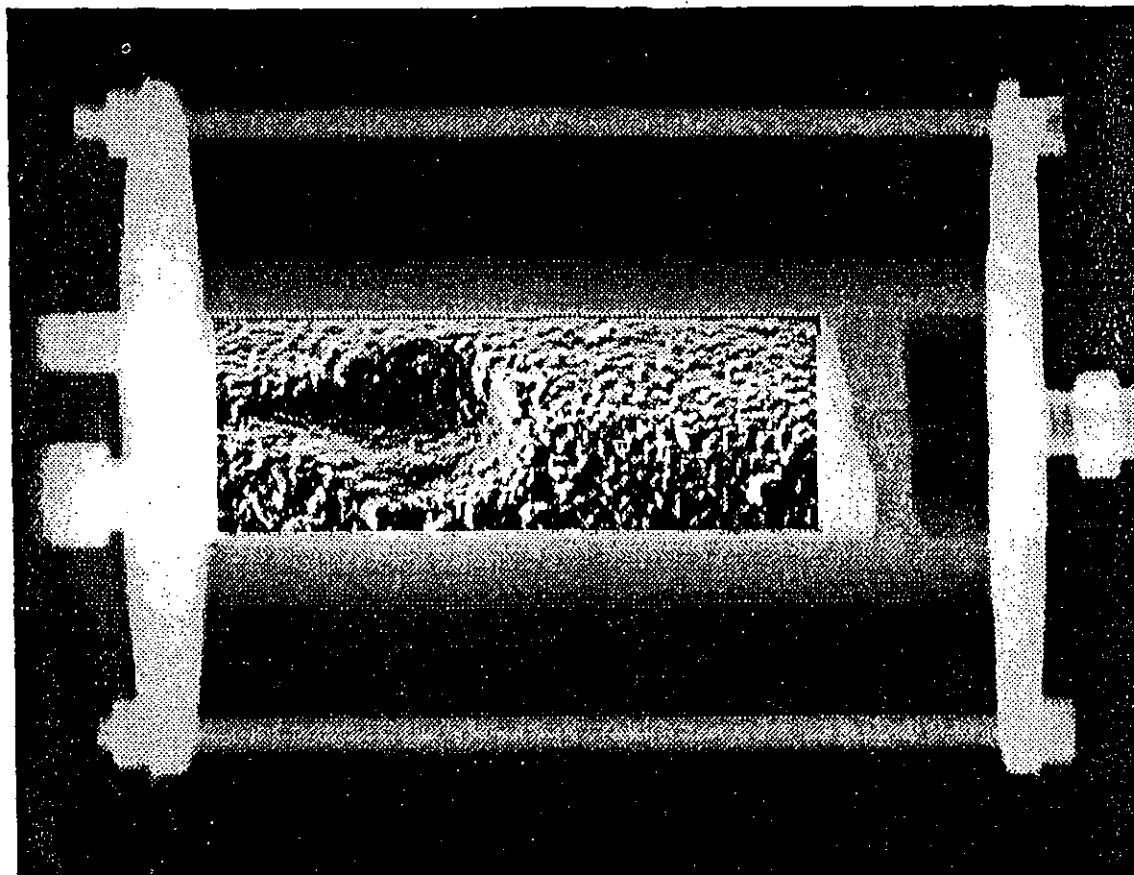
## RETOUCHED RADIOGRAPH SHOWING SIMULATED "PLASMA JET"



## EXAMPLE OF LOOK-UP TABLE OPERATOR GRADIENT ENHANCEMENT



## EXAMPLE OF HORIZONTAL GRADIENT FILTER APPLICATION



# LASER IN-BORE POSITION DIAGNOSTIC

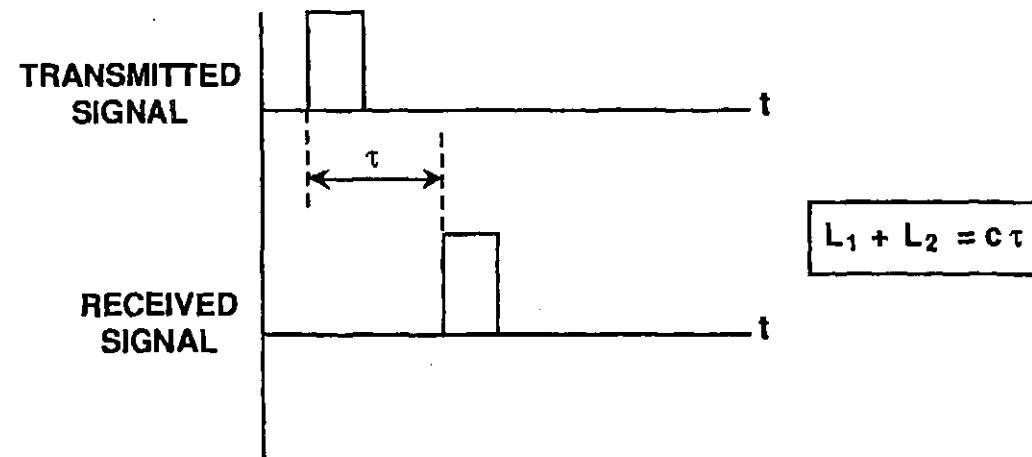
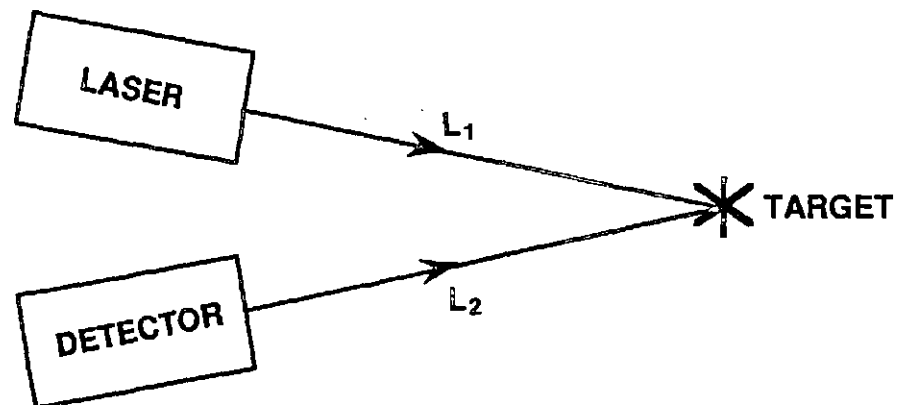
**GOAL:** Provide precise projectile position data for comparison to interior ballistic model predictions

**PROBLEM:** Microwave radars are expensive and have poor resolution at low velocity. Optical Doppler velocimeters are very expensive and difficult to field in ETC gun environments

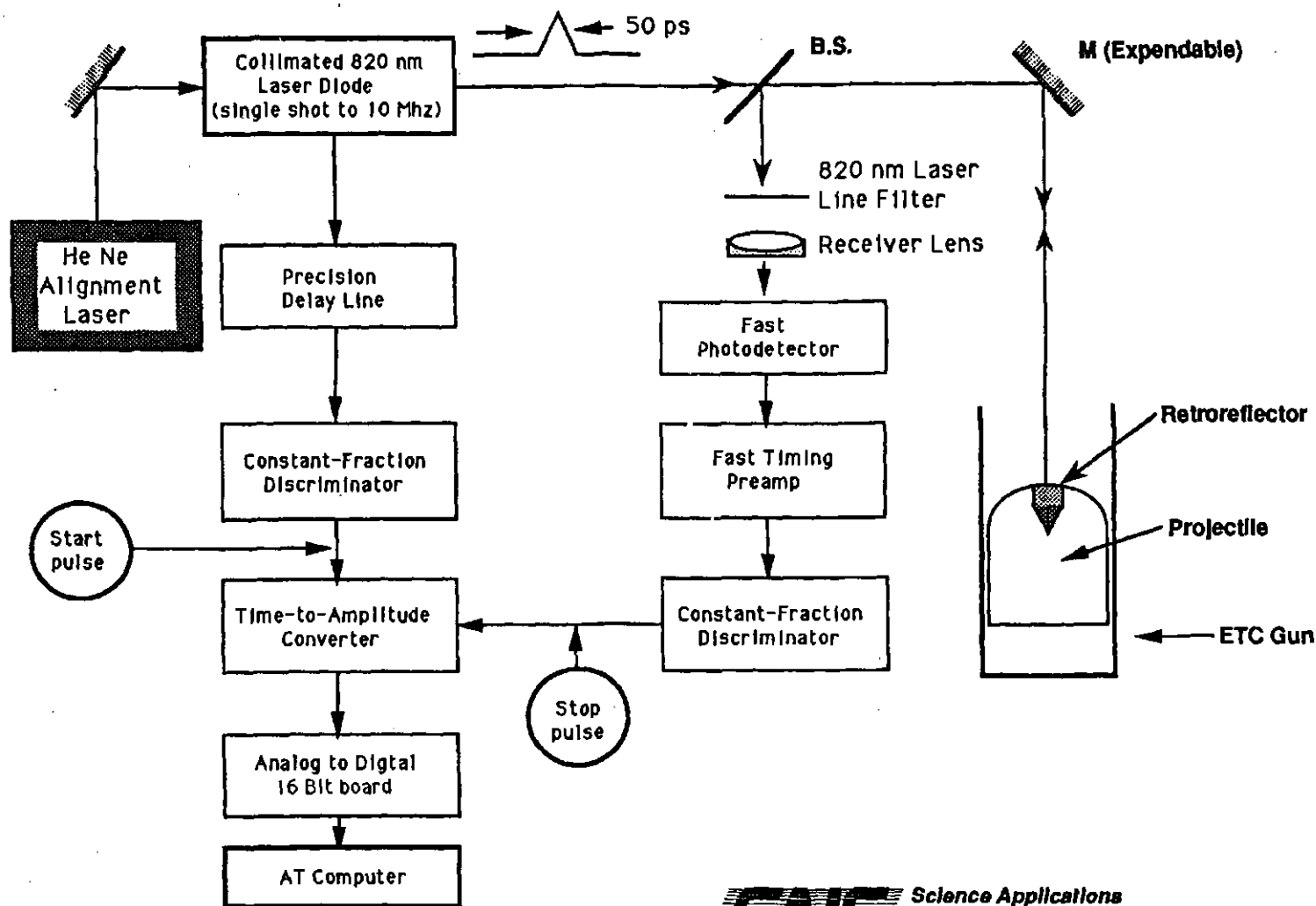
**APPROACH:** Use pulsed laser radar

- Inexpensive
- Robust
- Accurate; reads position at any gun velocity
- Easily calibrated in situ

# LASER RADAR OPERATING PRINCIPLE



# PROJECTILE VELOCITY MEASUREMENT VIA LASER RADAR



## LASER RADAR SYSTEM PARAMETERS

|                                         |                                              |
|-----------------------------------------|----------------------------------------------|
| <b>Laser Wavelength</b>                 | <b>820 nm</b>                                |
| <b>Laser Pulse Width</b>                | <b>50 ps</b>                                 |
| <b>Collimated Laser Beam Divergence</b> | <b>0.15 mrad</b>                             |
| <b>Absolute Position Accuracy</b>       | <b>2 cm</b>                                  |
| <b>Position Jitter</b>                  | <b>≤ 1.5 cm</b>                              |
| <b>Photodetector Signal Strength</b>    | <b>1.0 V</b>                                 |
| <b>Repetition Rate</b>                  | <b>40 kHz - 1MHz<br/>(A/D board options)</b> |

## LASER RADAR COMPONENT LIST

| <u>PART</u>                                           | <u>MANUFACTURER</u>  | <u>COST</u>    |
|-------------------------------------------------------|----------------------|----------------|
| 150mW, 50ps, 1MHz laser diode @ 820nm with collimator | Hamamatsu            | \$ 8500        |
| 35ps photodetector                                    | Opto-Electronics     | 3200           |
| Vibration isolated optical bench                      | Newport              | 2700           |
| Optical components and hardware                       | Newport/Melles Griot | 4900           |
| Analog timing electronics                             | EG&G/ORTEC           | 5250           |
| 1Mhz, 16 Bit, A/D DAS board                           | Analogic             | 3895           |
| Rack mount PC system                                  | Cyber Research       | 3595           |
| DAS software (snapshot)                               | Cyber Research       | 995            |
|                                                       |                      | <hr/> \$33,035 |



# **LASER RADAR SYSTEMS ISSUES**

## **OPERATION IN-BORE**

- Projectile blow-by must be minimized
- Requires precision retro-reflector mounted in projectile nose
- Requires precision optical alignment for each shot

## **TIMING ELECTRONICS**

- Millivolt resolution of time-to-amplitude converter signal is required
- Laser system and timing electronics must be electrically isolated and heavily shielded against harsh EMI environment of the ETC gun

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## FIRST PRINCIPLES MODELING OF A DNA 60mm ETC GUN DESIGN

CC. Hsiao, G. T. Phillips, and F.Y. Su  
Science Applications International Corporation  
San Diego, CA 92121

### ABSTRACT

The SAIC proprietary model BISON is a first principles CFD code which has recently been applied to the study of the interior ballistics phenomenology associated with a class of ETC gun designs. The BISON model solves the NS equations for an electrically conductive fluid but neglects magnetic forces. BISON treats multiple phases, turbulence, multi-species, and chemistry making it well suited for the study of interior ballistics.

BISON treats the advection terms in the conservation equations using a fourth order in space, second order in time FCT algorithm. Adaptive gridding is included for accuracy and economy and makes use of both continuous and discrete second order rezoning algorithms. A non-equilibrium multi-phase treatment is available in BISON through a discrete, stochastic particle model which follows Lagrangian computational particles which are fully coupled to the continuum flow. In addition, the multi-species capability in BISON allows the treatment of equilibrium two-phase flow. Multiple fluid species are treated through separate continuum continuity equations for each species. Real equations of state for each species are provided through a unique non-iterative multi-species pressure and temperature solver. Turbulence is treated via a two-equation (k- $\omega$ ) model which has been validated for a variety of free and boundary layer shear flows. Reactions within the flow are computed using an eddy-breakup model which we validated under a previous DOE IC engine program. This model assumes that the chemical kinetic rates are fast compared with the turbulent mixing rates so that flame propagation is mixing controlled.

This presentation will demonstrate the effectiveness of the BISON model in modeling complex interior ballistics processes. A test case will be shown which describes the interior ballistics of a 60 mm ETC gun fixture which is being used in the DNA ETC Gun Program. Comparison of pressure transducer data with model predictions clearly shows that the computational approach is capable of capturing the detailed structure present in the experimental data.

# ***First Principles Modeling of a DNA 60mm ETC Gun Design***

by

**CC Hsiao**

**Gary Phillips & Fred Su**

**Science Applications International Corporation**

**July 9-11, 1991**

presented at

**JANNAF Workshop ETC Modeling & Diagnostics**

**Aberdeen Proving Ground, MD**

July 9, 1991



# BISON Model



## High Order Numerics

4th Order in Space, 2nd Order in Time  
FCT Scheme  
High Order Adaptive Gridding  
Arbitrary Problem Geometry Specification

## First Principle Physical Models

Plasma Model  
Multi-Phase Continuum Model  
Multi-Phase Discrete Particle Model  
Chemical Reactive Flow Model  
Turbulence Model  
Real Equations-of-State

Species Transport Equations  
Navier-Stokes Equations  
Turbulence Equations

## Governing Equations

July 9, 1991



# Plasma Model



## Physics Approximations

Multi-level multi-species Saha  
code for ionization  
High Beta plasma  
Hydrodynamic time scales  $\gg$   
Plasma Times



**Solve for Potential**  
**Derive Electric Field**  
**Add Heat to Fluid**



Can be coupled to PFN  
Specify equipotential surfaces  
or current density

**Flexible Boundary Conditions**



Real EOS table  
Conductivity table

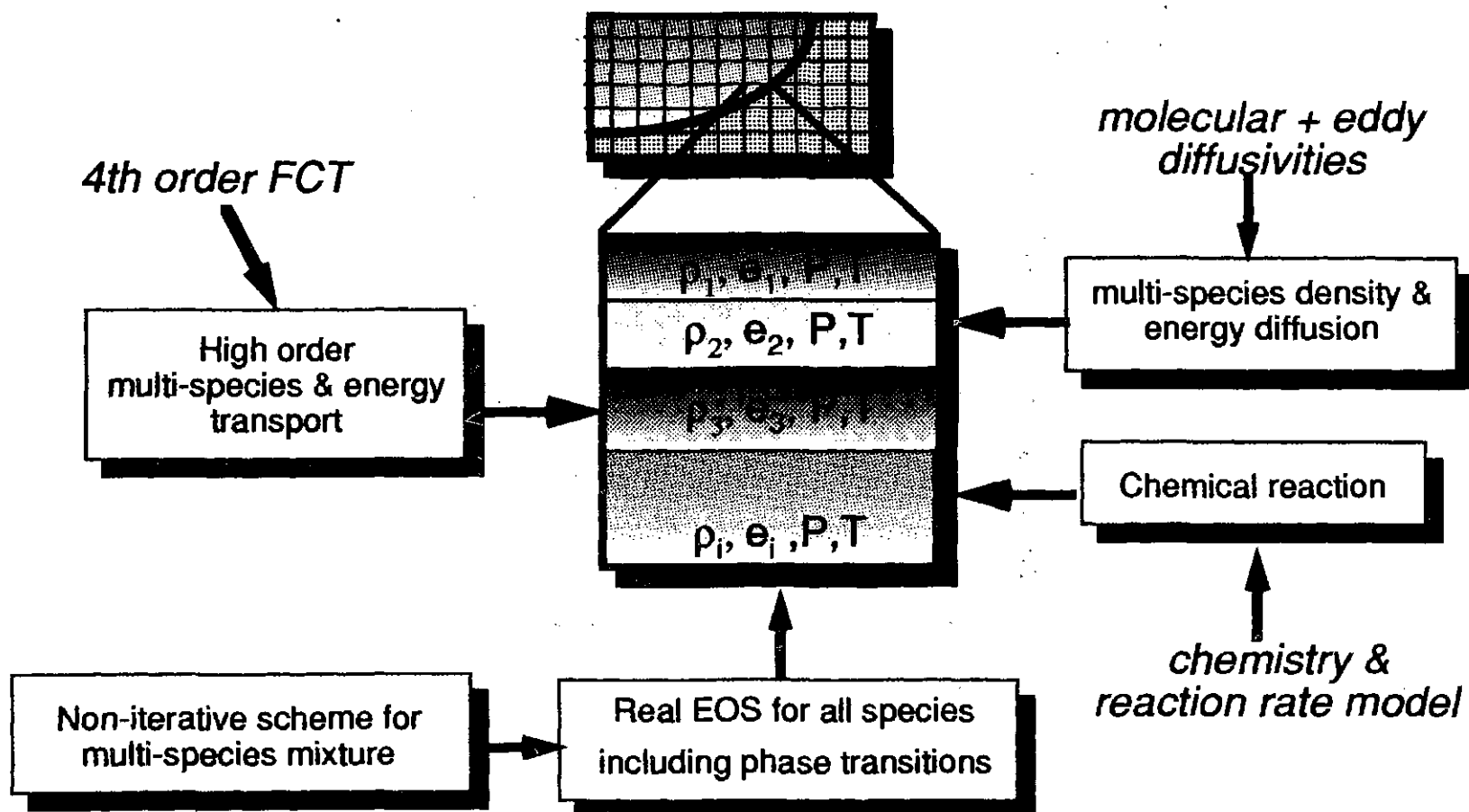
**Table Driven Material  
Properties**

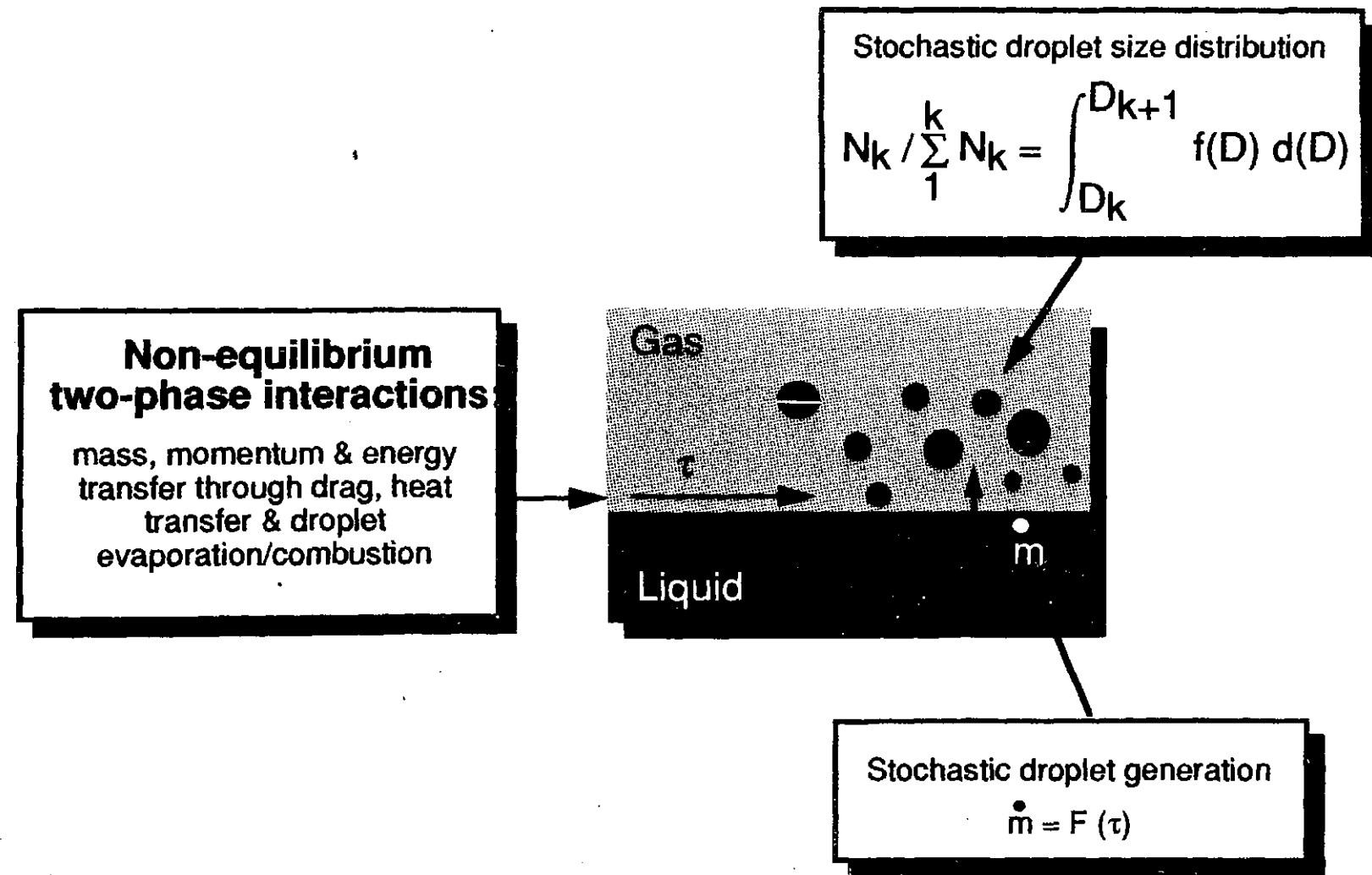
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# FMC Multi-Phase Continuum Model SAE

An Employee Owned Company

Assumption: Time scale to reach thermodynamic equilibrium is smaller than computational time step







July 9, 1991



# Chemical Reactive Flow Model

SAE  
An Employee Owned Company

Real EOS determine post-reaction  
thermodynamic states and heat releases

## Single Step Chemical Reaction



Chemical Kinetics  
Arrhenius form  
"Bulk Burn" rate

Turbulence Model  
Eddy Breakup Time

## Effective Reaction Rate Model

Chemical reaction time scale  
Turbulent mixing time scale

Effective reaction rate  $\tau = f(\tau_c, \tau_t)$

**Turbulent Energy & Dissipation Rate Equations****Advection    Production    Dissipation    Diffusion**

$$\frac{\partial(\rho\kappa)}{\partial t} + \frac{\partial(\rho u_j \kappa)}{\partial x_j} = \left( \alpha^* \rho \bar{S} - \beta^* w \right) \kappa - \xi^* \rho \kappa \frac{\partial u_k}{\partial x_k} + \frac{\partial}{\partial x_j} \left[ (\mu + \sigma^* \rho \epsilon) \frac{\partial \kappa}{\partial x_j} \right]$$

$$\frac{\partial(\rho w^2)}{\partial t} + \frac{\partial(\rho u_j w^2)}{\partial x_j} = \left\{ \alpha \rho \bar{S} - \left[ \beta + 2\sigma \left( \frac{\partial l}{\partial x_j} \right)^2 \right] w \right\} w^2 + \frac{\partial}{\partial x_j} \left[ (\mu + \sigma \rho \epsilon) \frac{\partial w^2}{\partial x_j} \right]$$

**Law of the Wall****Eddy Diffusivity****Reynolds' Stress Tensor****Turbulent heat flux vectors****Turbulent species flux vectors****Mixing time scale for reaction rate model****Fluctuating vel. for 2-phase particle model**

July 9, 1991

**FMC**

# *Real Equations-of-State*

**SAC**  
An Employee Owned Company

## **Utilizing existing EOS Packages**

DNA EOS Library  
Analytical EOS  
Equilibrium Chemical Codes  
Bureau of Standard EOS data

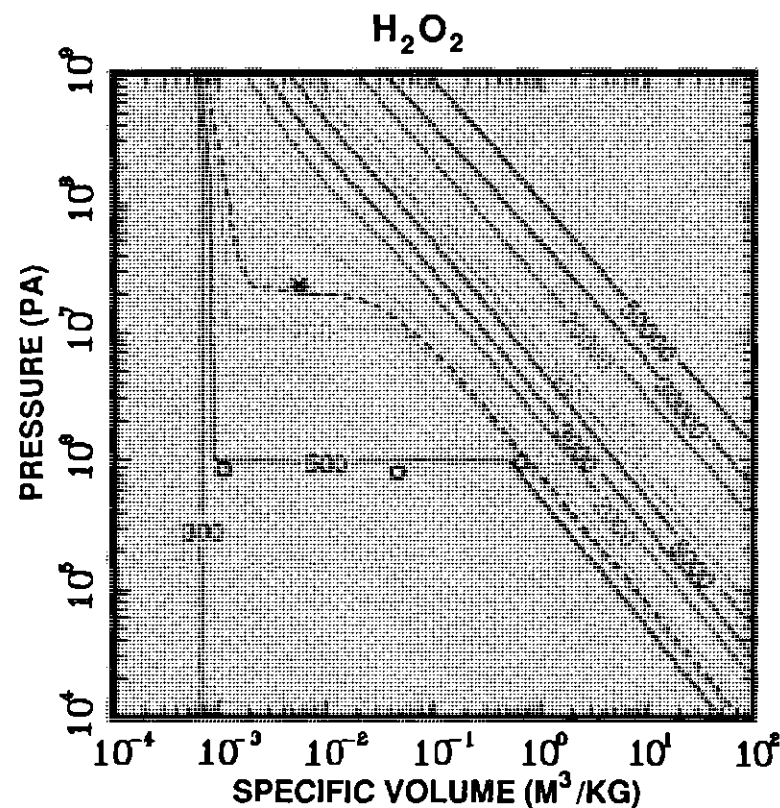
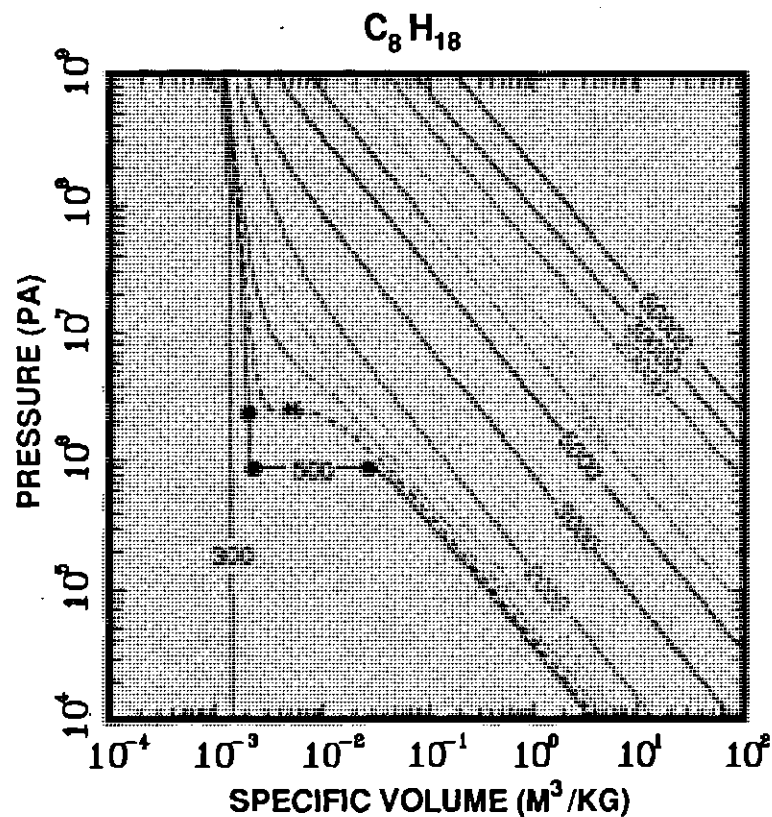
Verified with available  
experimental data

**Range of Validity covers all  
possible ETC Gun conditions**

High density, high pressure liquid state  
Liquid-gas phase transition  
Supercritical state  
High energy plasma state

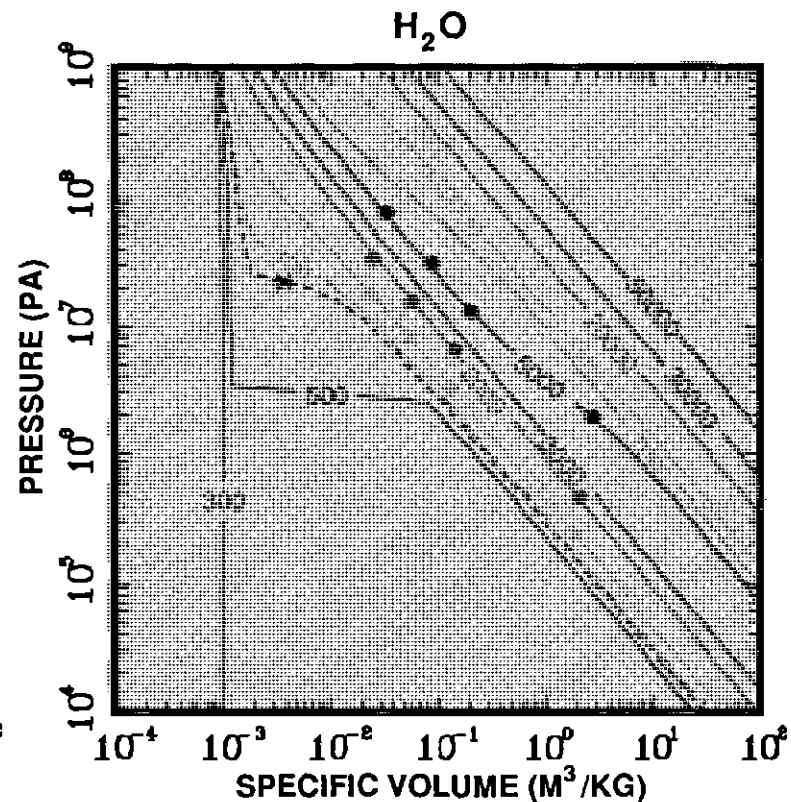
Efficient and easy-to-use  
table lookup format

# FMC Developed Composite Real EOS



- - Data from Thermophysical Properties of Matter, Purdue University, 1982
- \* - Critical point, from Handbook of Chemistry and Physics, 66th Ed. 1986

- - Data from Hydrogen Peroxide Physical Properties, FMC, 1969
- \* - Critical point, Hydrogen Peroxide Physical Properties, FMC, 1969



• - data calculated from NASA-CET89 code

\* - Critical point, from Handbook of Chemistry and Physics, 66th Ed. 1986

June 25, 1991

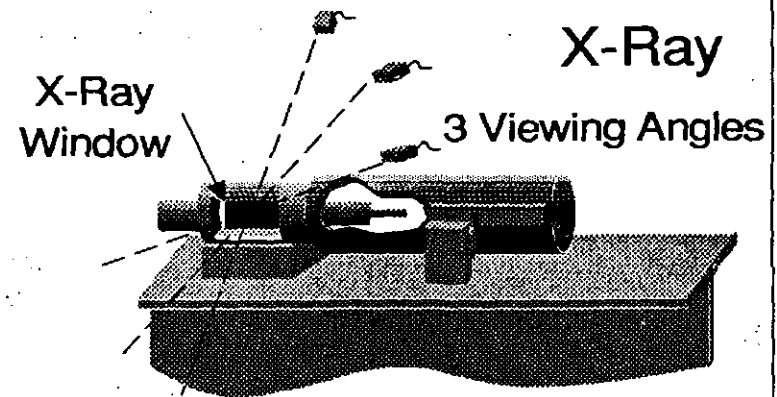
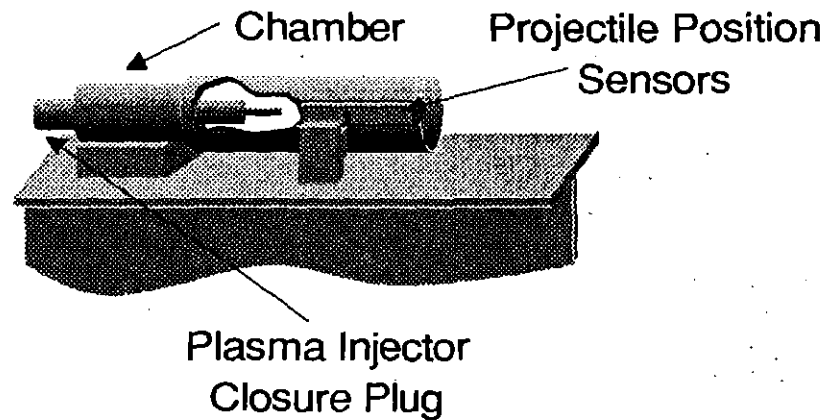
**FMC**

# Phenomenology Experiments

## Burn Rate Tests

**SAIC**  
An Employee Owned Company

### Burn Rate



- Gain an understanding of plasma/fluid interactions
- Allow computation of gas generation rates
- Provide data input for model verification

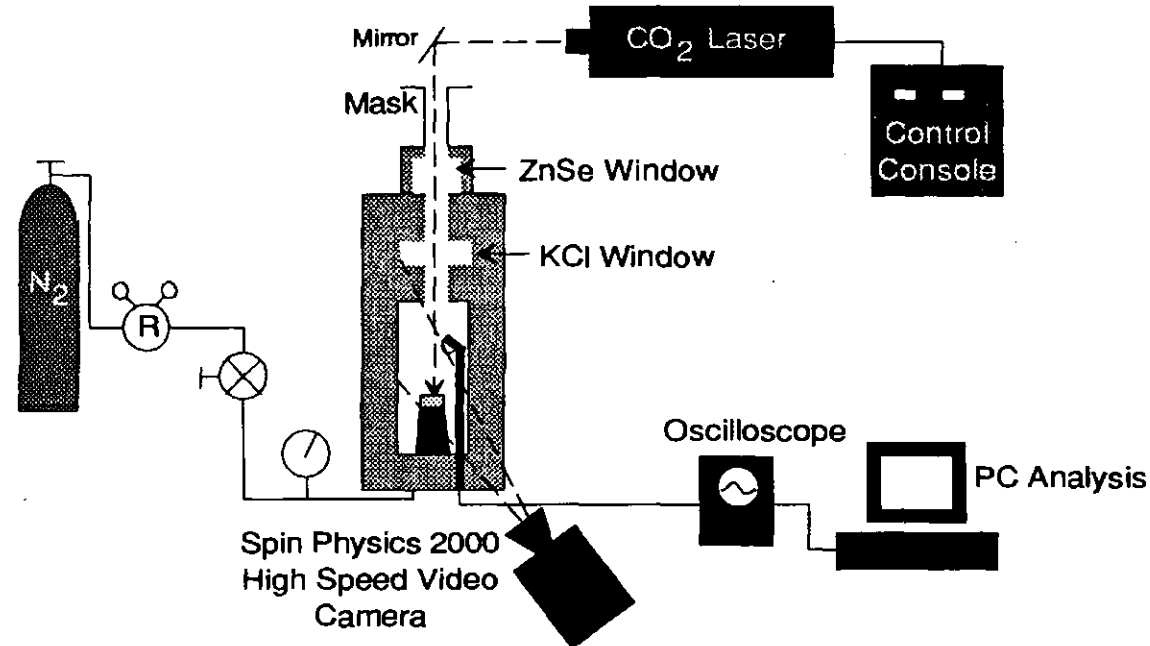
June 25, 1991

**FMC**

# Phenomenology Experiments

## Laser Pyrolysis Ignition Tests

**SAIC**  
An Employee Owned Company



- Provide fuel-oxidizer chemical kinetic data
- Provide ignition delay time and temperature at high P
- Provide data for chemical reaction computer sub-model

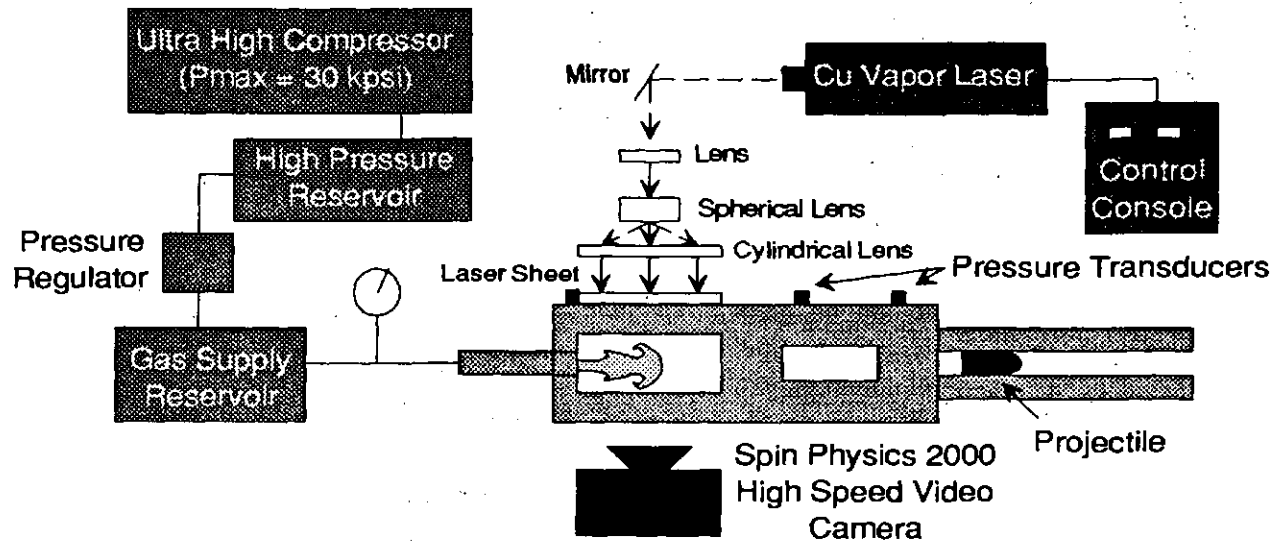
June 25, 1991

**FMC**

# Phenomenology Experiments

## Jet Penetration Tests

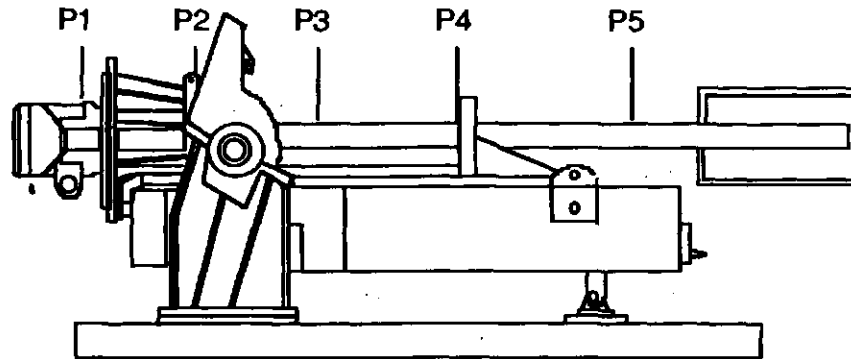
**SAIC**  
An Employee Owned Company



- Measure instantaneous gas jet contours and entrainment processes at near gun pressures (up to 30 kpsi)
- Assess shear layer stripping and droplet generation
- Provide input data for model verification



# *DNA 60mm Shot 26*



60 mm Subscale Gun Fixture

|                    |         |
|--------------------|---------|
| Electric Energy:   | 0.8 MJ  |
| Chemical Energy:   | 4.7 MJ  |
| Elec. Pulse Width: | 4 msec  |
| Projectile Mass:   | 2.75 kg |
| Muzzle Energy:     | 1.23 MJ |



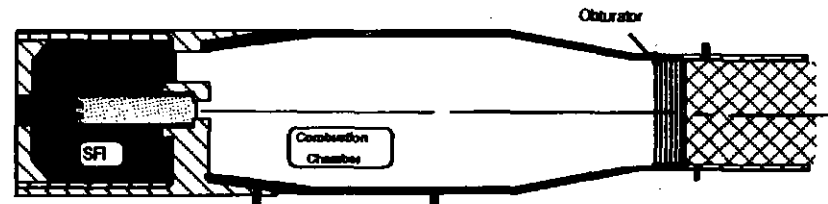
- 2D axisymmetric geometry
- SFI annular orifices (3) are replaced by an annular ring having the same surface area
- 5 species:  $C_8H_{18}$ ,  $H_2O_2$ ,  $H_2O$ ,  $CO_2$ , and Air are included in the computation
- 4 material regions: plasma channel, polyethylene tube, fuel rich (SFI), and fuel lean propellant (combustion chamber), are in the computation

July 9, 1991

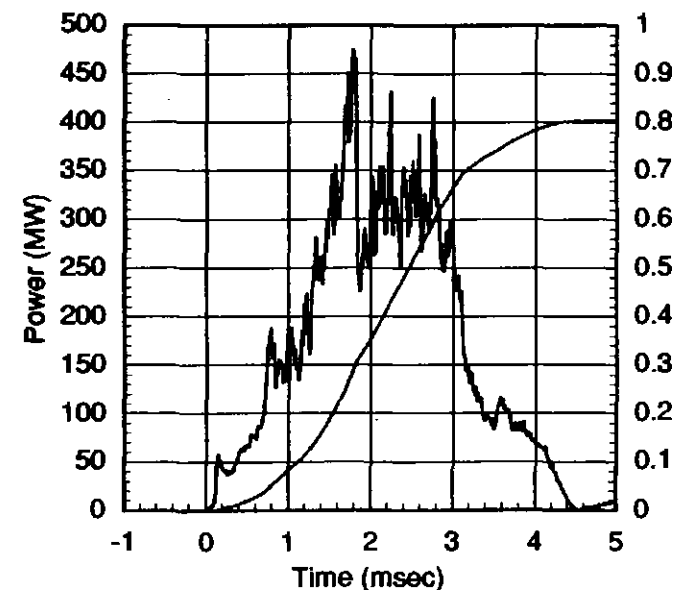
**FMC**

## Capillary & SFI Modeling

**SAIC**  
An Employee Owned Company



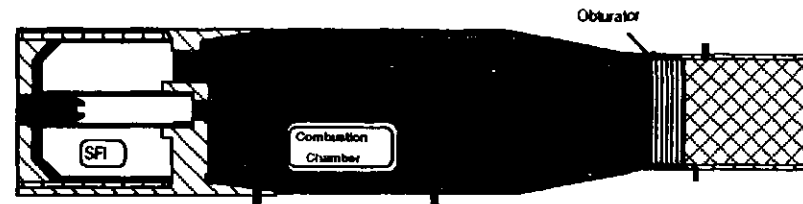
- Electrical energy data from FMC experiments are directly linked to the computation
- Time delay for fuse-wire breakdown is accounted for
- Material strength of polyethylene tube is ignored
- Plasma channel growth is correlated to electrical energy input



July 9, 1991



# Reaction Chamber Modeling

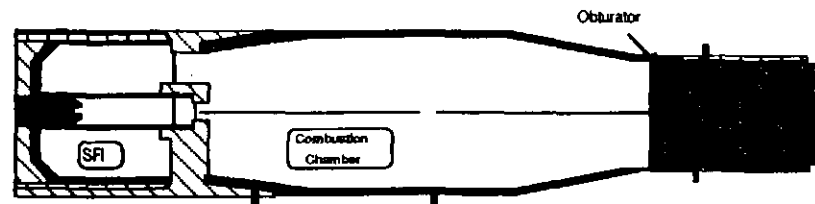


- Flow field in combustion chamber is directly coupled with plasma capillary and SFI
- Chemical kinetic rates are assumed to be fast with respect to turbulent mixing (implies combustion is mixing controlled)
- Single step chemical reaction is assumed

July 9, 1991



# Projectile Dynamics Modeling



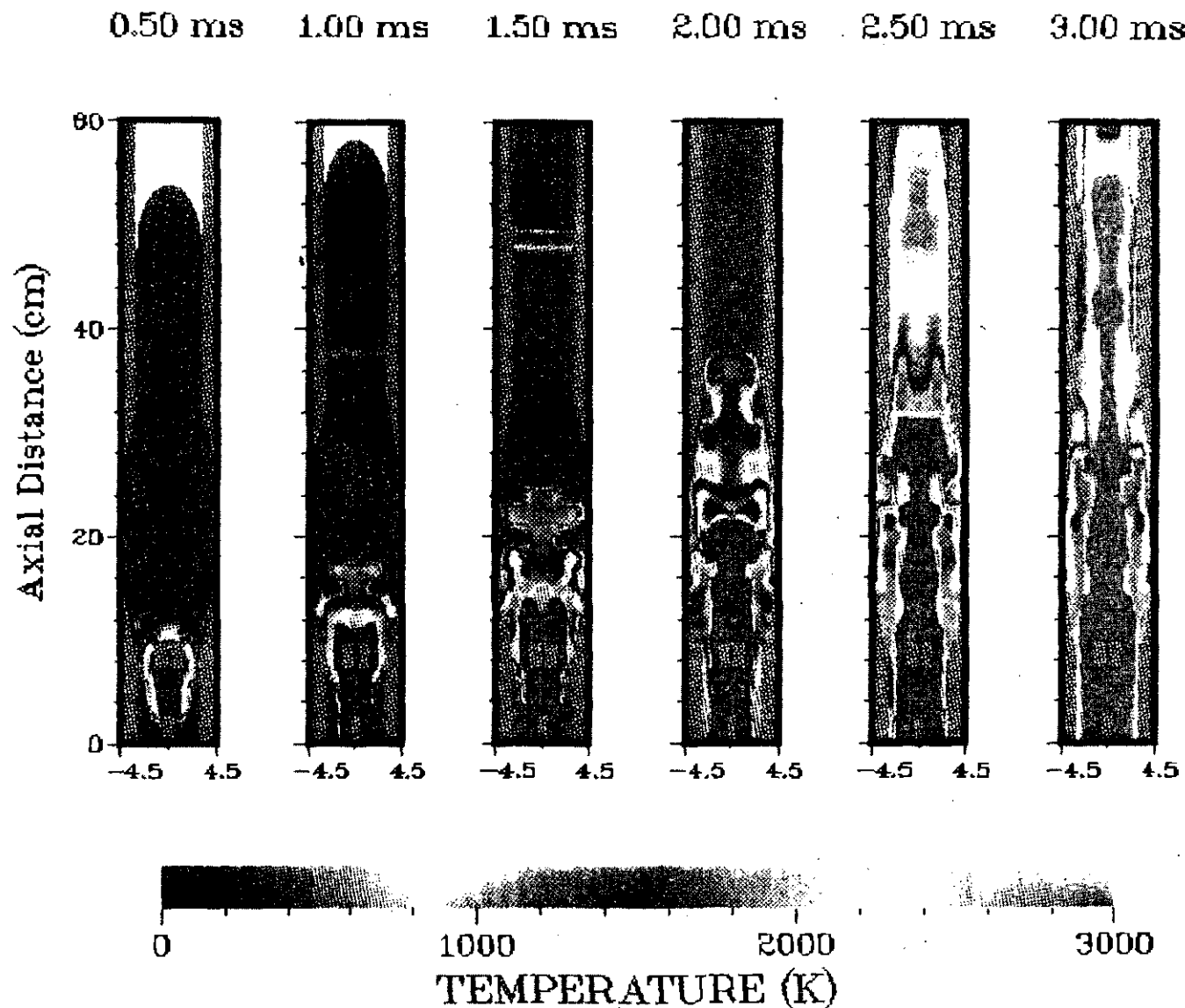
- Dynamic rezoning follows projectile motion
- Problem geometry is reconstructed according to new grid
- Air ahead of projectile is ignored ( error  $< 1\%$ )
- Bore friction force is neglected

June 25, 1991

**FMC**

# Temperature Contours

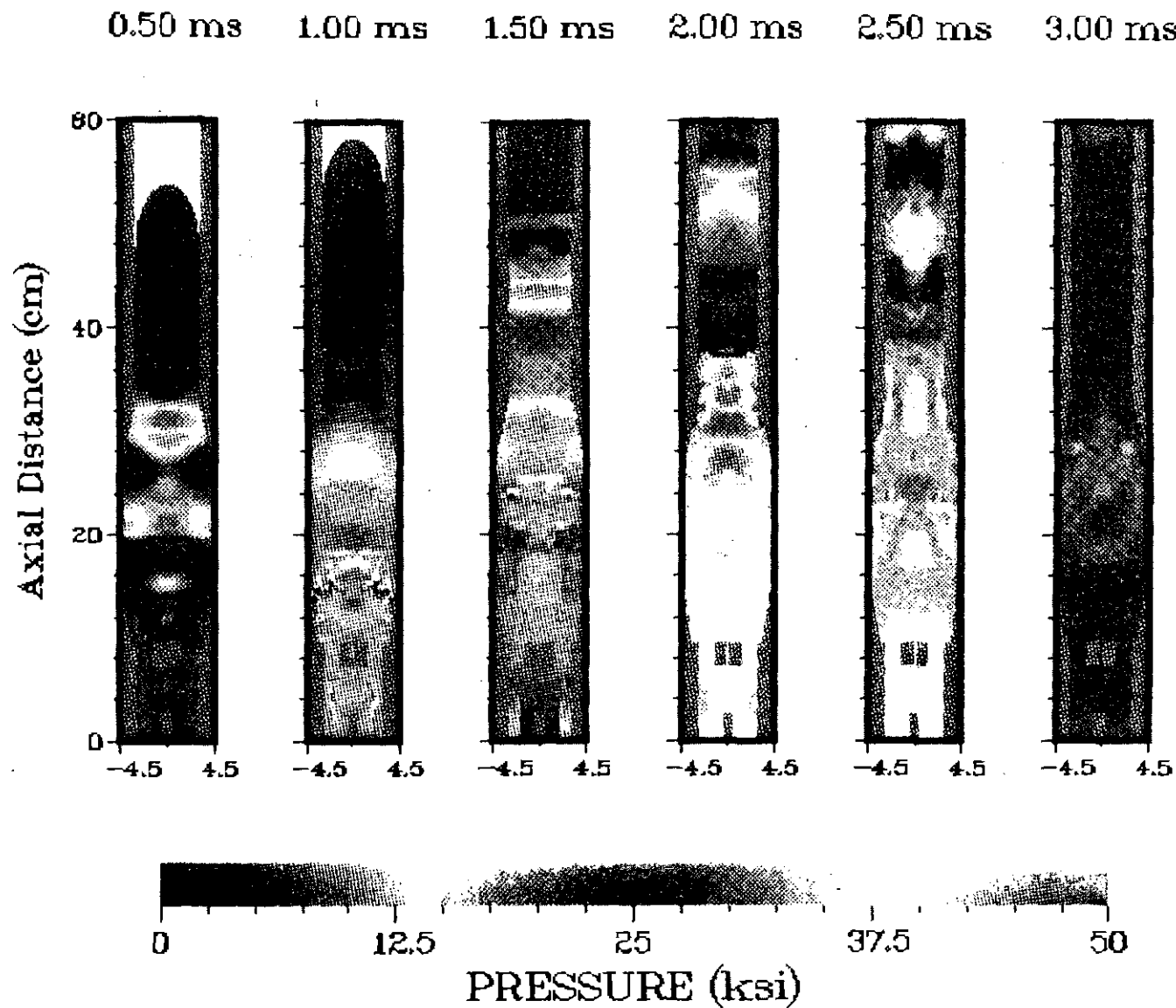
**FMC**  
An Engineered Control Company



June 25, 1991

**FMC**

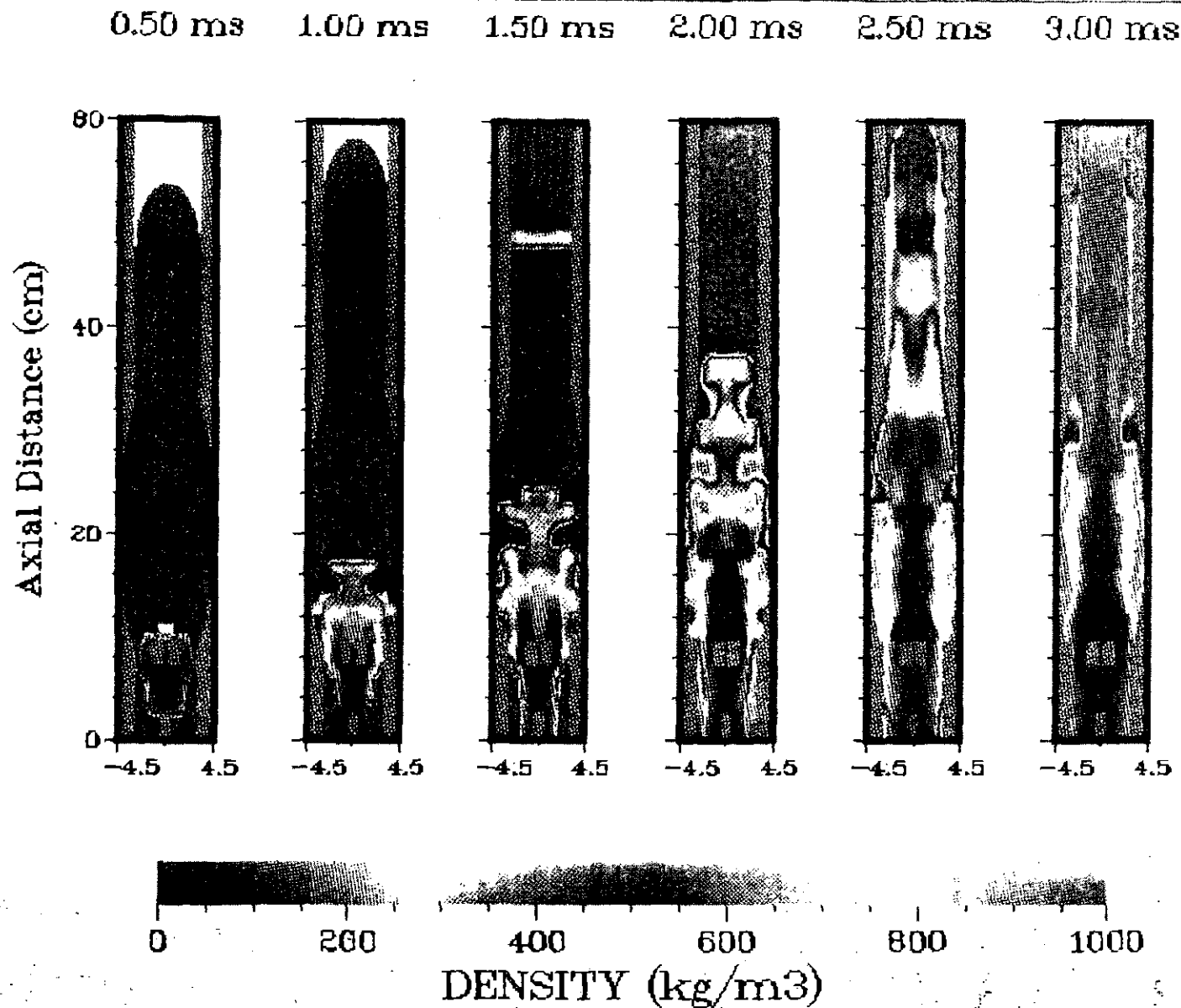
# Pressure Contours



June 25, 1991

**FMC**

# Density Contours

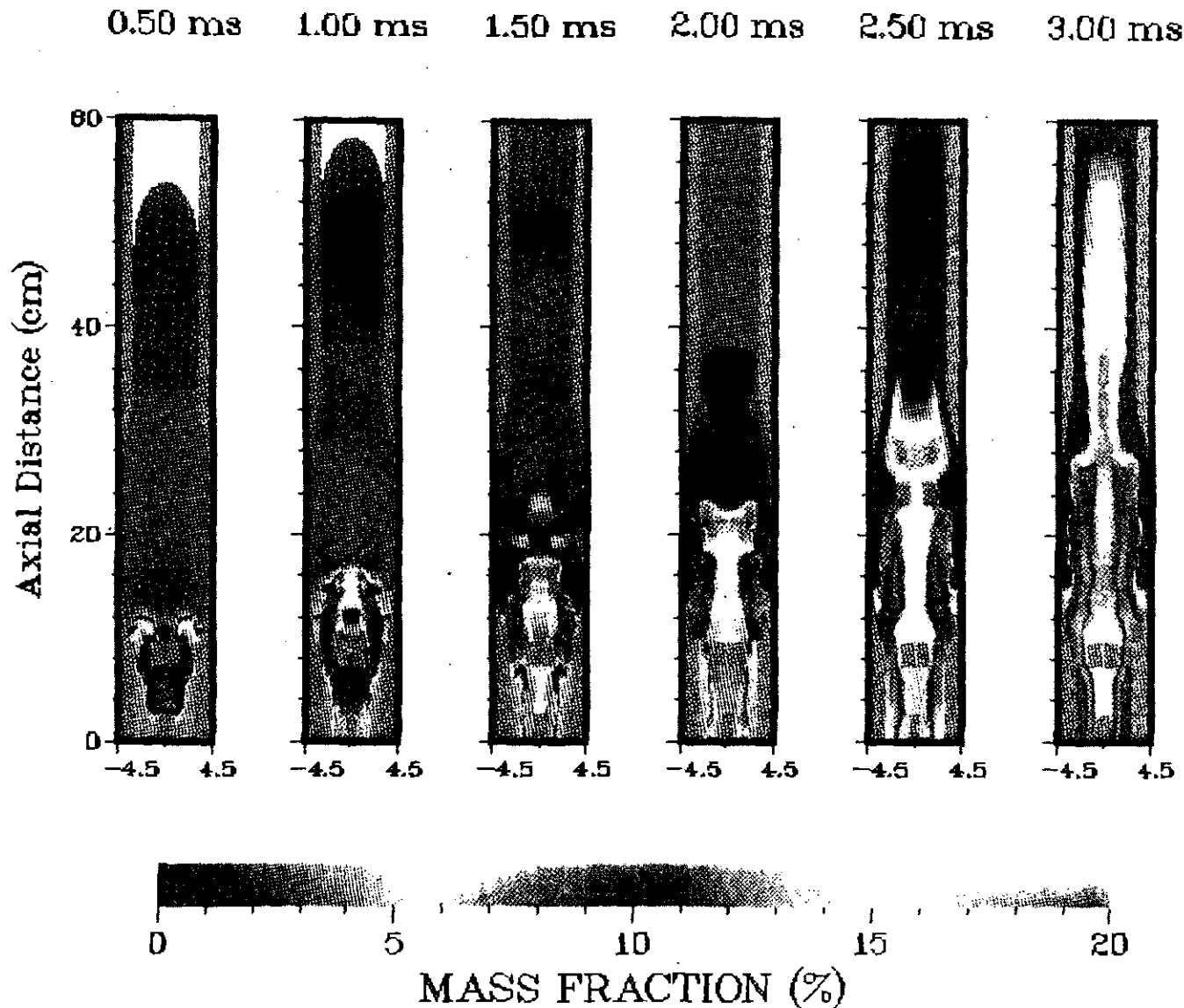
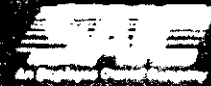




June 25, 1991

**FMC**

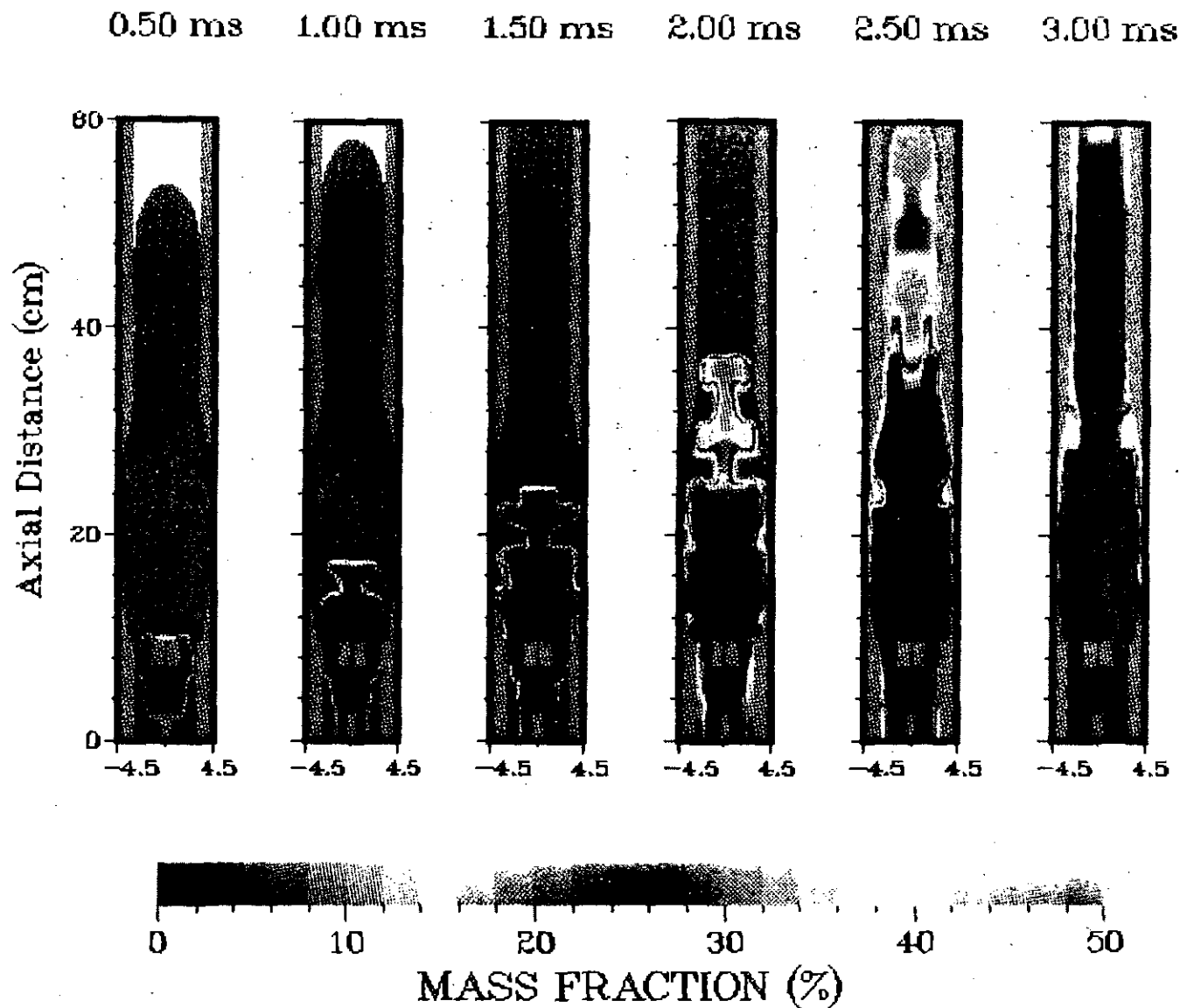
# Fuel Mass Fractions



June 25, 1991

**FMC**

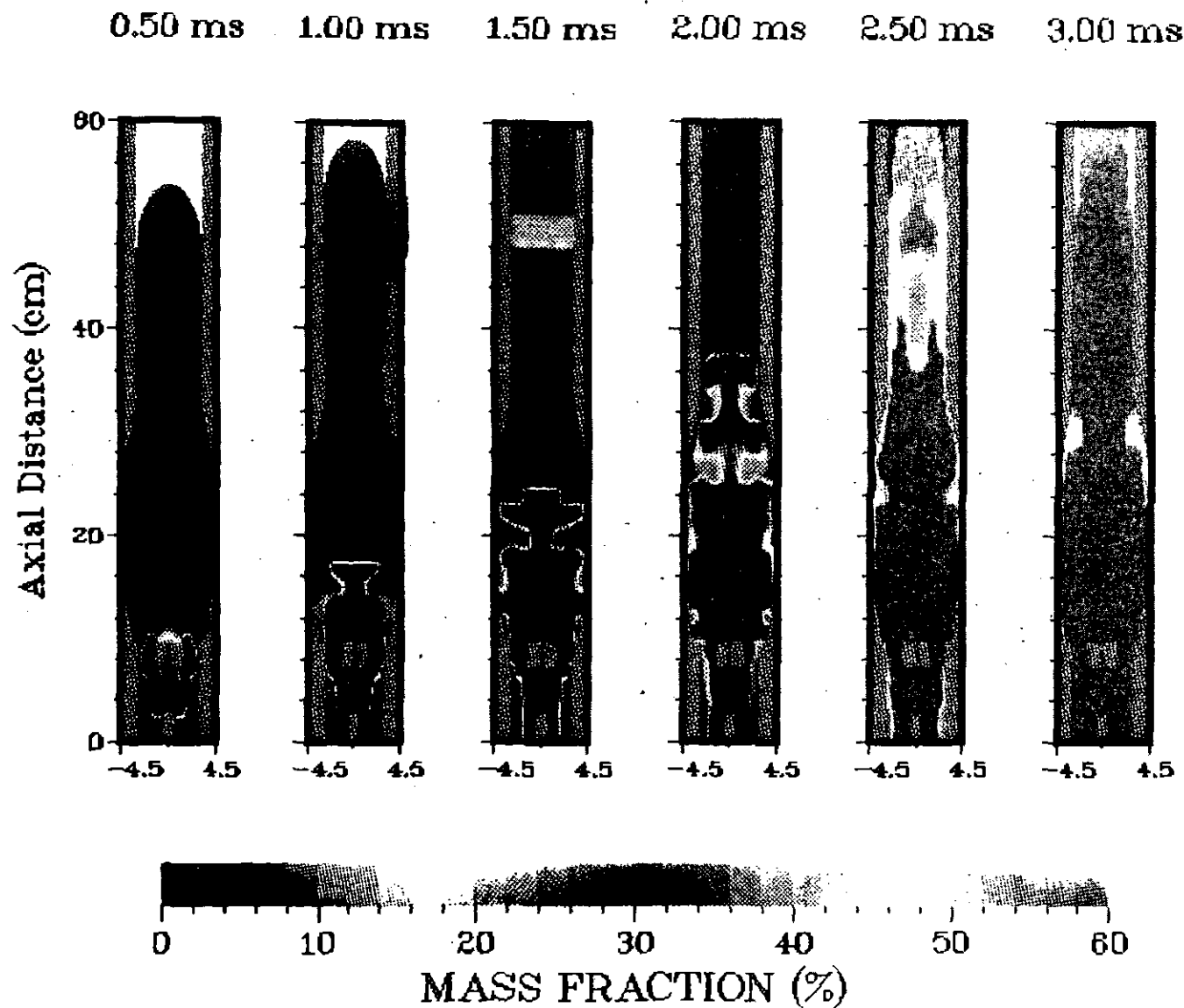
# Oxidizer Mass Fractions



June 25, 1991

**FMC**

# *H<sub>2</sub>O Mass Fractions*



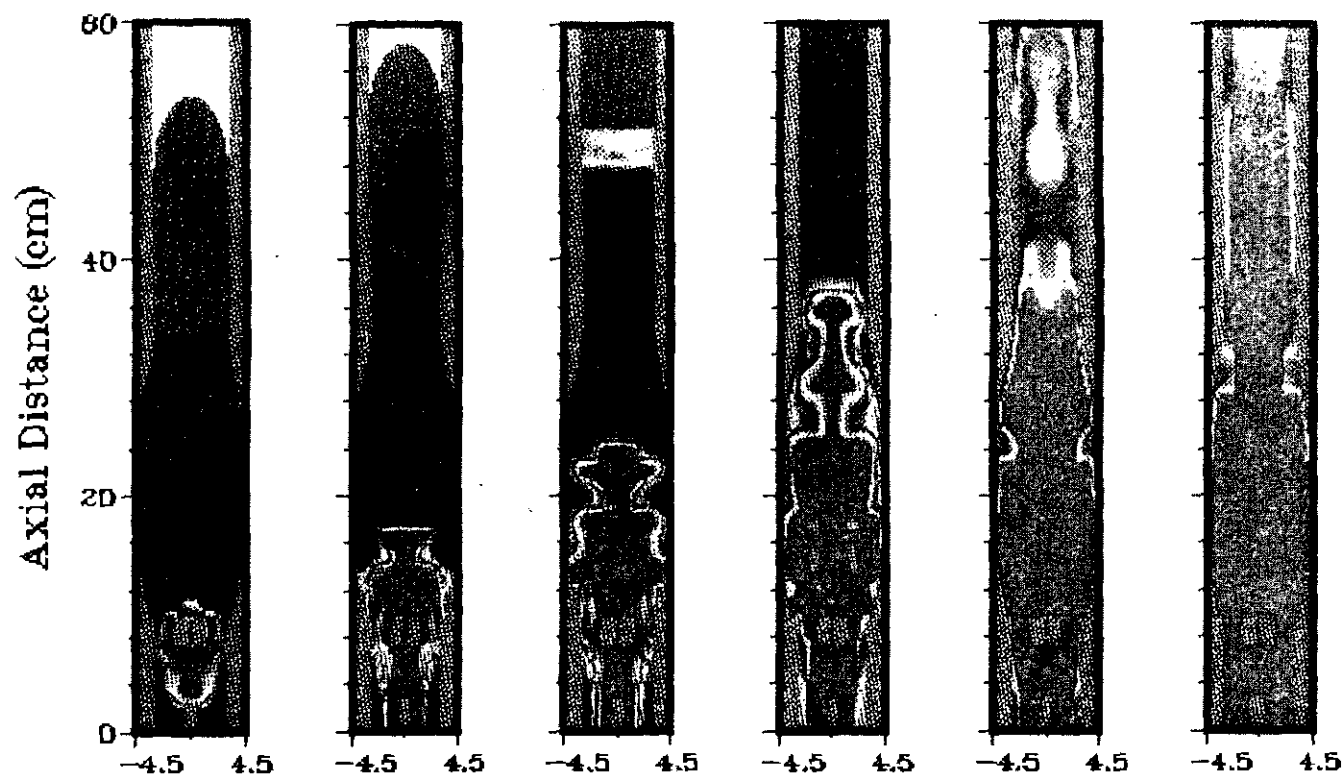
June 25, 1991

**FMC**

# *CO<sub>2</sub> Mass Fractions*



0.50 ms    1.00 ms    1.50 ms    2.00 ms    2.50 ms    3.00 ms

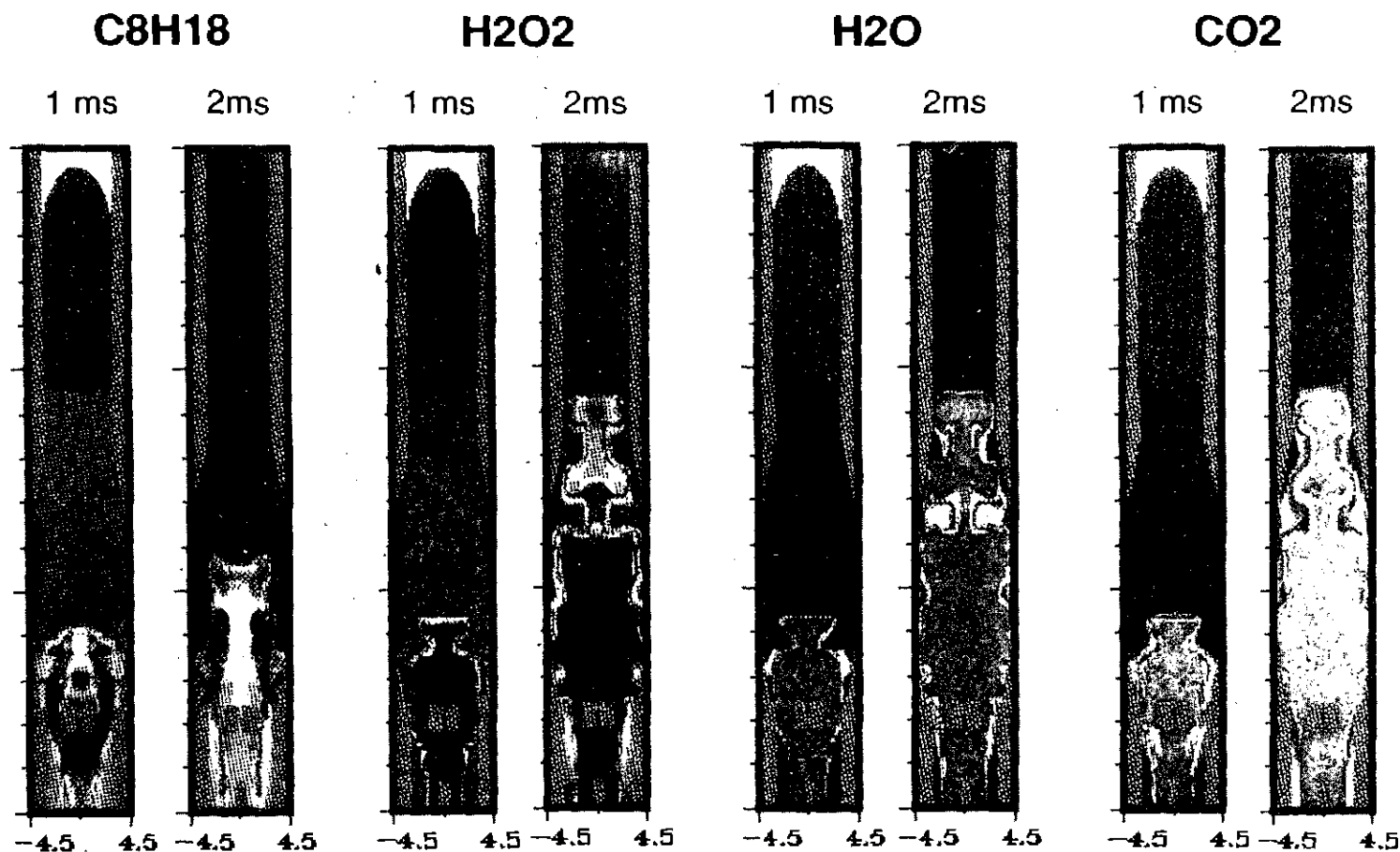
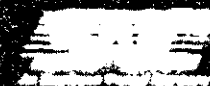


MASS FRACTION (%)

June 25, 1991

**FMC**

# Species Concentrations



C8H18, CO2

0

4

8

12

16

20

(%)

H2O2, H2O

0

10

20

30

50

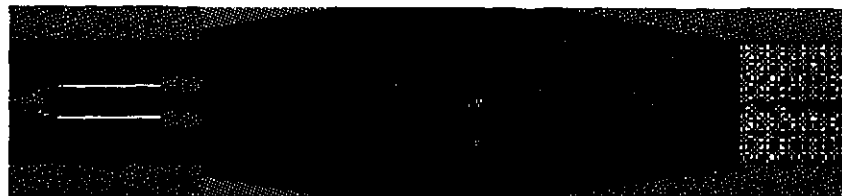
50

(%)

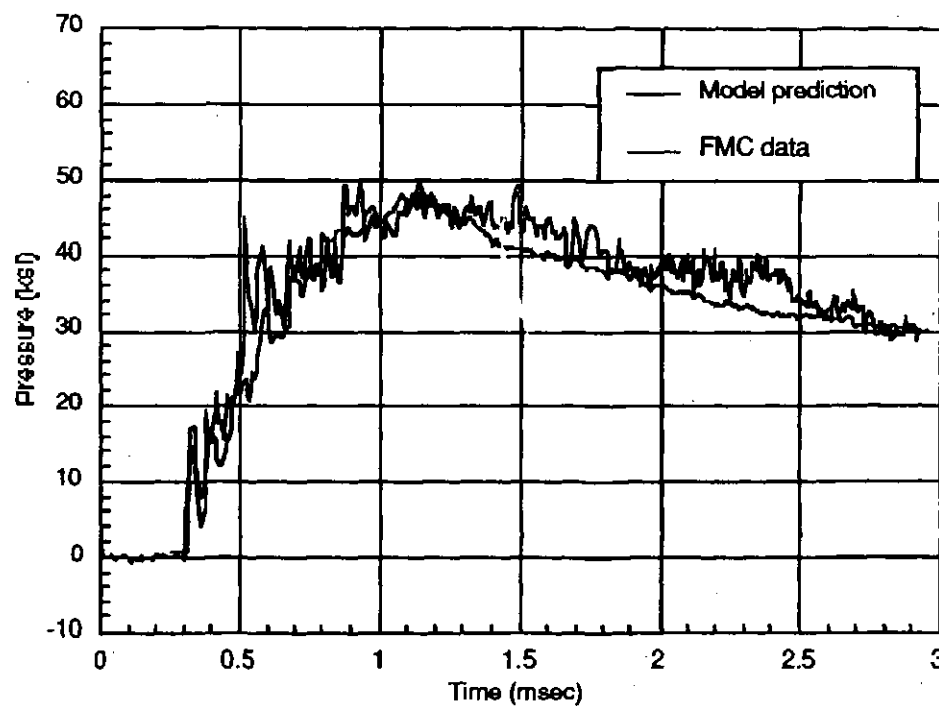
July 9, 1991

# FMC Pressure Waveform Comparison

**SAIC**  
An Employee Owned Company



P1



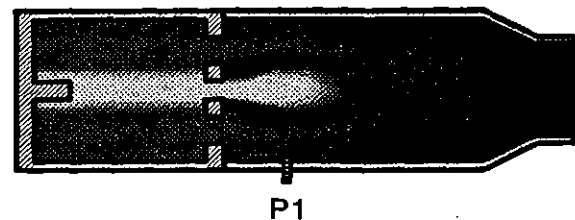
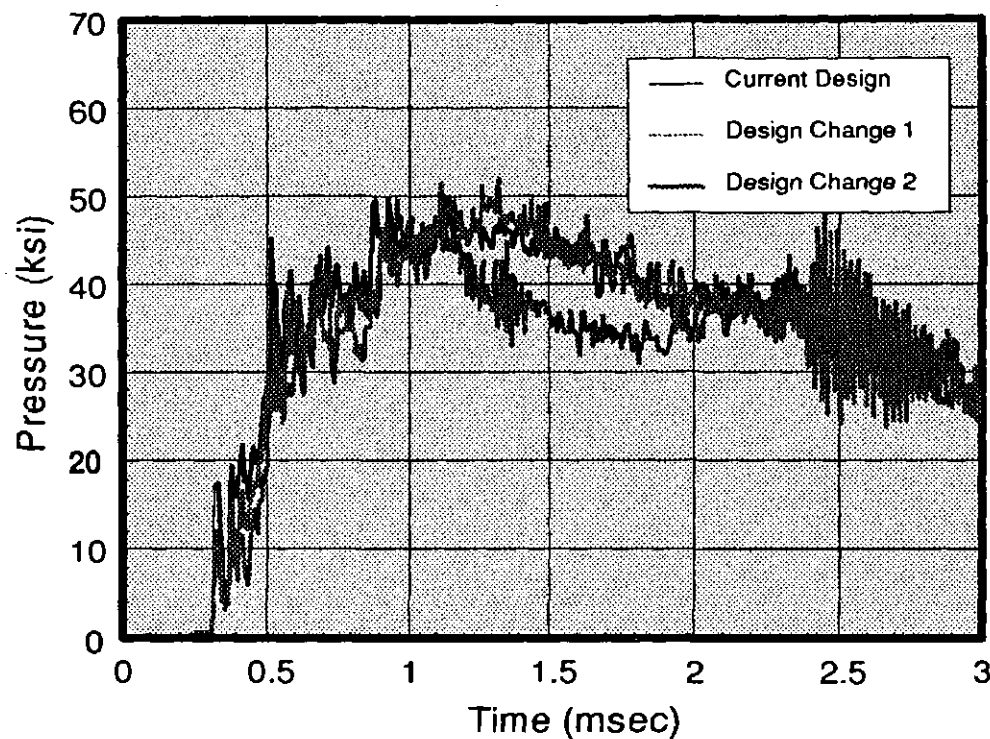
June 25, 1991



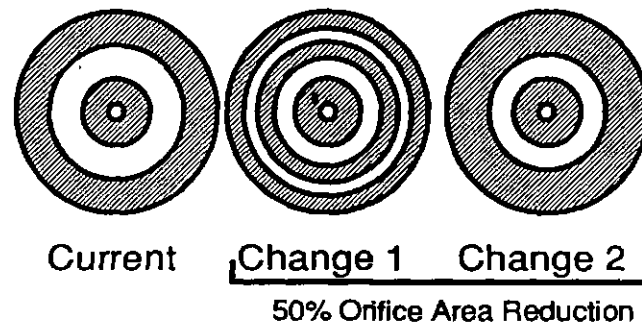
# SFI Performance Studies



Pressure Transducer P1



SFI Face Plate



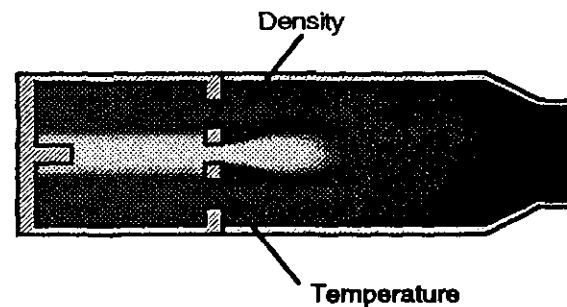
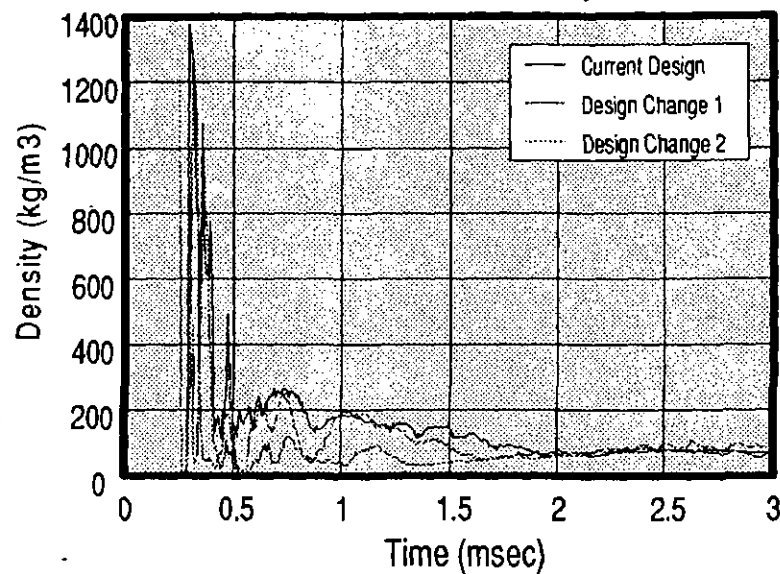
June 25, 1991



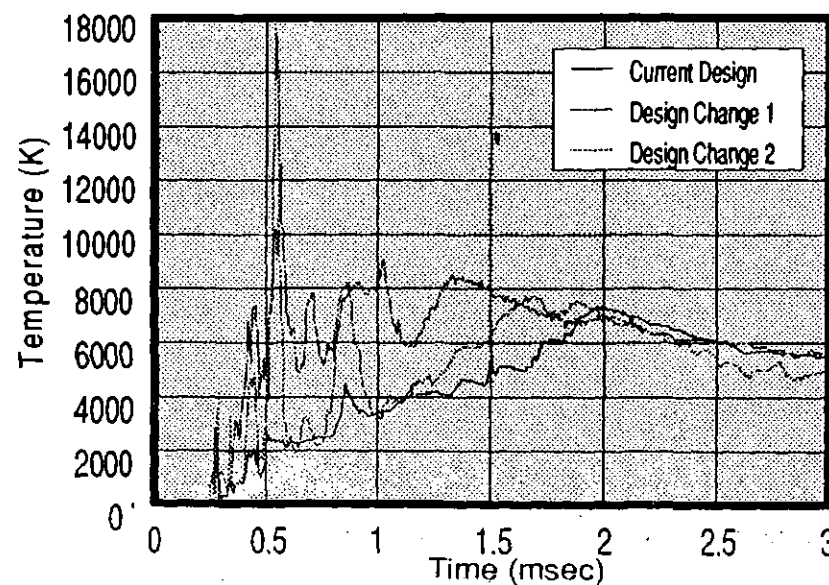
# SFI Performance Studies



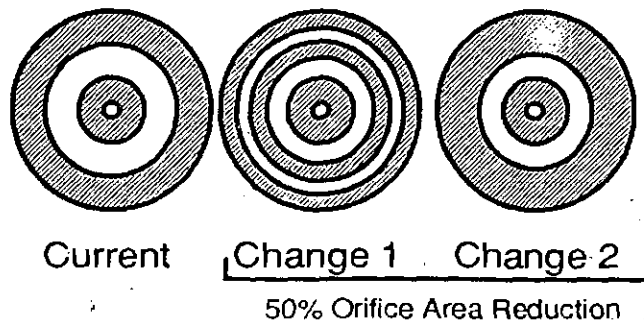
## Fuel Jet Density



## Fuel Jet Temperature



## SFI Face Plate

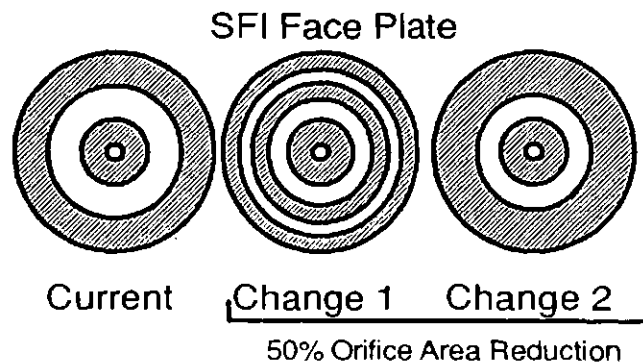
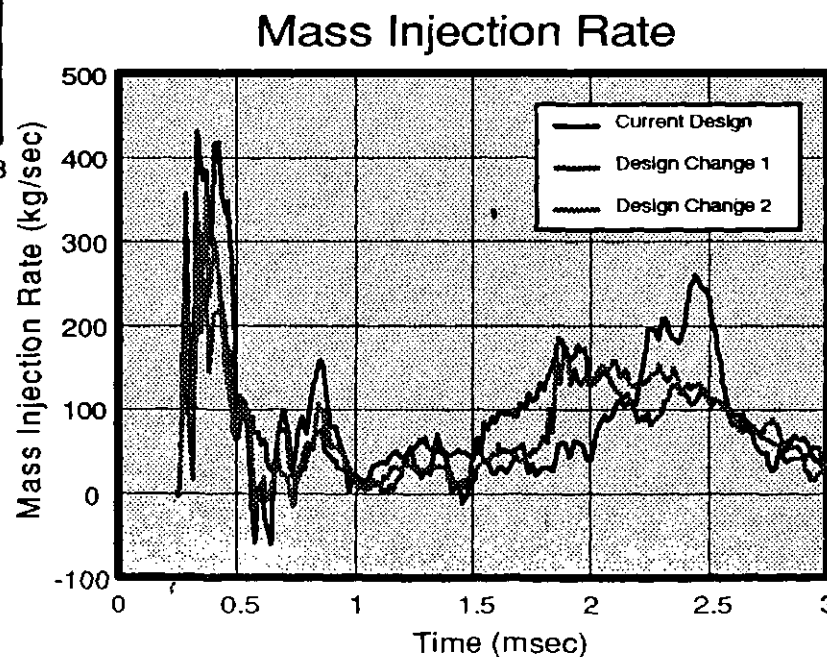
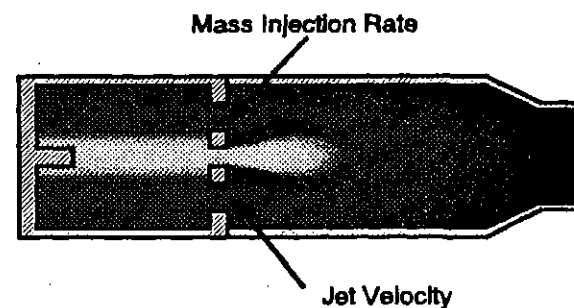
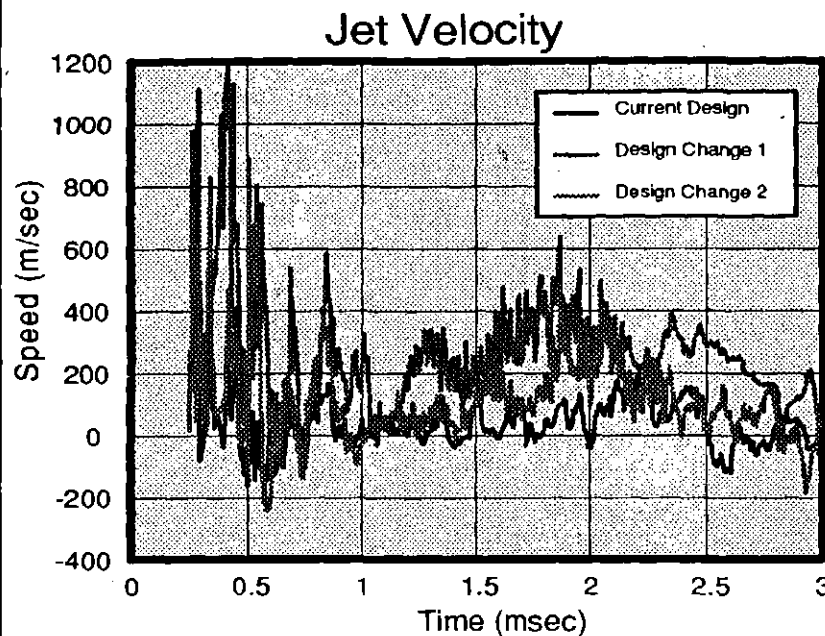




June 25, 1991



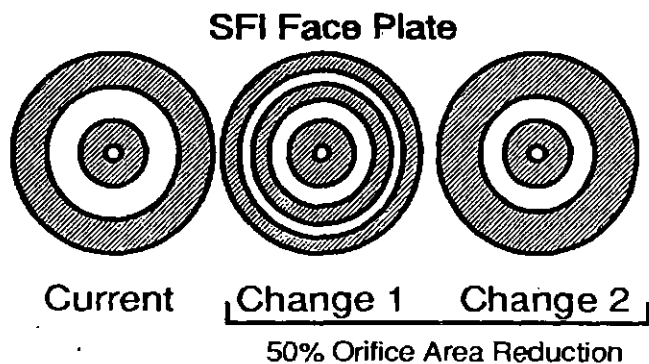
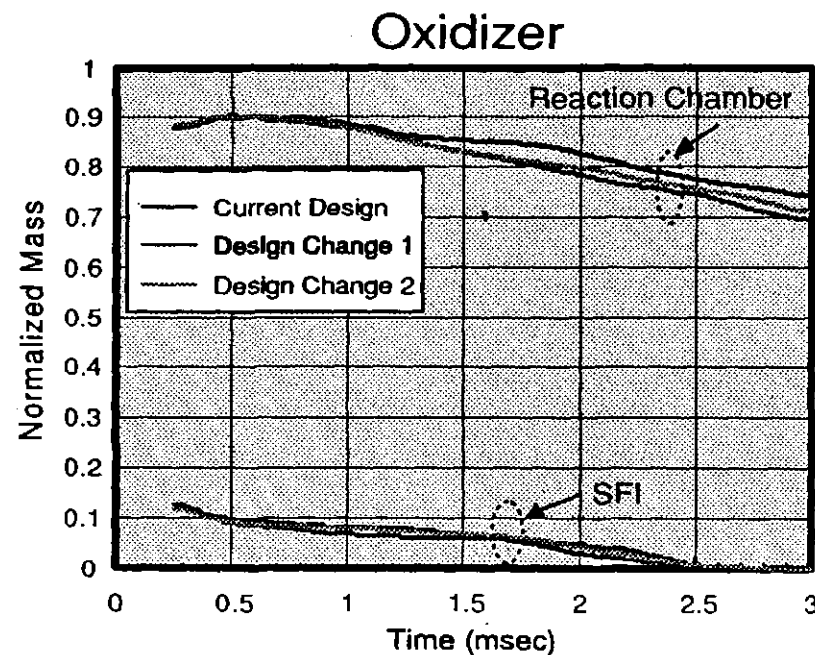
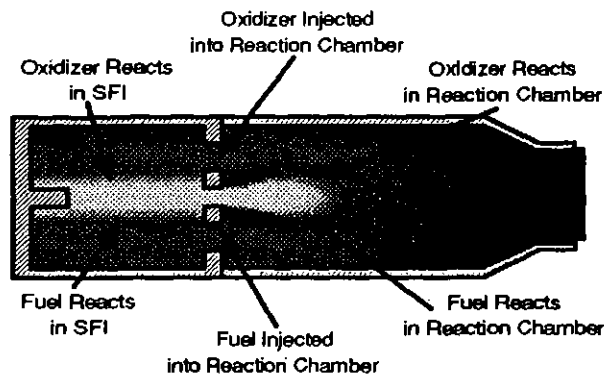
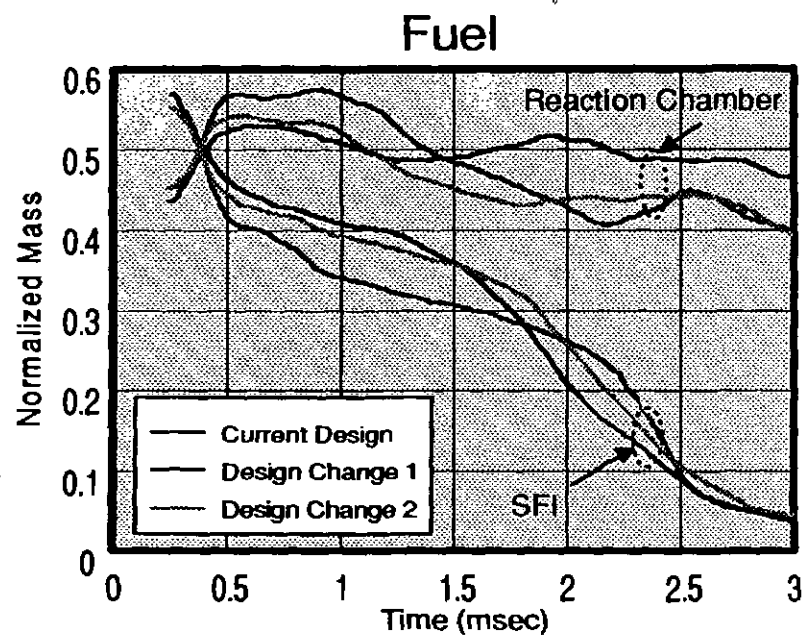
# SFI Performance Studies



June 25, 1991



# SFI Performance Studies



## PHYSICS OF ETC PLASMA-FLUID INTERACTIONS

B. A. Kashiwa, H. A. Davis, and R. J. Trainor, Jr.  
Los Alamos National Laboratory  
Los Alamos, NM 87545

### ABSTRACT

Two fundamental elements of the Electrothermal/Chemical (ETC) Gun process are discussed. The first involves the nature of discharge arc itself, and the second involves the microphysical interaction of the expanding hot gas with a cool condensed phase propellant. Magnetohydrodynamic calculations suggest the existence of a so-called filament discharge in the hot expanding gas. These calculations are discussed. Also, recent experimental evidence suggests the importance of Rayleigh-Taylor instability in the development of a cavity in a liquid, at prototypical ETC Gun pressures. The latest multidimensional hydrodynamic analysis of this instability effect is presented.

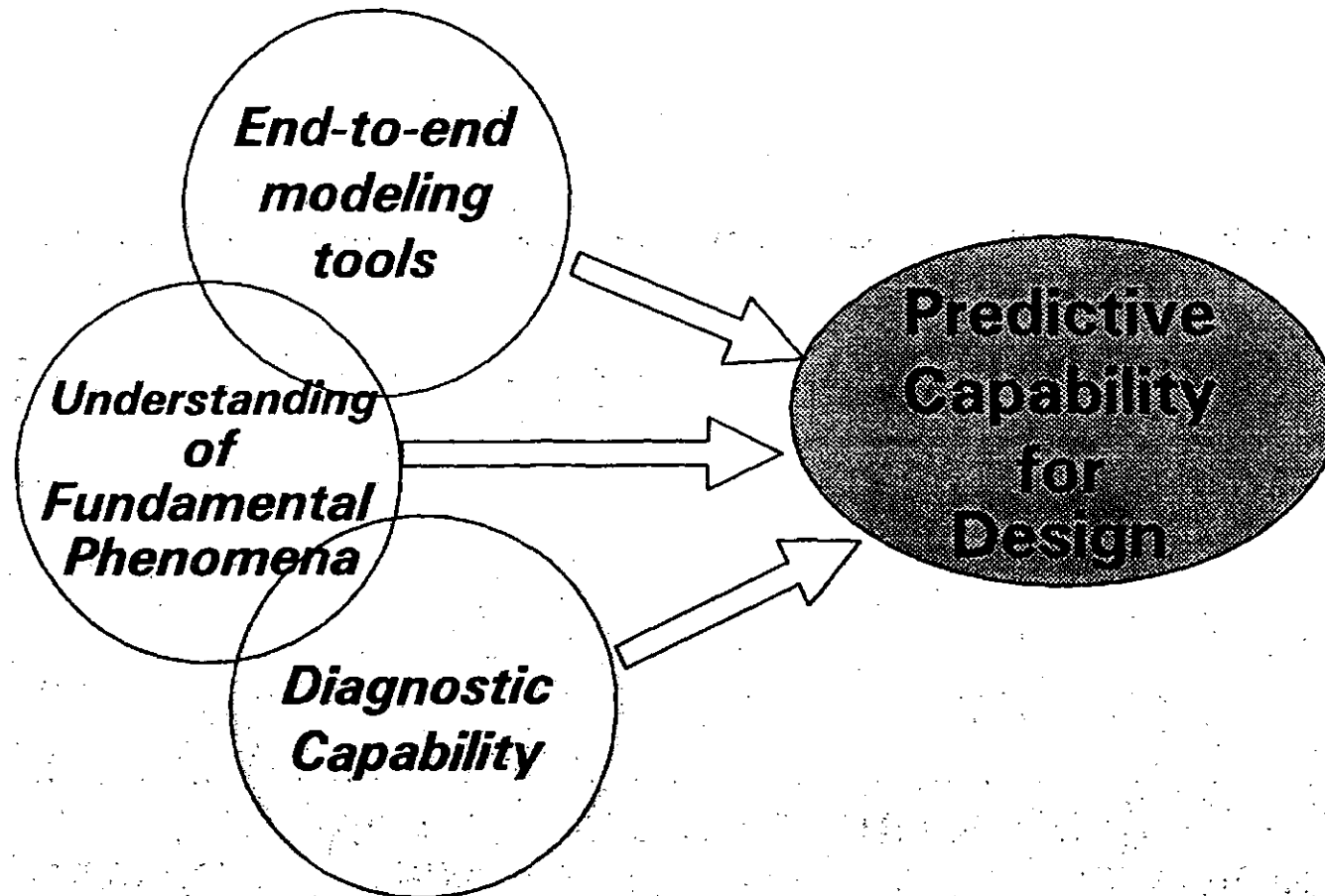
B. A. Kashiwa, H. A. Davis, and R. J. Trainor  
Los Alamos National Laboratory

## Physics of ETC Plasma-Fluid Interactions

JANNAF Workshop  
July 9-11, 1991  
Aberdeen, Md

# Los Alamos Goal Is Predictive Capability For ETC Design

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# Overview of Los Alamos ETC Activities

## *Working Toward A Predictive Capability*

---

1. End-to-end code development

2. Benchmarking expts. on 20 mm ET gun

3. Plasma-working fluid interaction expts.

4. Modeling of P/W-F experiments

5. Projectile velocity diagnostics --

*This talk*

*Hal Davis  
next talk*

*Dick Bartsch  
tomorrow AM*

---

Los Alamos

# **Los Alamos ETC Code Uses Multidimensional Hydrocode Library**

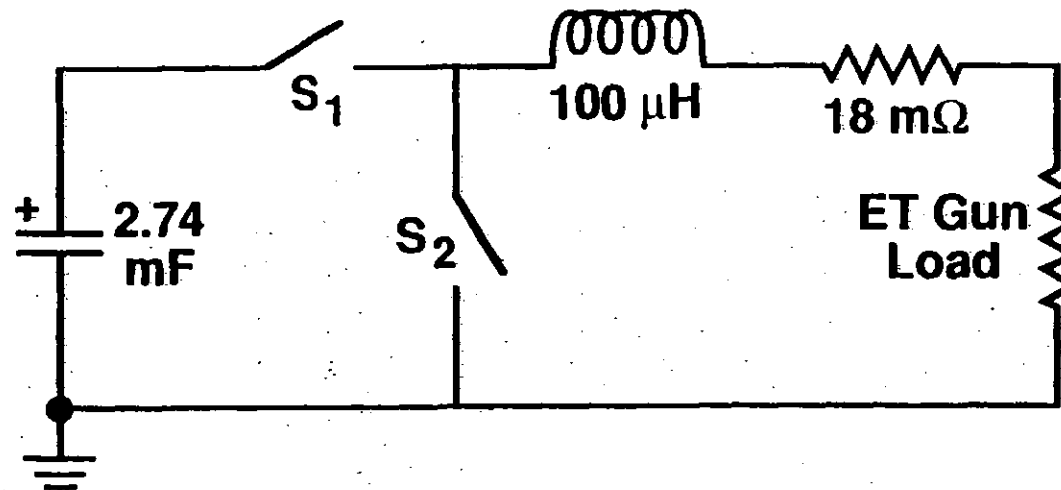
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- **End-to-end code combines hydrocode library (CFDLIB), circuit code analysis and capillary plasma tube model.**
  - ▶ **Useful engineering analysis tool**
  - ▶ **Now developing into wide-range predictive tool**
- **Gun chamber and tube treated with multidimensional code which treats a turbulent, chemically-reacting, multispecies fluid**
  - ▶ **Predominantly Eulerian frame used**
  - ▶ **Two propellant burn models (Arrhenius & bulk burn)**
  - ▶ **Can access variety of modules (e.g., turbulence, EOS)**
- **Reference on interfaces, numerical techniques, models:  
B. A. Kashiwa et al., Proc. 27th JANNAF Combust. Mtg., 1990**

# Los Alamos 20 mm ET Gun

## *Used For Code Benchmarking*

---



|           |        |               |              |
|-----------|--------|---------------|--------------|
| Voltage   | 4 kV   | Energy        | 22 kJ        |
| Current   | 10 kA  | Impedance     | 0.2 $\Omega$ |
| Power     | 22 MW  | Max. velocity | 0.6 km/s     |
| Rise time | 0.6 ms | Max. pressure | 6 kpsi       |

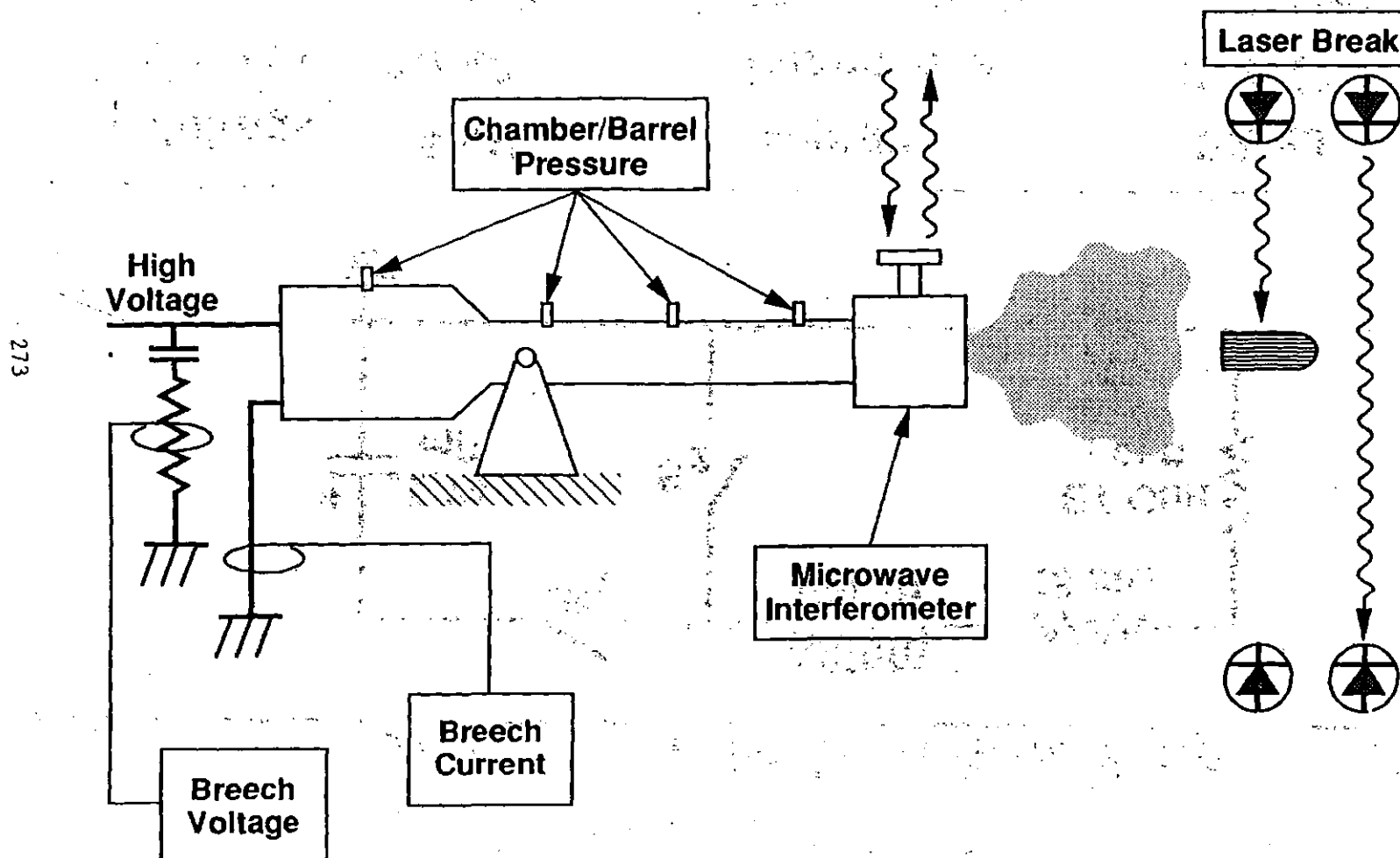
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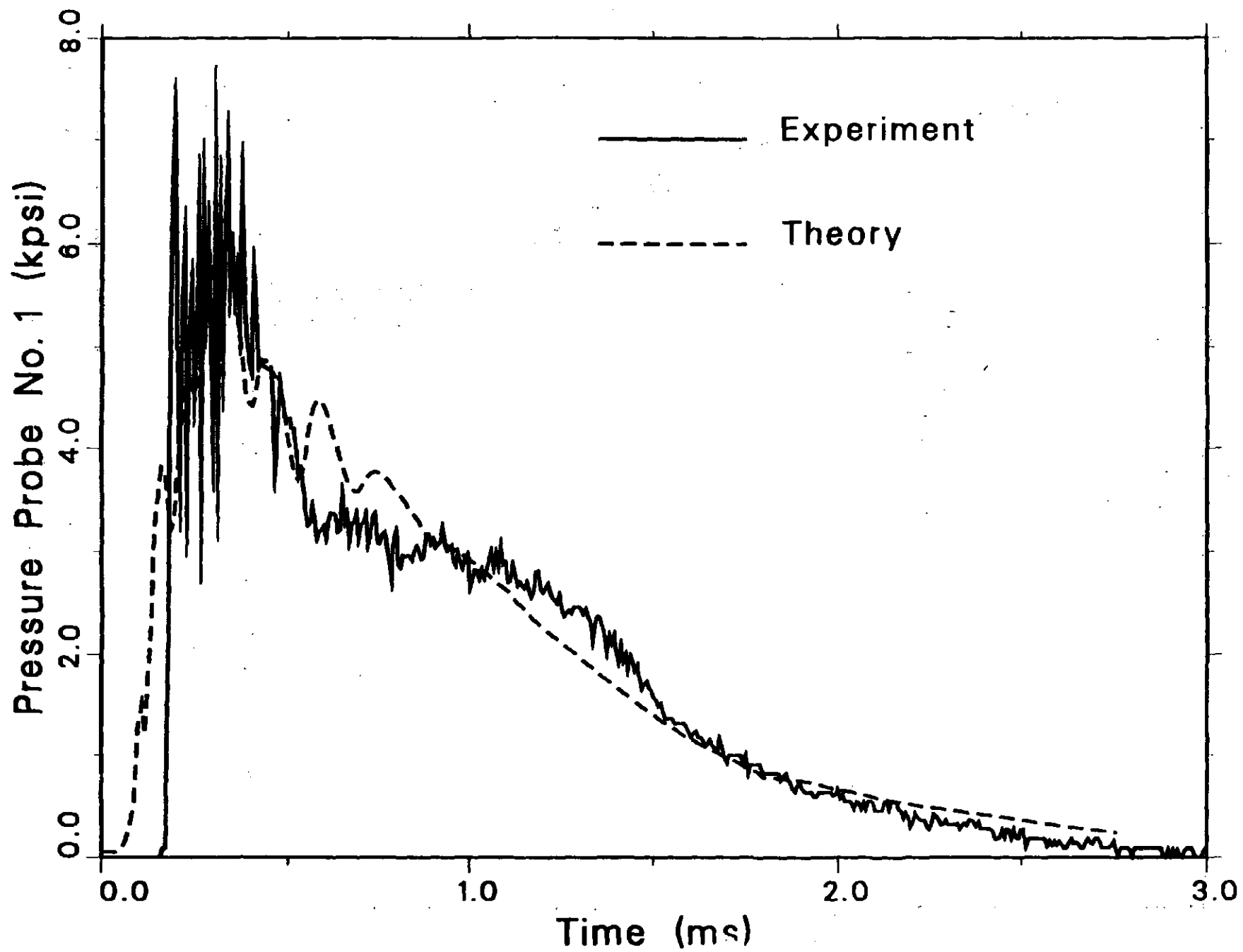
Los Alamos

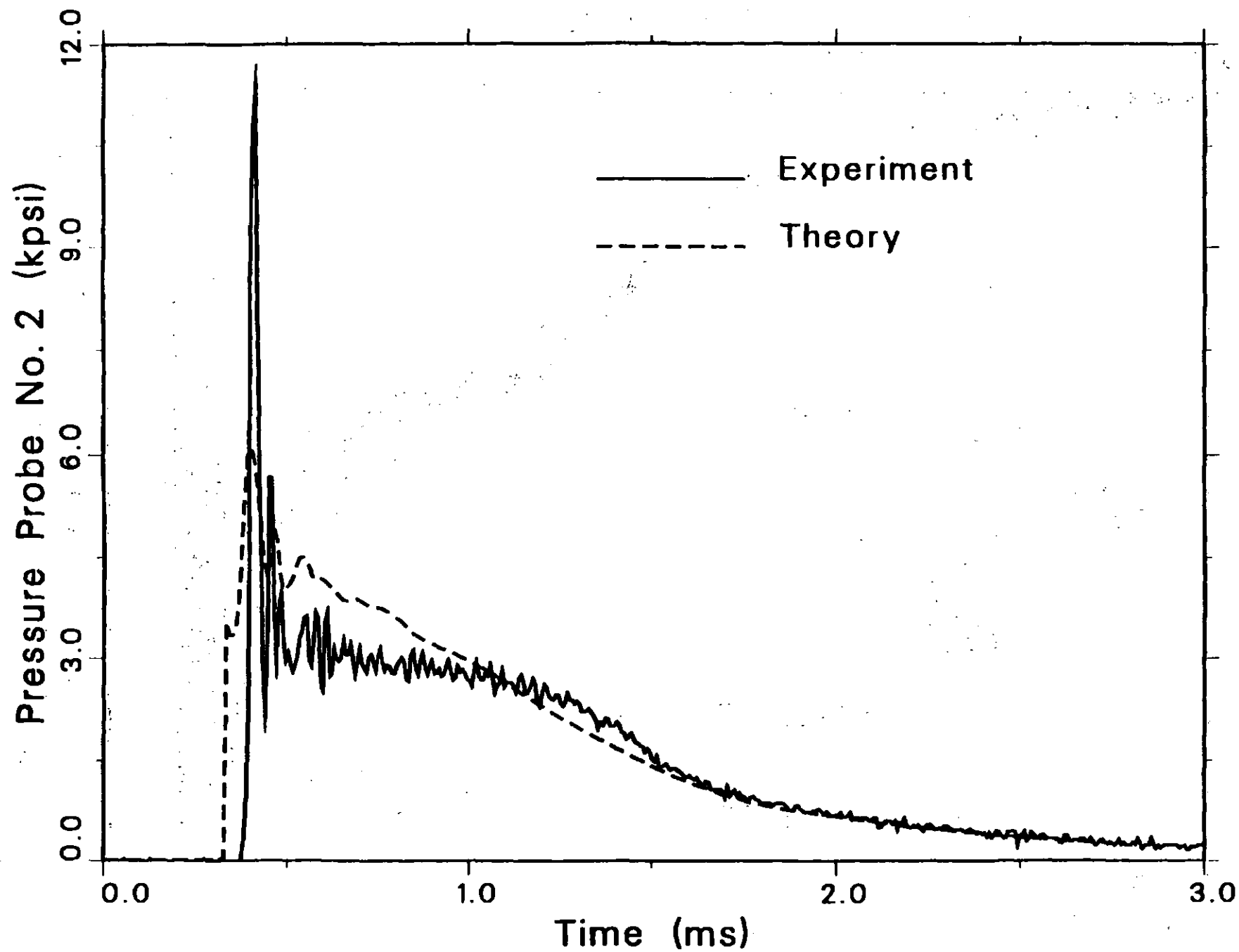
LA-12218-1



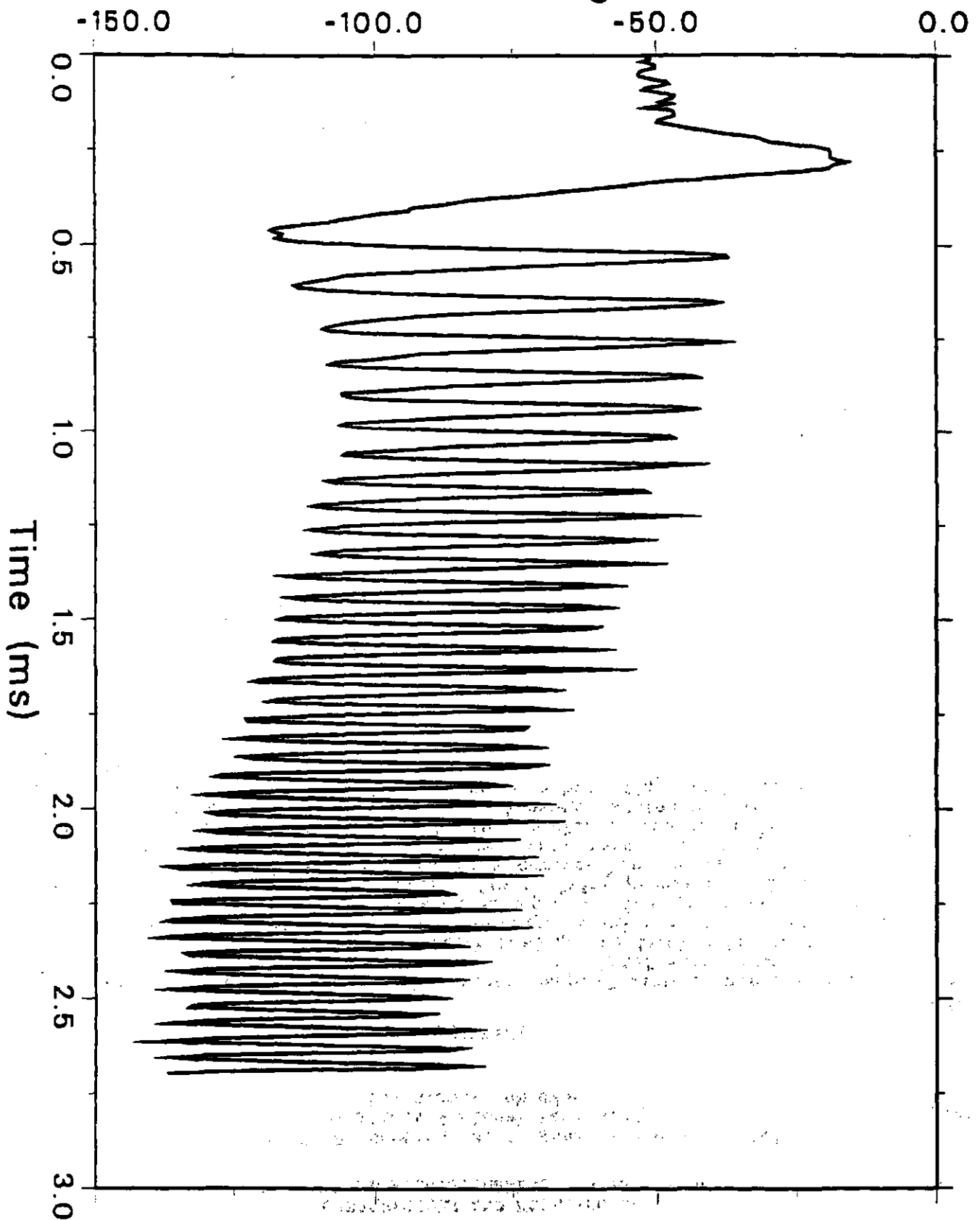
# Los Alamos ET Gun Diagnostics







## Interferometer Signal (mV)



**OBSERVATIONS AND MODELING OF  
FUNDAMENTAL ELECTROTHERMAL GUN PHENOMENA**

H. A. Davis, R. R. Bartsch, B. A. Kashiwa and N. T. Padial  
Los Alamos National Laboratory  
Los Alamos, NM 87545

**ABSTRACT**

We have begun experimental studies coupled with computer modeling of fundamental electrothermal gun processes. In initial work, now complete, we used a 20-mm-bore steam driven electrothermal gun to develop diagnostics and to benchmark Los Alamos ET gun computer modeling. Results of current experiments, now underway, to image the interaction of a plasma with a working fluid will be reported. The object is to determine fluid mixing processes, first with non-combustible working fluids and then with combustible fluids. Initially, the interaction of an exploded wire plasma with water is being studied with time-resolved X-ray photography. The interaction is contained in a dielectric chamber surrounded by a steel housing. A short section of barrel is used to allow for fluid expansion. First shots have been fired and images have been produced.

H.A. Davis, R.R. Bartsch,  
B.A. Kashiwa, and N.T. Padial  
Los Alamos National Laboratory

# Observations and Modeling of Fundamental Electrothermal Gun Phenomena

JANNAF Workshop  
9-11 July, 1991  
Aberdeen, Md

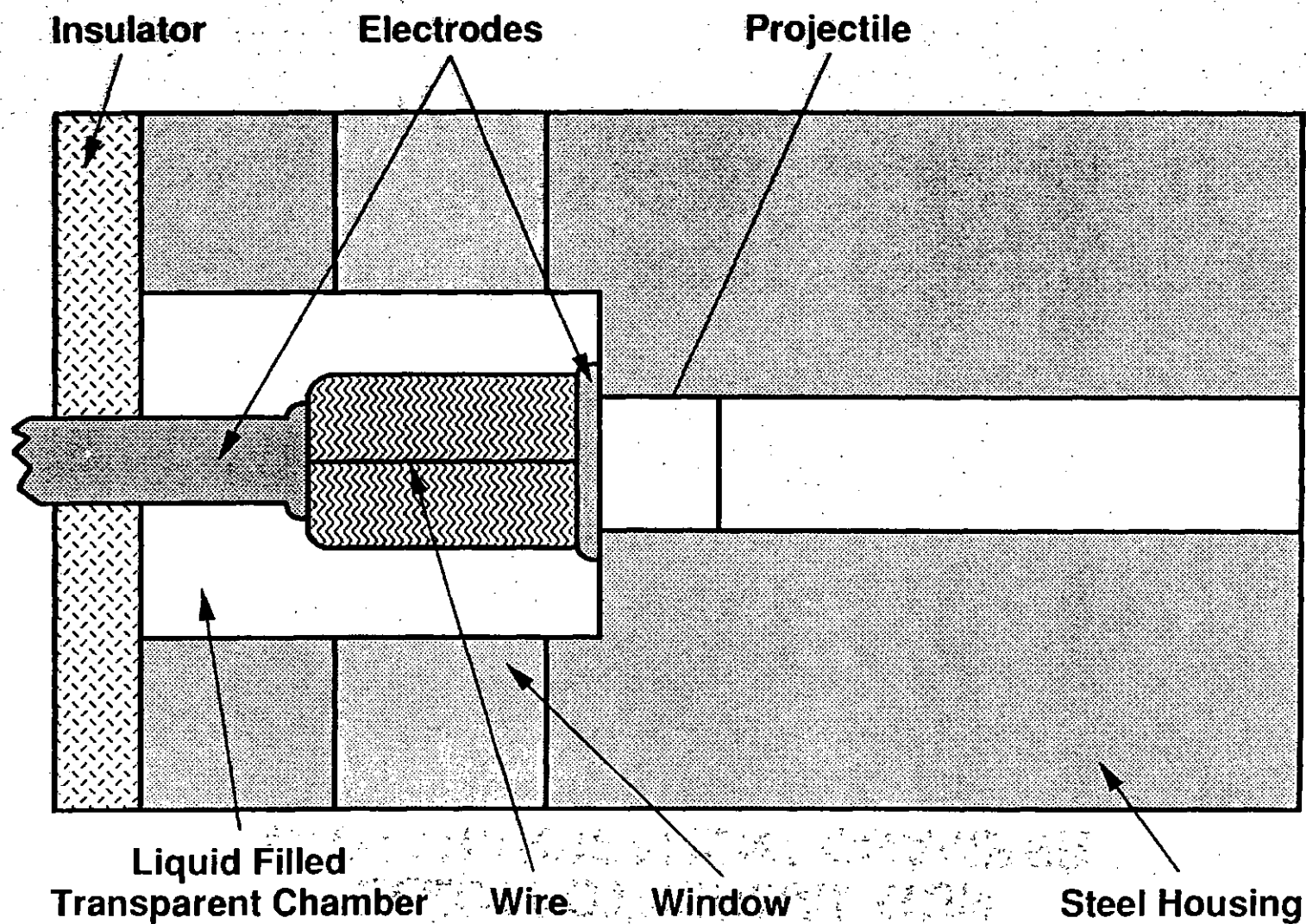
# Los Alamos Research Goal

## *Investigate Fundamental ETC Phenomena*

---

- Understand Mixing and Control Through Well Diagnosed Experiments (Imaged Chambers)
- Develop Predictive Computer Models Using Experimental Observations
- Approach - Begin with Plasma Embedded in Working Fluid (Inert and Combustible)

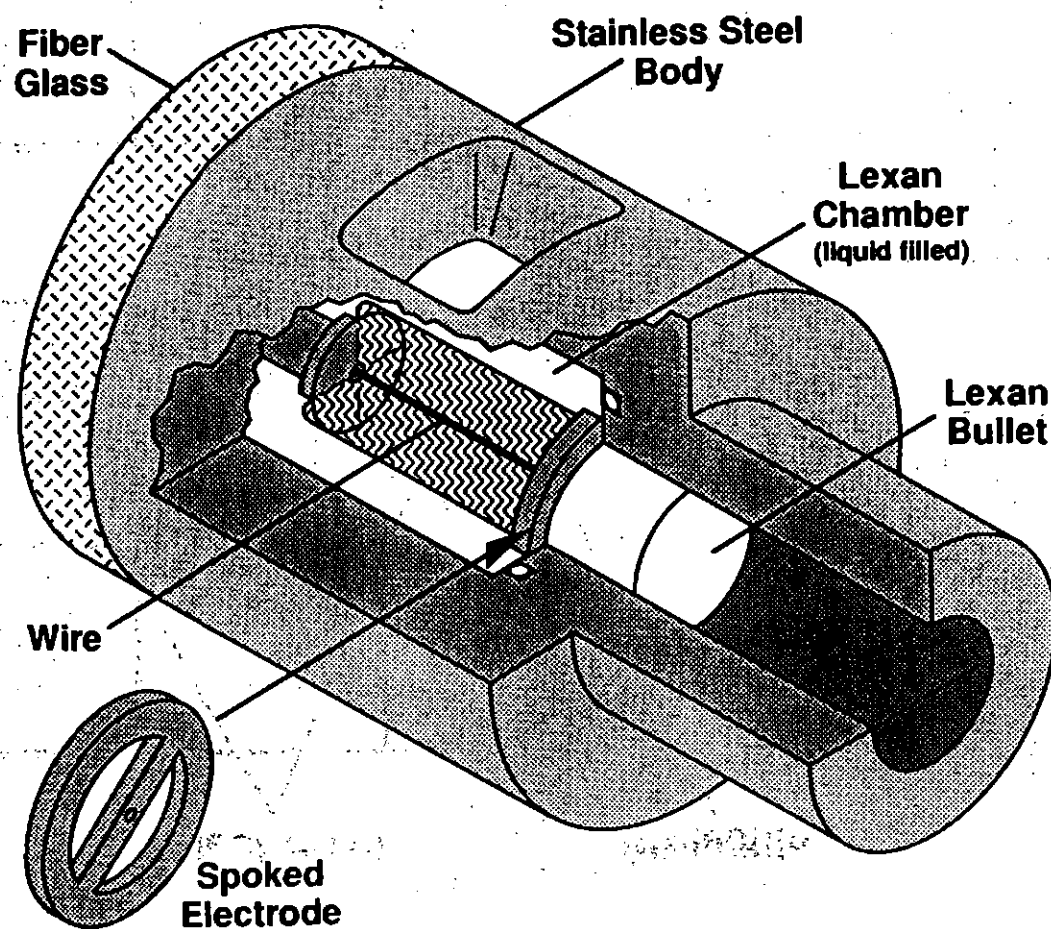
## Plasma/Working-Fluid Interacteron Chamber



Los Alamos



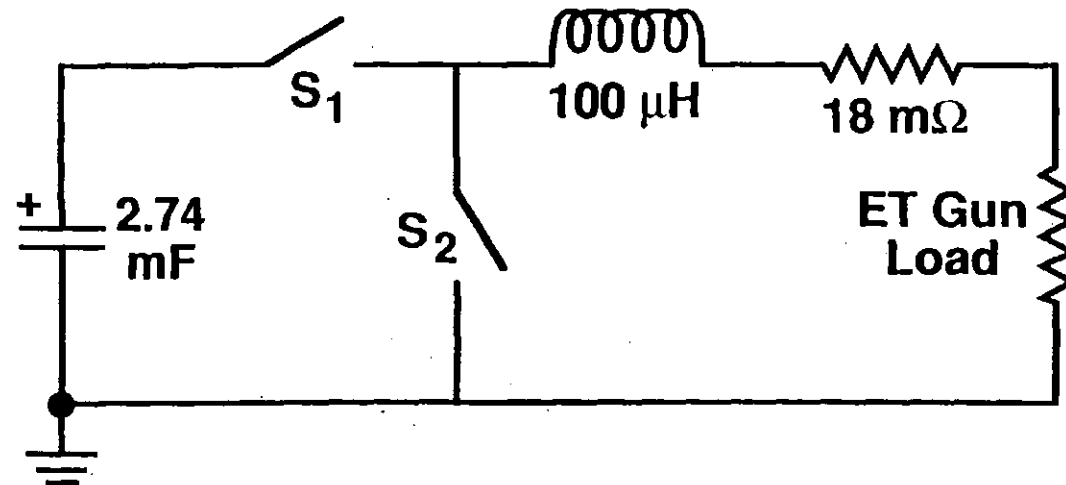
# ELECTROTHERMAL GUN WITH TRANSPARENT CHAMBER



Los Alamos

# Electrical Drive Circuit

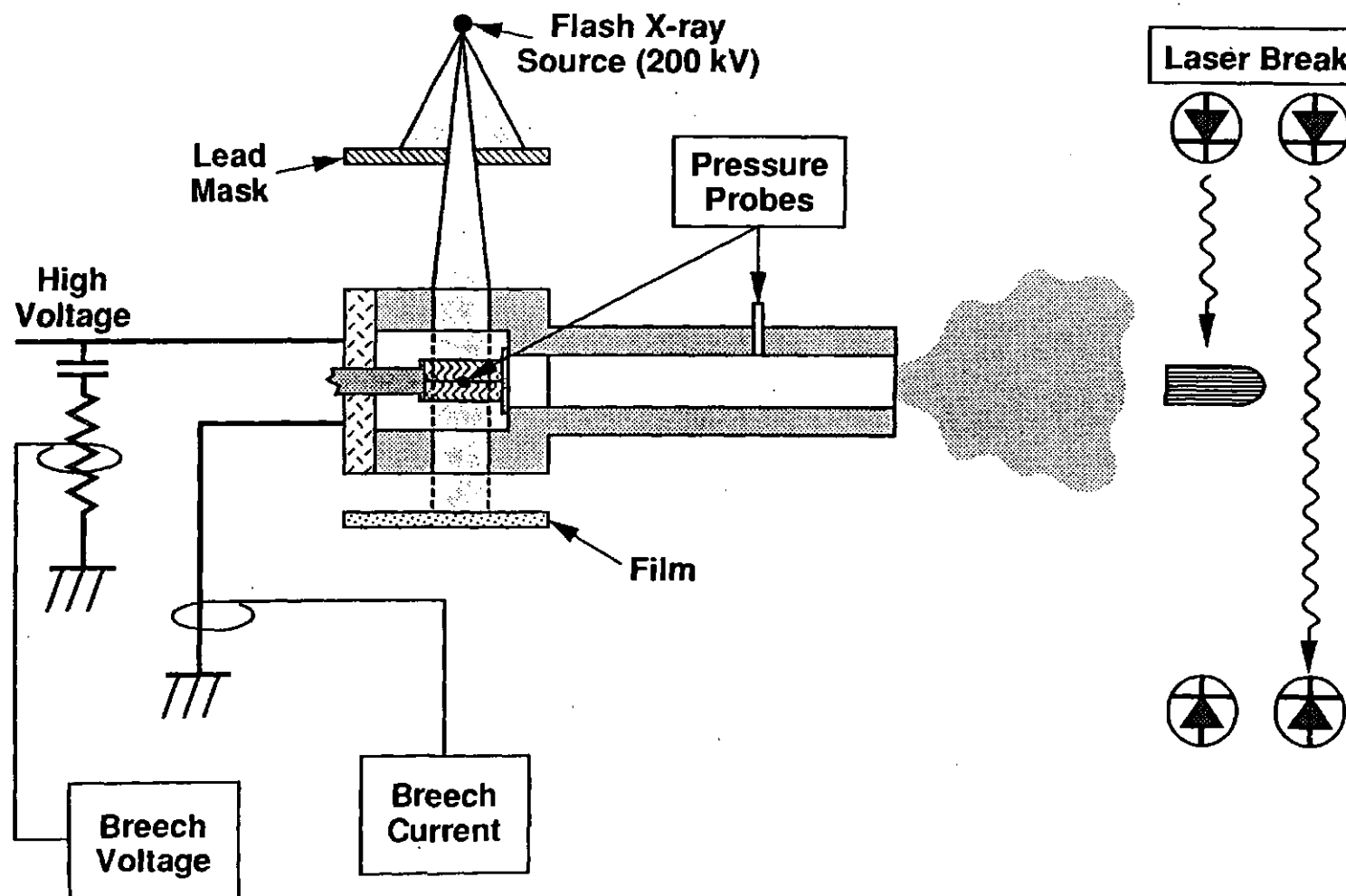
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|                     |                 |
|---------------------|-----------------|
| Load Voltage        | 4-8 kV          |
| Load Current        | 6 kA            |
| Energy Delivered    | 10 kJ in 0.5 ms |
| Peak Pressure       | 10-20 kpsi      |
| Projectile Velocity | 250-300 m/s     |

Los Alamos

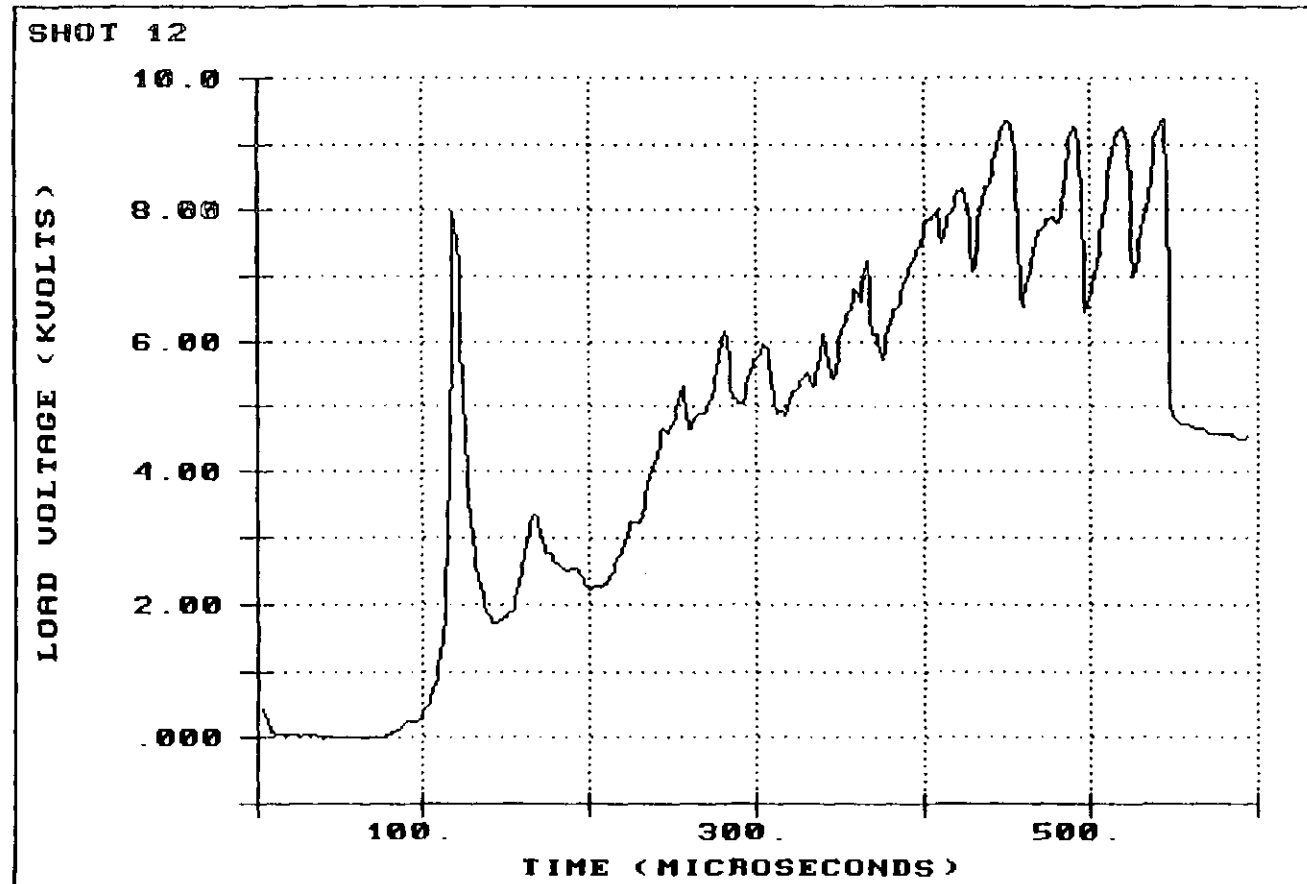
# Plasma/Working-Fluid Interaction Experiment



283

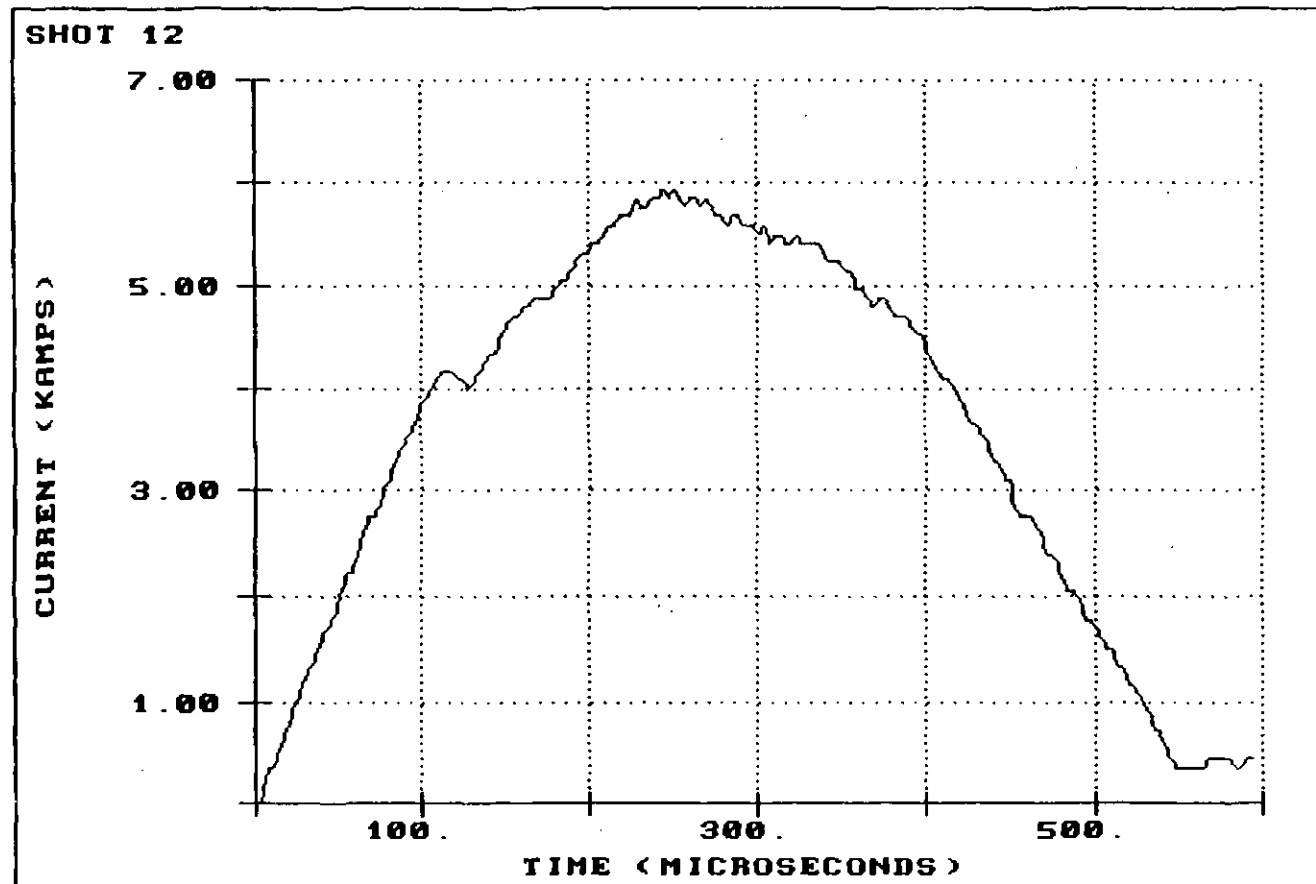
Los Alamos

# Load Voltage Waveform

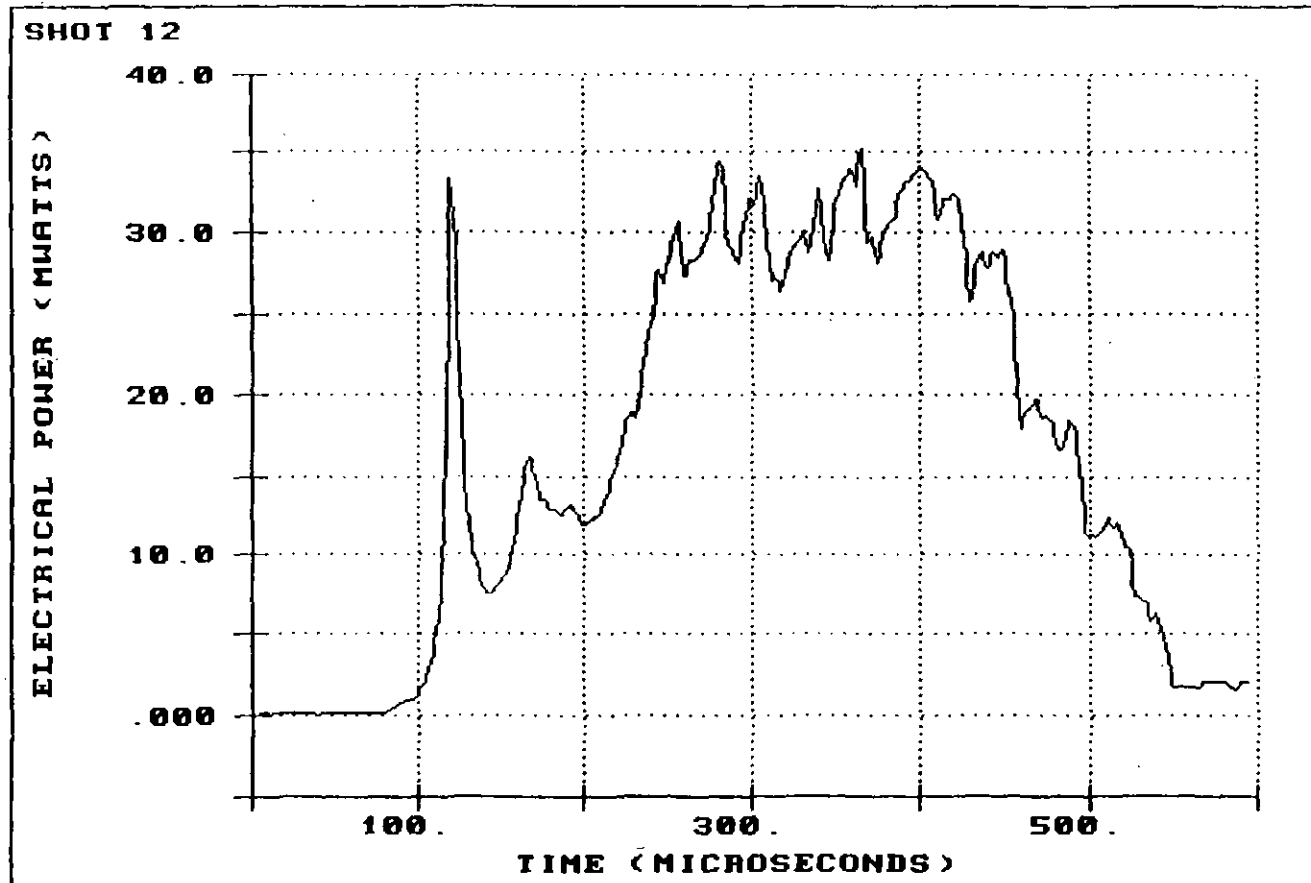


Los Alamos

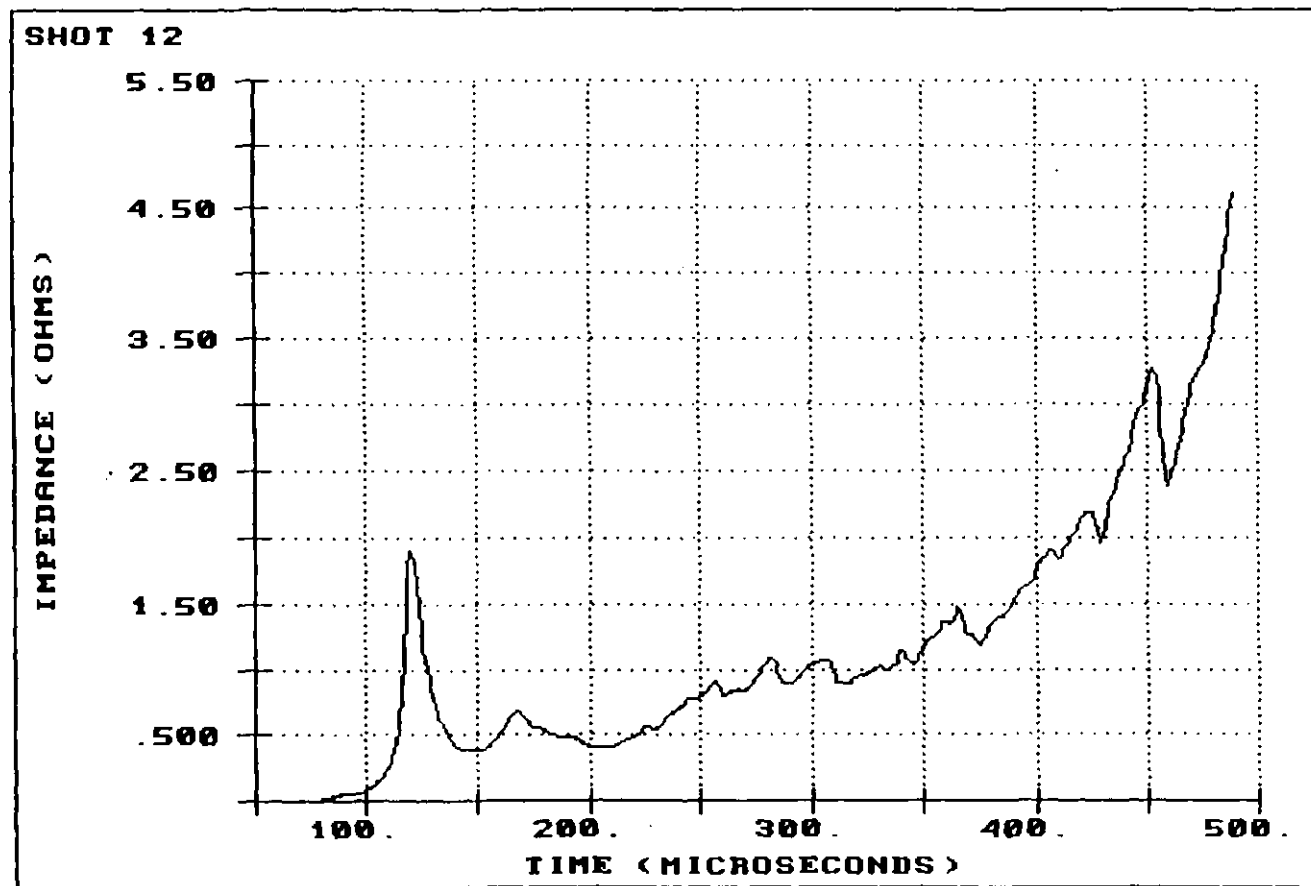
# Load Current Waveform



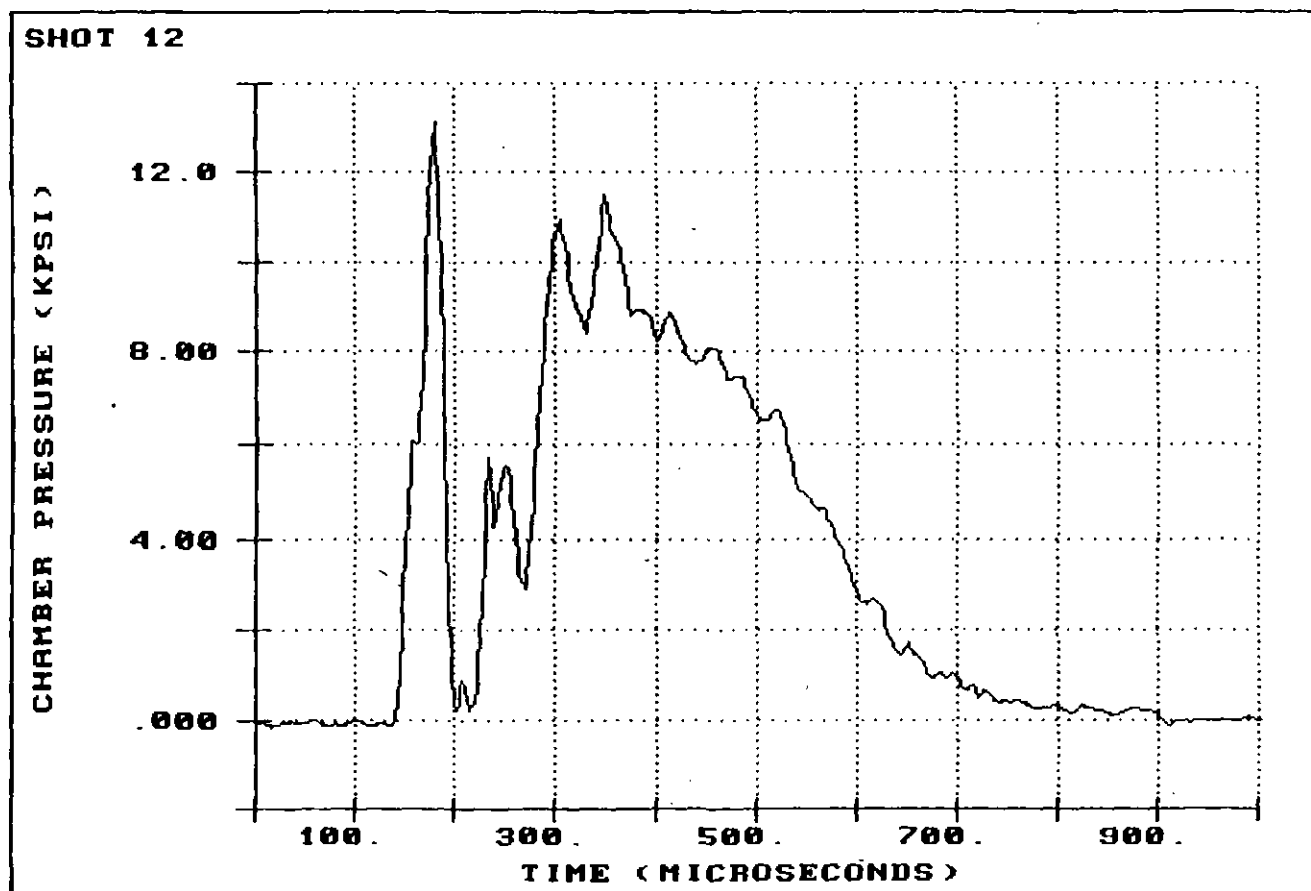
# Load Electrical Power



# Load Resistance



# Chamber Pressure



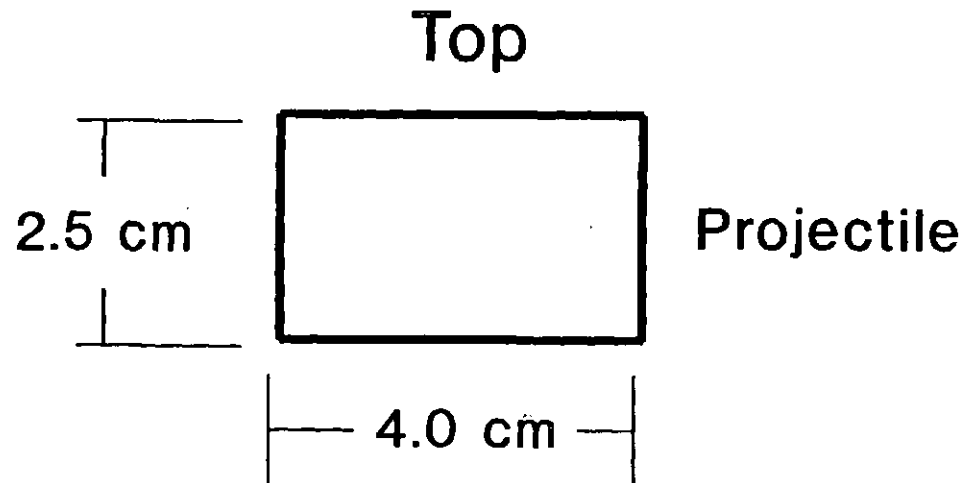
Los Alamos



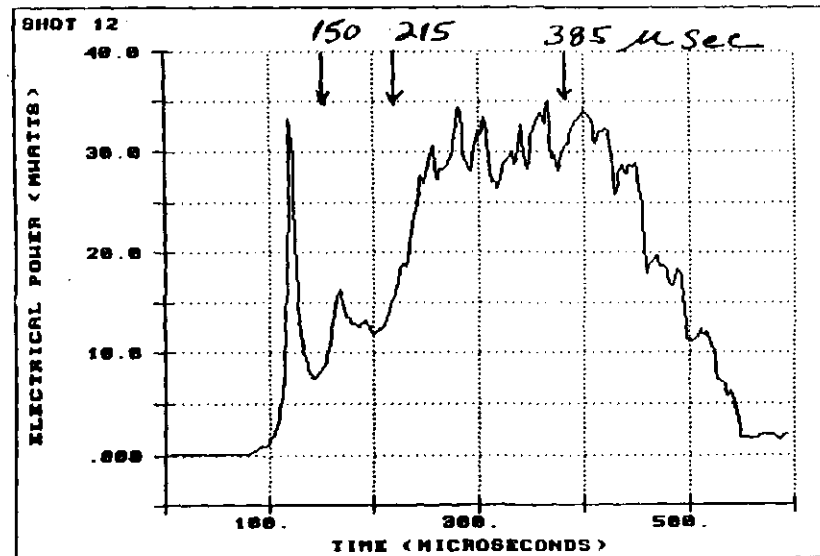
# Radiographic Configuration

*Copper Fiber-0.33 mm Diameter*

## Orientation



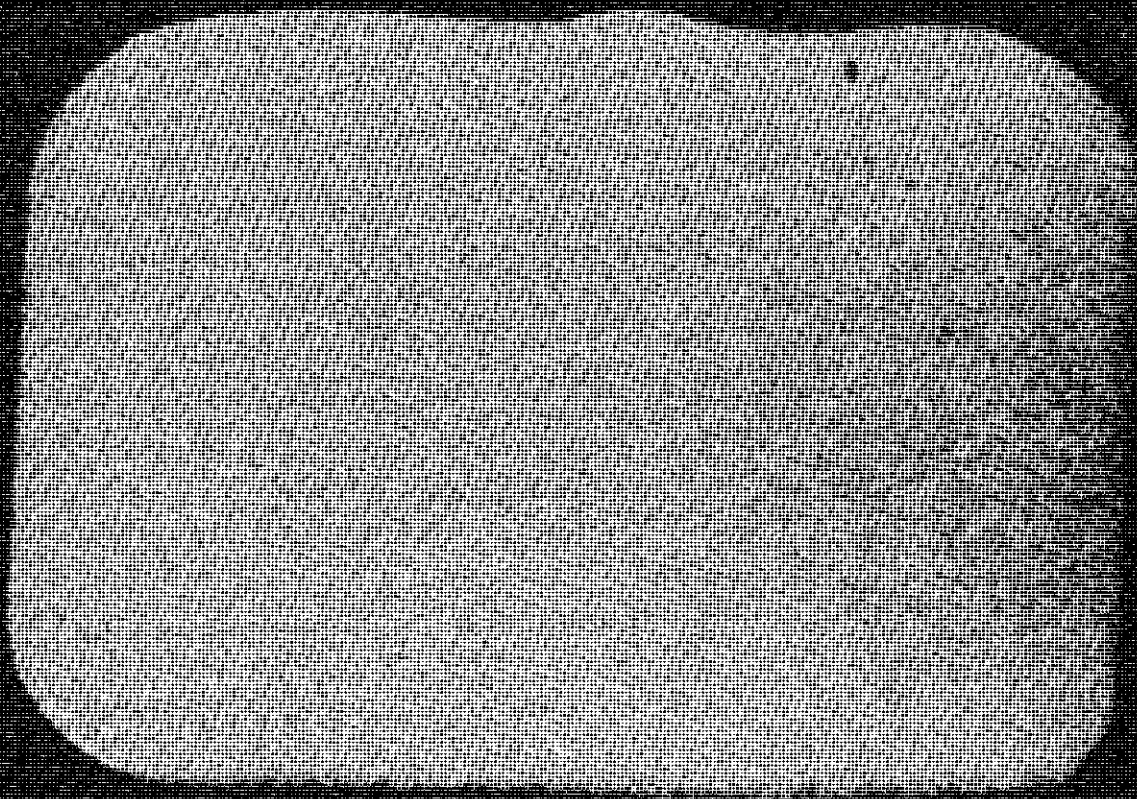
## Time



Los Alamos

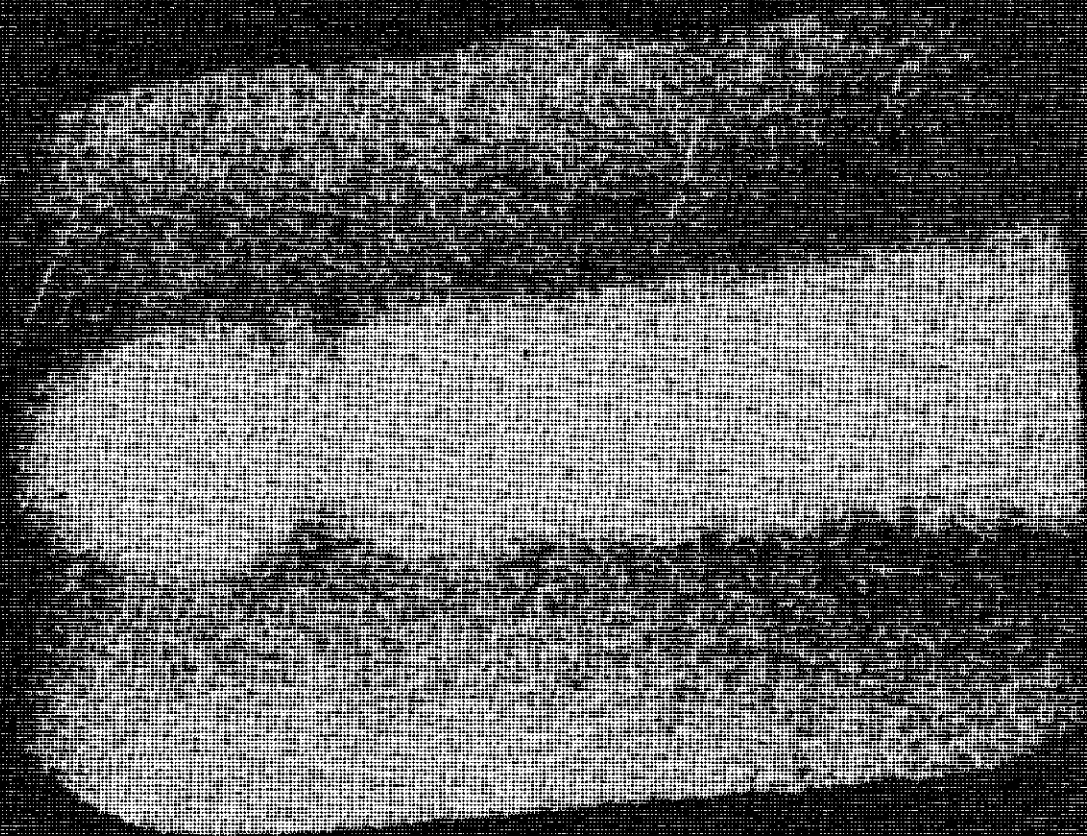
# Static Chamber

STATIC



Copper = 150 microsec

SHOT 20



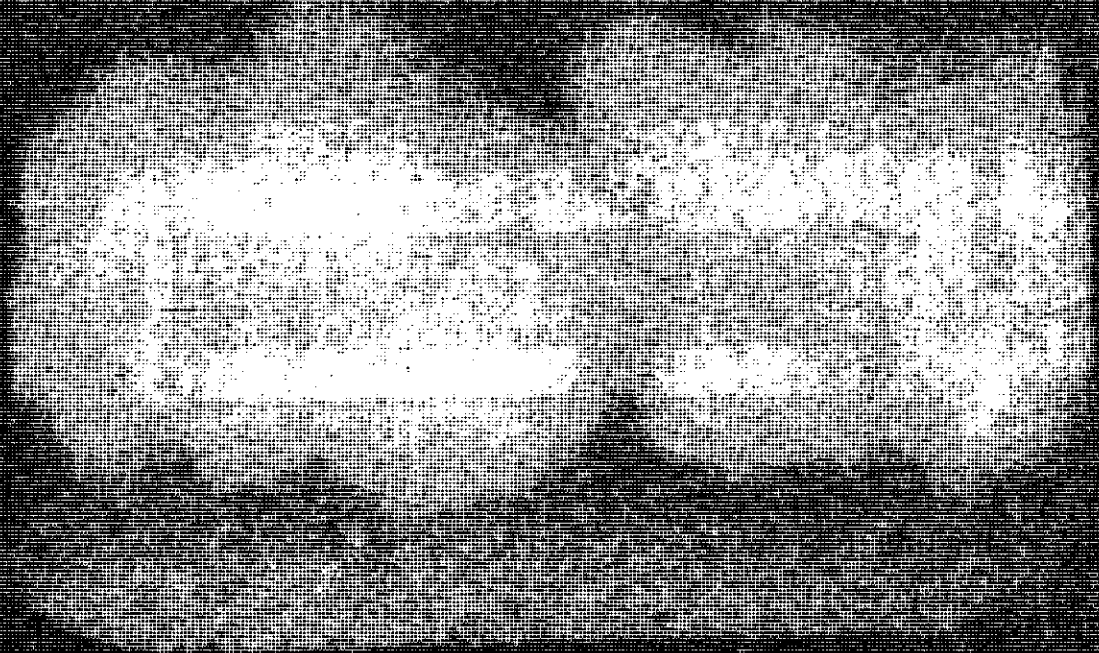
Copper - 215 microsec

SHOT 18



Copper - 385 microsec

SHOT 17

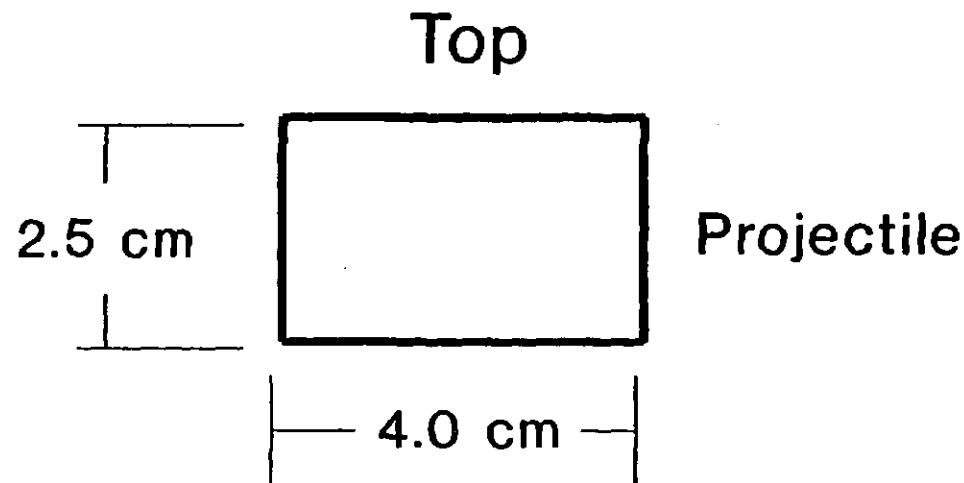


# Radiographic Configuration

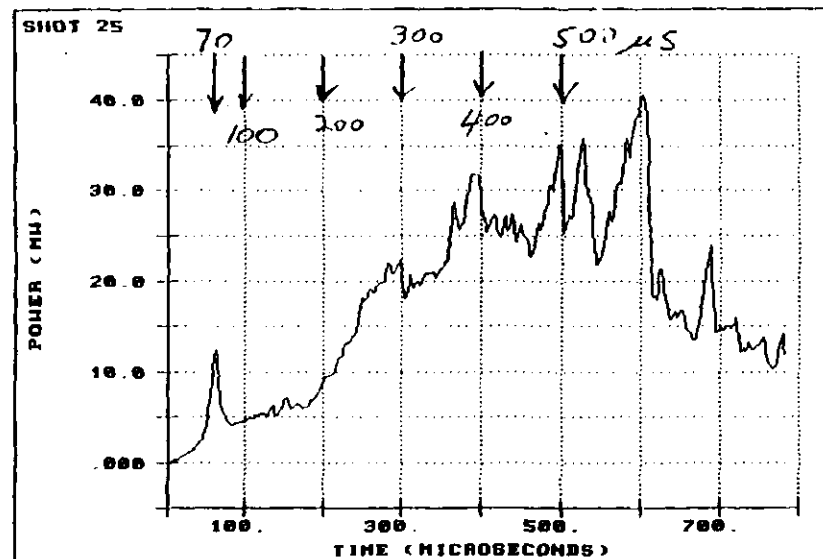
## *Carbon Fiber-0.5 mm Diameter*

---

Orientation



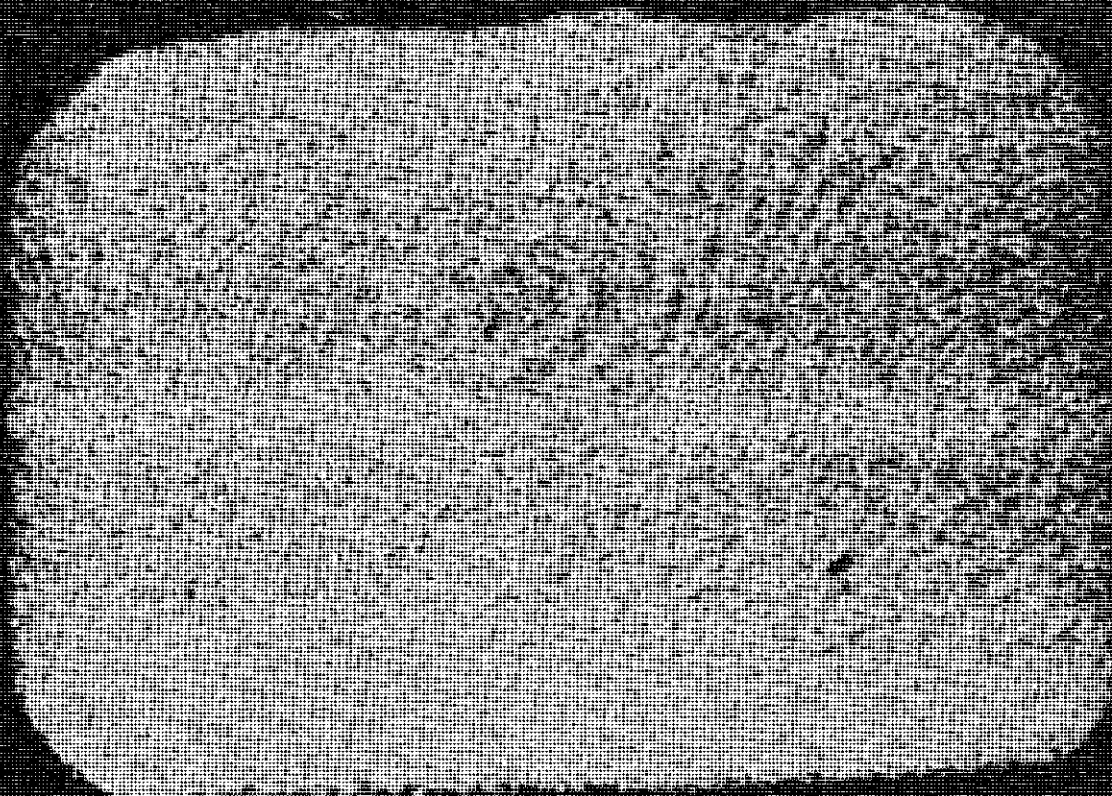
Time



Los Alamos

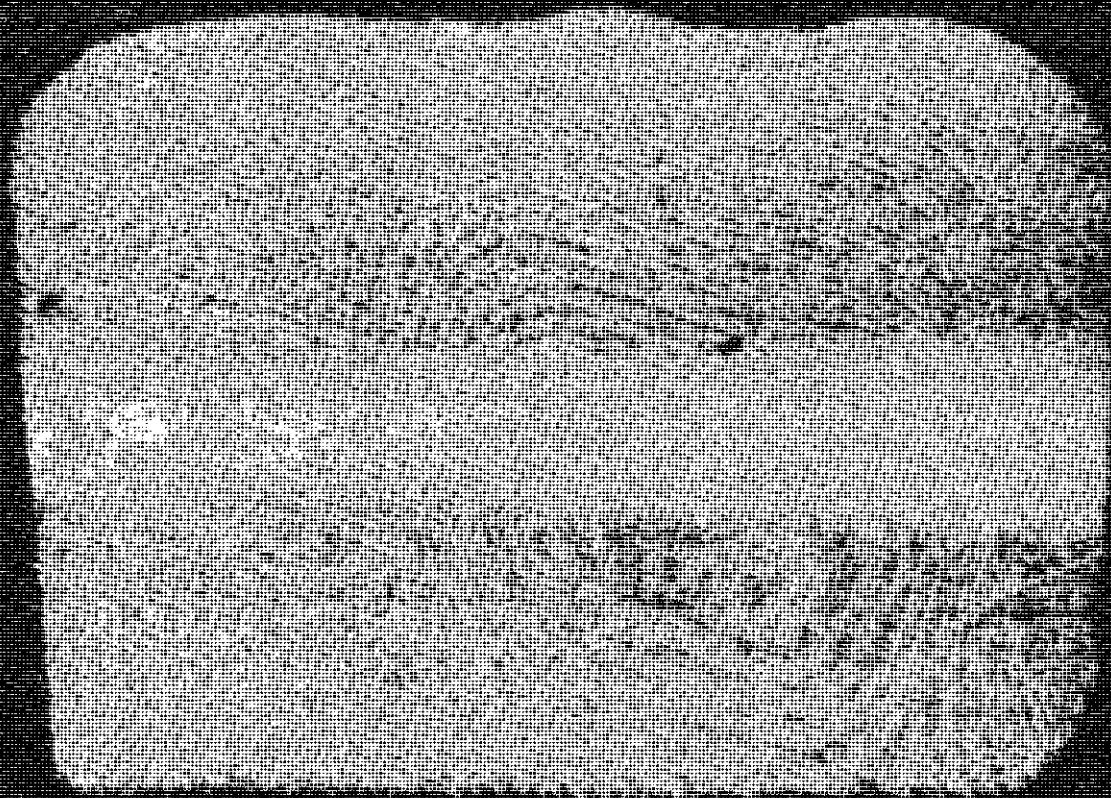
Carbon - 70 microsec

SHOT 27



Carbon - 100 microsec

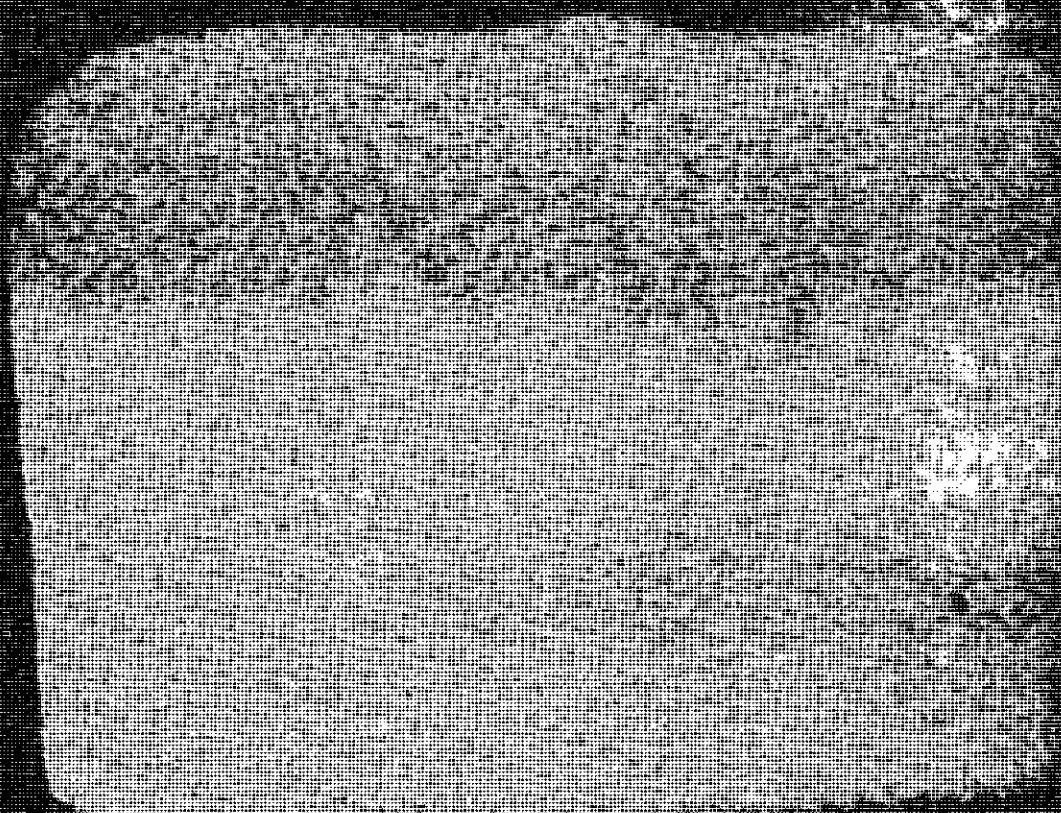
SHOT 25





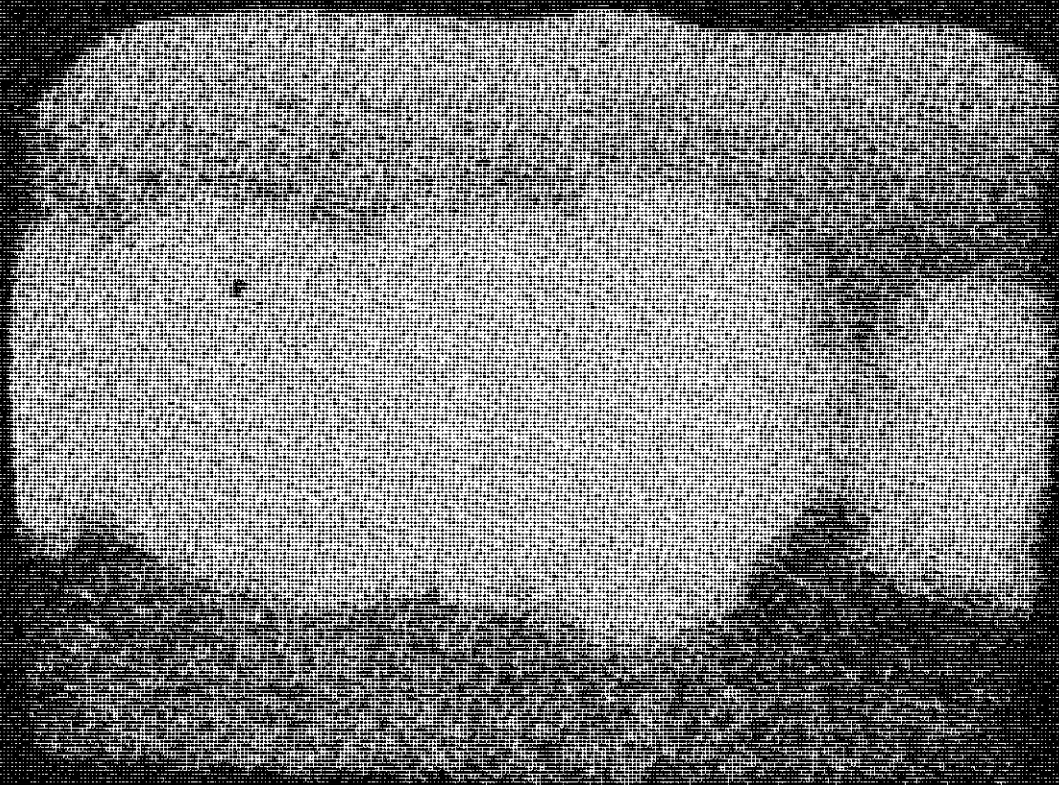
Carbon - 200 microsec

SHOT 23



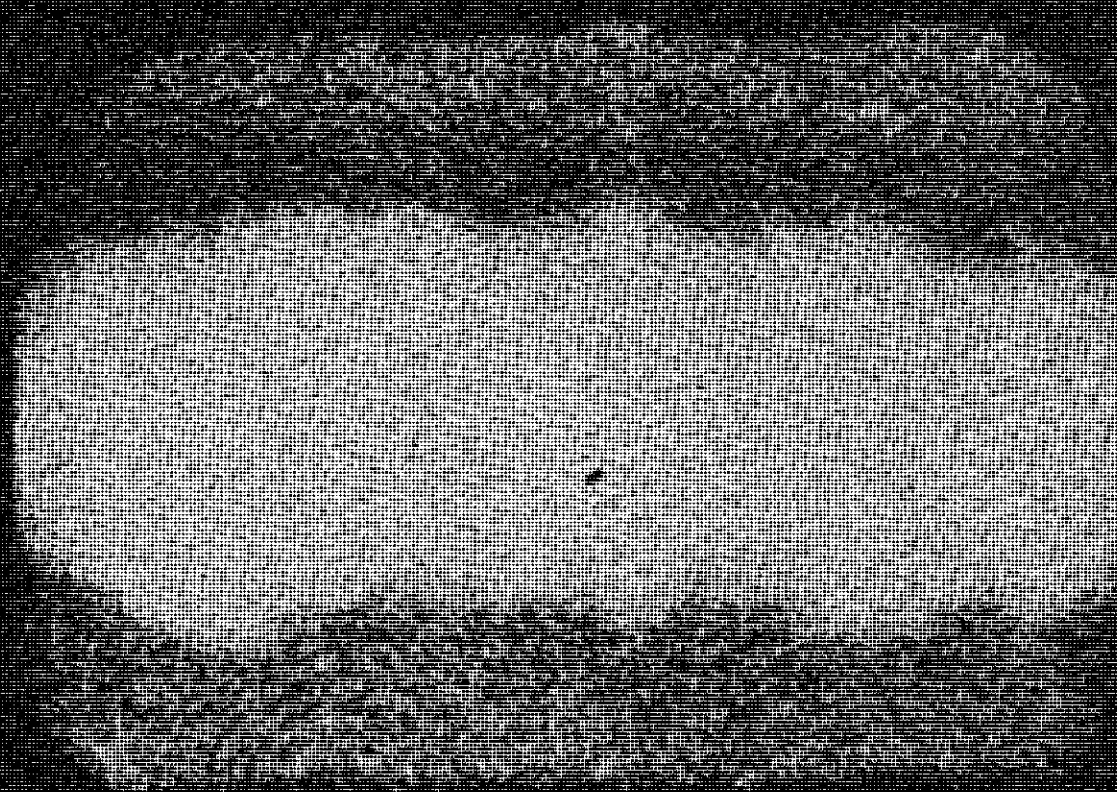
Carbon — 300 microsec

SHOT 22



Carbon - 400 microsec

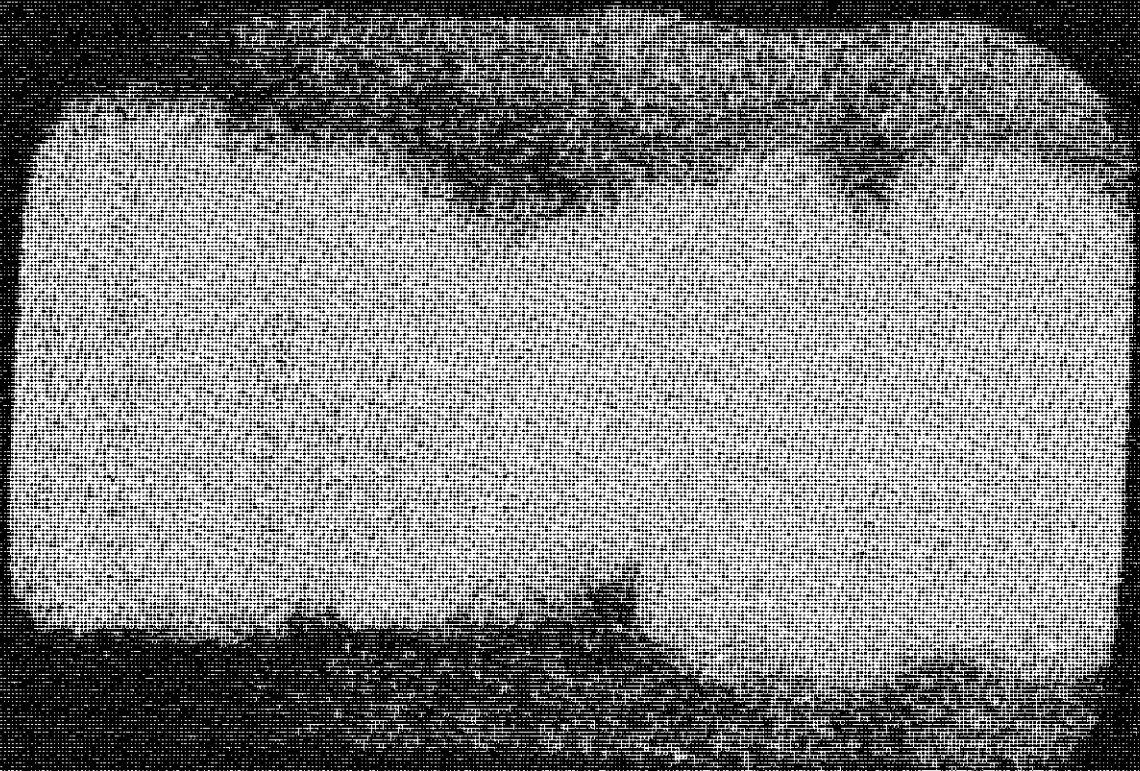
SHOT 28





Carbon - 500 microsec

SHOT 29



# What is the Mechanism Driving A Large Scale Instability?

---

- Simulate discharge using simple heat source to replace plasma model:

$$\dot{e}\rho = A e^{-\alpha r^2} \left[ 1 + B \sin^2(az) \right] \cos^4(ct)$$

*Gaussian  
radial  
deposition*

*Periodic  
axial  
deposition*

*Time-dependent  
modulation*

- Parameters chosen to match experiment. Amplitude chosen to give total power deposition of 20 kJ/ms.

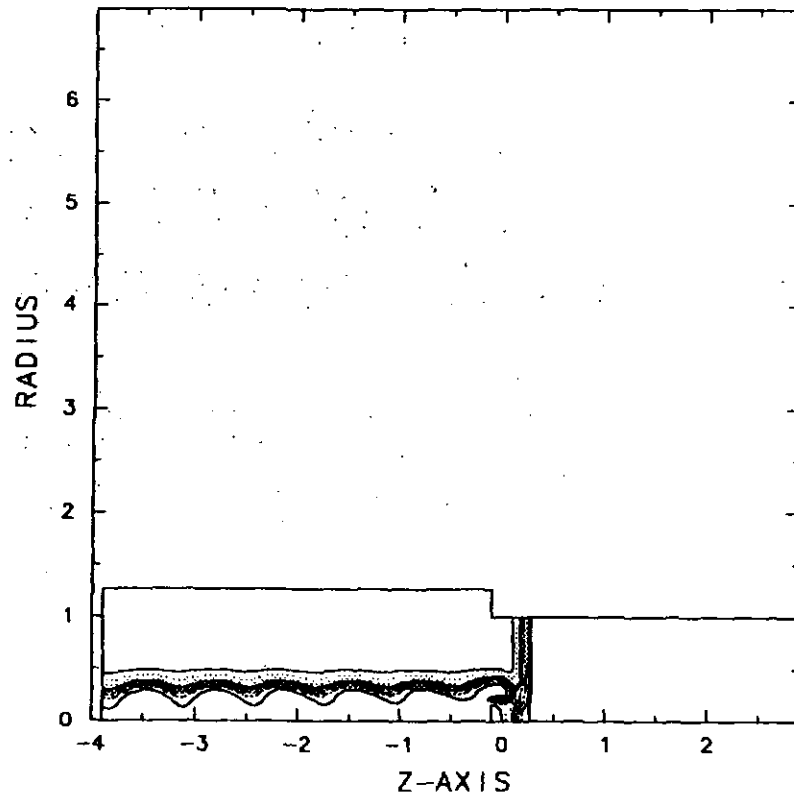
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Los Alamos

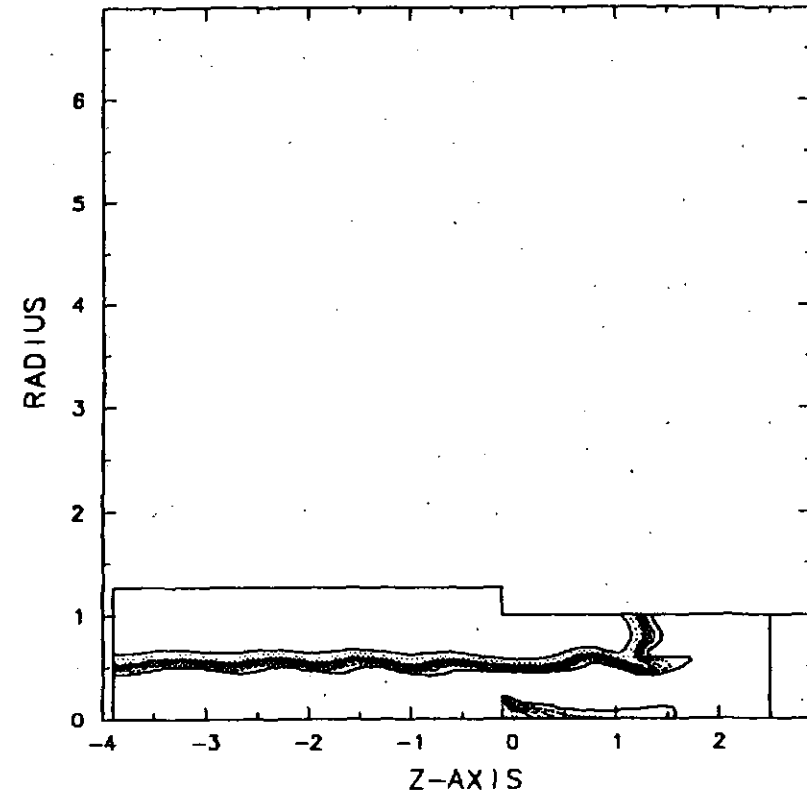
# Perturbation Is Stabilized

---

$t = 0.1 \text{ ms}$



$t = 0.2 \text{ ms}$

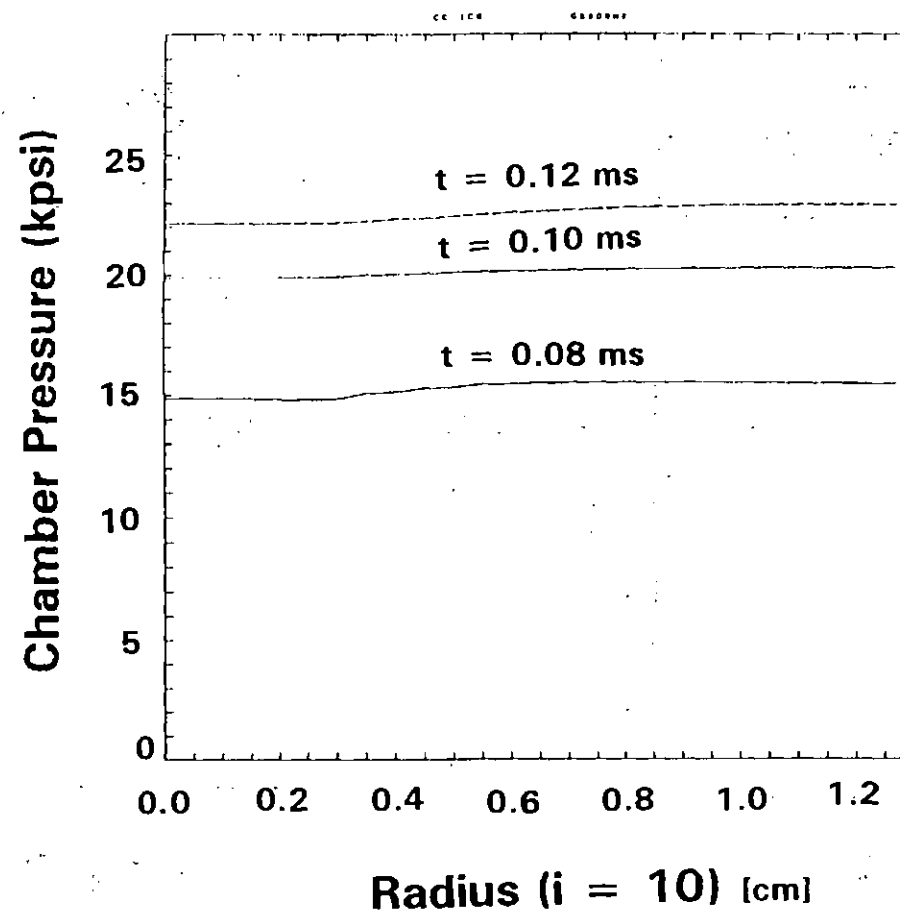


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# Chamber Pressure vs. Radius at Different Times

---

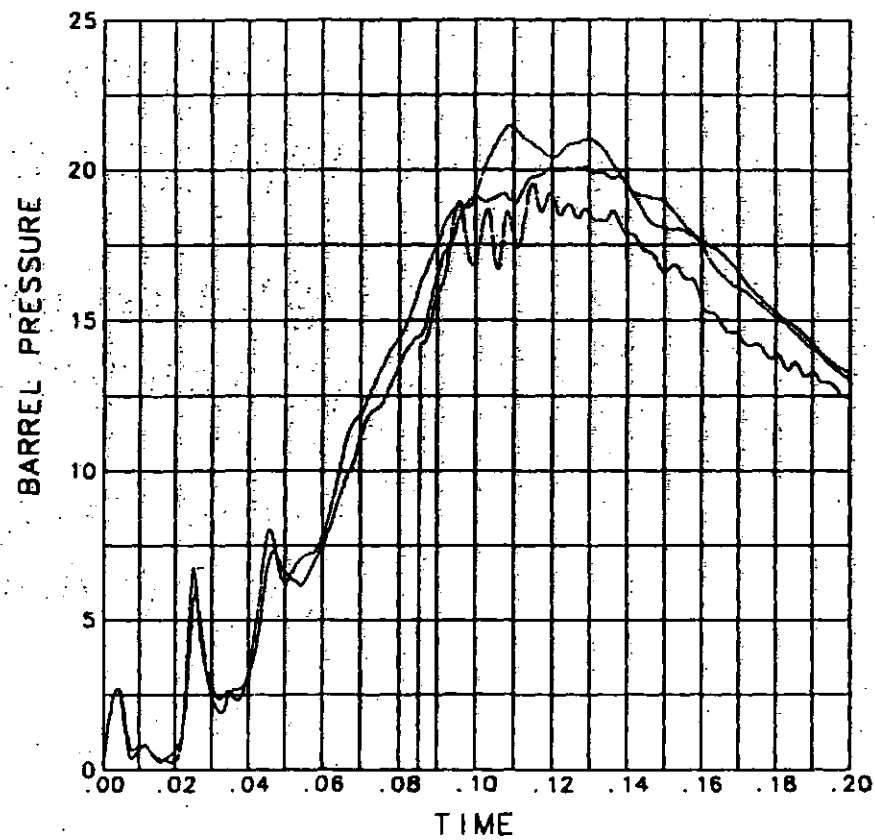


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Los Alamos

# Chamber Pressure vs. Time

---



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Los Alamos

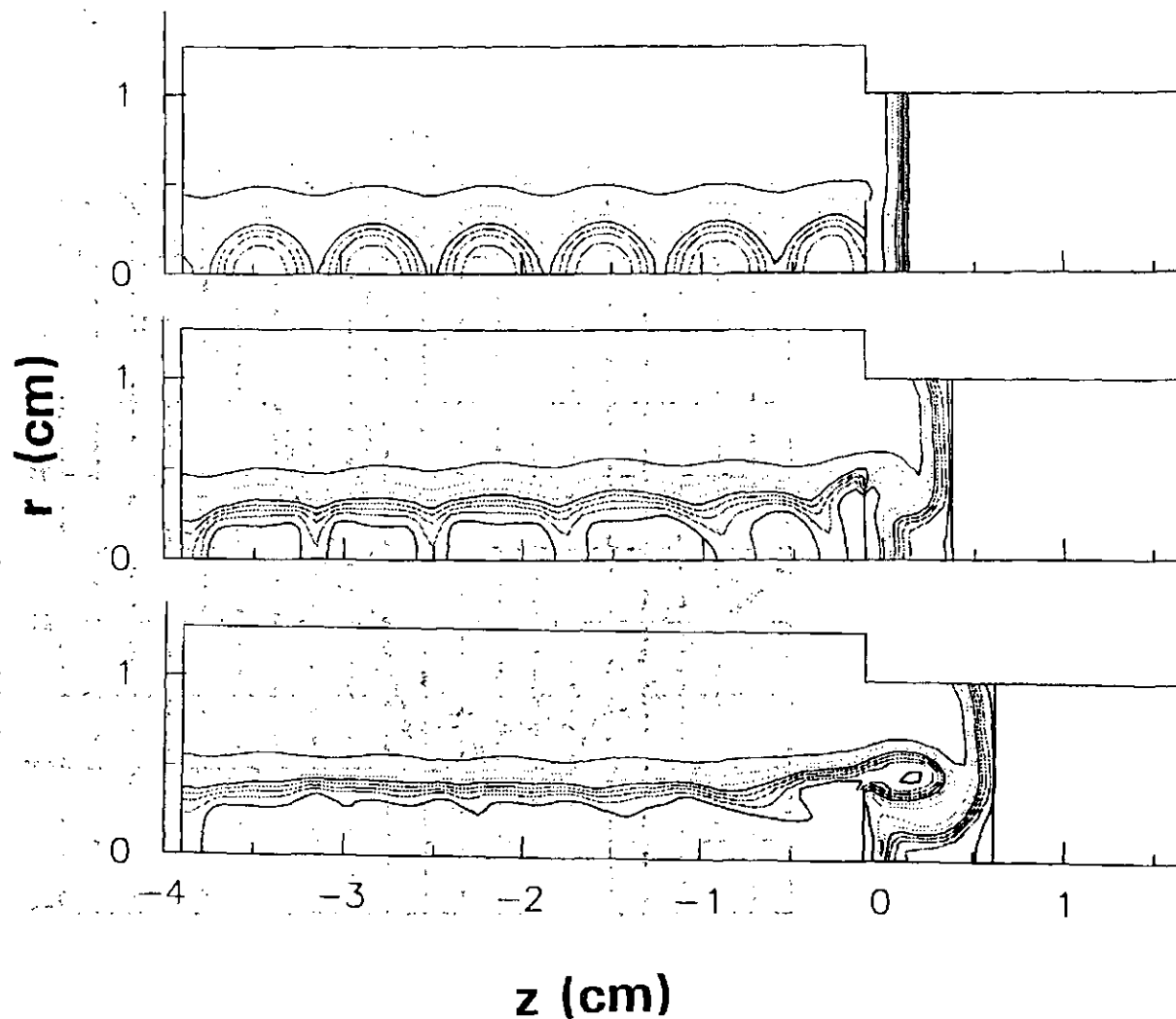


# Perturbation Is Unstable With Time Modulation

0.08 ms

0.12 ms

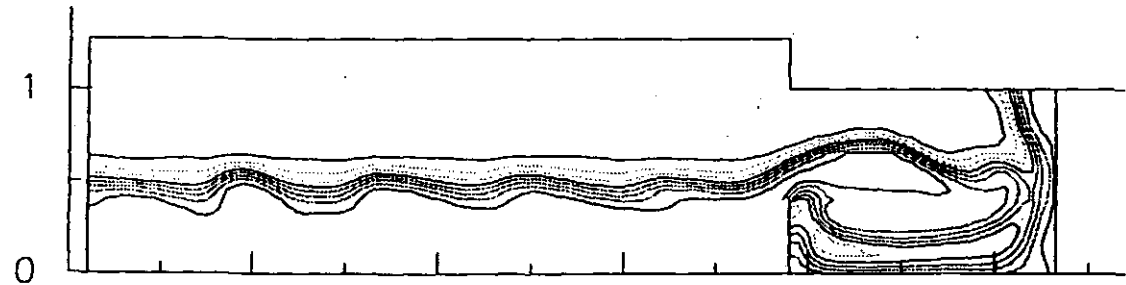
0.14 ms



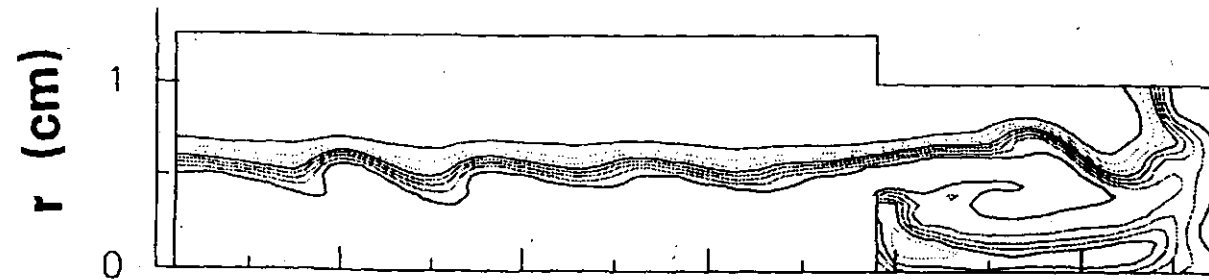
Los Alamos

# Perturbation Is Unstable With Time Modulation

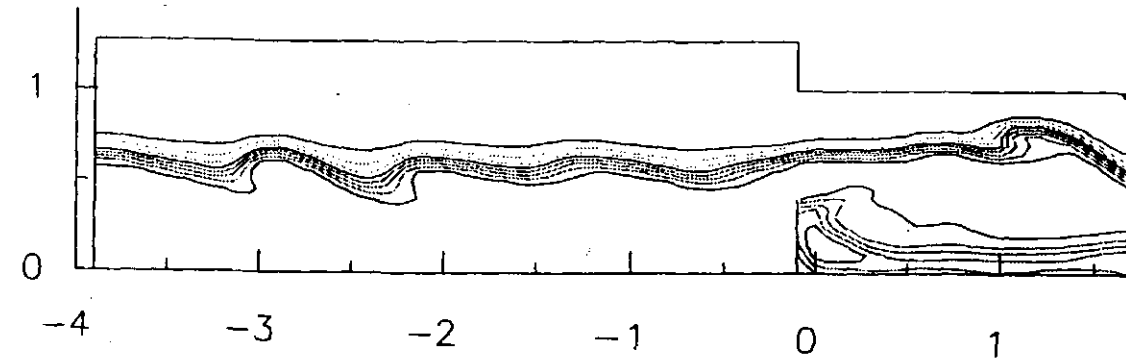
0.18 ms



0.20 ms



0.22 ms

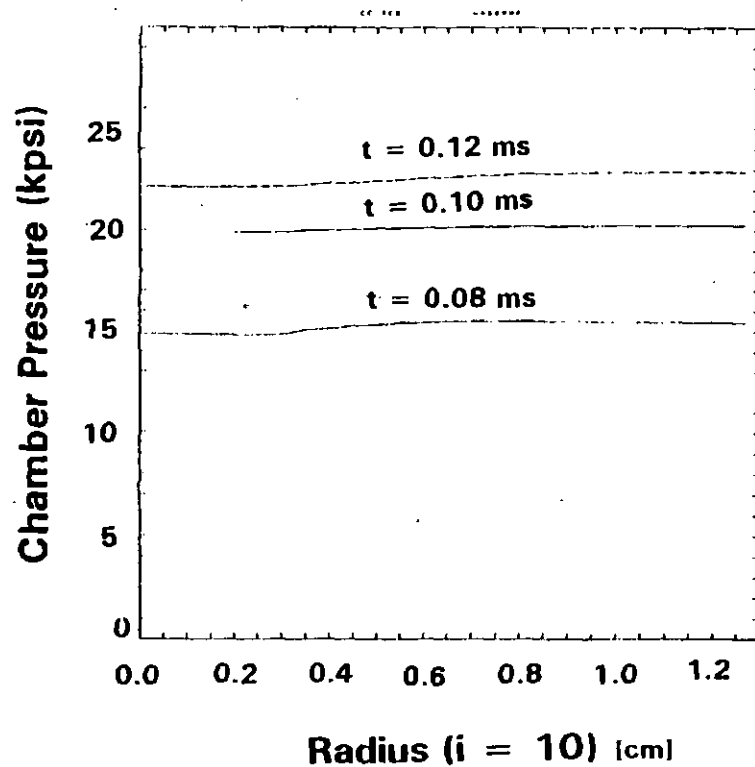


$z$  (cm)

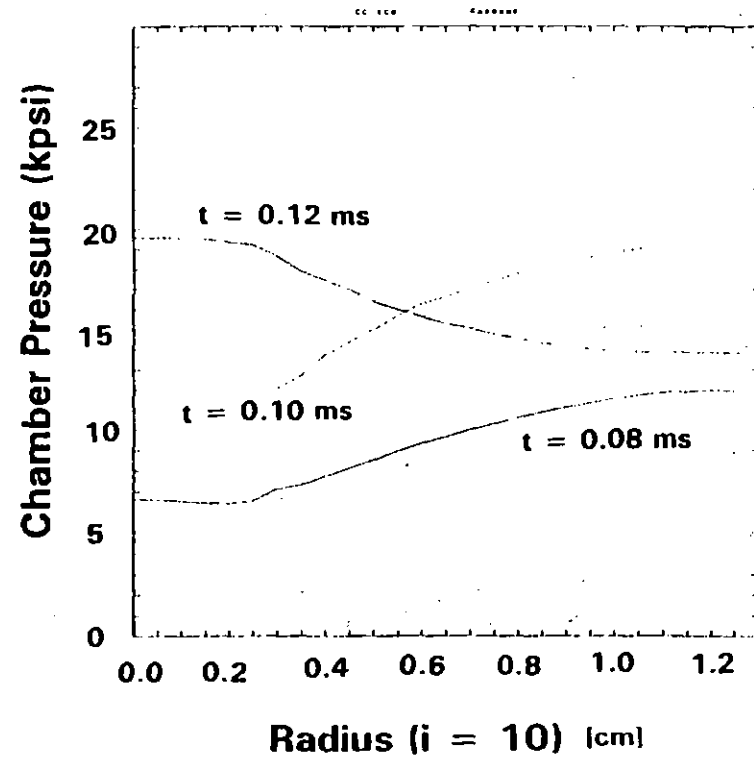
Los Alamos

# Chamber Pressure vs. Radius At Different Times

## Without Modulation



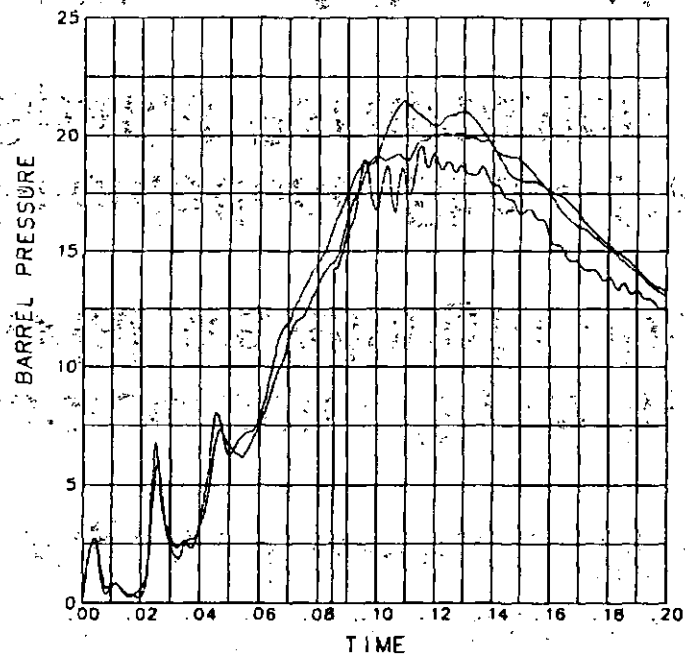
## With Modulation



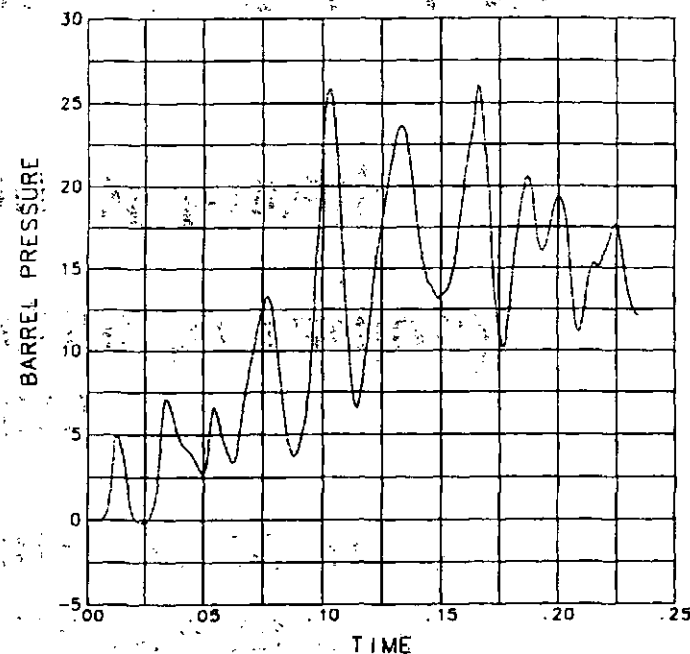
# Chamber Pressure vs. Time

---

Without modulation



With modulation



# Summary

---

- Pressure and Electrical Measurements Suggest Pressure Waves are Important
- Radiographs Show Instability (axial wavelength about equal to radius)
- Calculations Show Damping of Purely Spatial Perturbation
- Addition of Power Modulation in Calculations (at Chamber Transit Period) Produces Instability

# Future Directions For ETC Computational Developmnet

---

- Incorporate detailed plasma dynamics
  - ▶ Sensitivity of conductivity to P and T
  - ▶ Can P waves be sustained by sensitivity of ohmic heating to pressure fluctuations?
- Couple circuit dynamics
- Examine potential of driving instabilities in propellants
- How can we avoid resonance between pressure waves and plasma dynamics? Begin examining different kinds of electrode configurations

# Future Experiments

---

- Study Different Configurations
  - ✓ Vary Geometry
  - ✓ Combustible Working Fluids
  - ✓ Vary Power Input
- Improve Measurements
  - ✓ Orthogonal X-Ray Views
  - ✓ Time Sequence on Single Shot
  - ✓ Time Resolved Photography
  - ✓ Time and Spatially Resolved Spectroscopy

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## ELECTROTHERMAL-CHEMICAL GUN MODELING

David W. King, Olin Rocket Research  
and  
Hugh McElroy, Olin Ordnance

### ABSTRACT

A presentation will be made describing the nature of ET-C Gun Modeling. The key physics regarding combustion and arc physics will be discussed with regard to implementing a 2-D CFD model of the gun. At OLIN, both liquid and solid propellant 2-D modelling technology is being developed. The status of liquid propellant model will be presented along with example calculations.

# **ELECTROTHERMAL-CHEMICAL GUN MODELING**

**HUGH A. McEIROY  
OLIN ORDINANCE**

**DAVID Q. KING  
ROCKET RESEARCH COMPANY  
OLIN DEFENSE SYSTEMS GROUP**

**JULY 11, 1991**

## ET-C CODES AND APPLICATIONS

### 0-D Codes

#### EQUATION OF STATE FOR HIGH PRESSURE CHEMICAL EQUILIBRIUM

- USED FOR INITIAL PROPELLANT SCREENING
- PROVIDES IMPETUS AND FLAME TEMPERATURE

HUNTER & BLAKE  
give Impetus,  $\gamma$

BKW gives Curve Fit  $\gamma(P, T)$

XNOVA/KTC  
 $\gamma = \text{fixed}$

XNOVA/KTC  
REAL GAS  
 $\gamma(P, T)$

2D/L  
LIQUID  
PROPELLANT

2D/S  
SOLID  
PROPELLANT

### 1-D Codes

- MANY APPROXIMATIONS
- $\gamma$  = FIXED INCONSISTANT WITH ET-C PROPELLANTS

- AWAITING TEST

### 2-D Codes with Circuit Simulation

- STEAM GUN SIMULATIONS  
AGREE WITH TEST
- BURN RATE MODEL IS CRITICAL

- INITIAL OPERATION 5-13 S
- PACKED BED MULTIPHASE

## **KEY PHYSICS ISSUES IN ETC MODELING**

- **1D, QUASI 1D, 2D**
  - **1D MODELS OR QUASI 1D REGIONS HAVE INFINITE SOUND SPEED IN RADIAL DIRECTION, FINITE IN AXIAL DIRECTION**
  - **PECULIAR EFFECTS ARE OBTAINED IN RADIAL DIRECTION AT INTERFACE OF 1D TO 2D REGION**
- **2D MODEL CAN REPRESENT RADIAL VARIATION, WHICH PLAY A ROLE IN HIGH FREQUENCY PRESSURE WAVES**

## **EQUATION OF STATE**

---

- **REAL GAS IN EQUILIBRIUM**
- **MULTIPHASE**

## **COMBUSTION**

---

- **GAS PHASE IN CHEMICAL EQUILIBRIUM**
  - KINETIC RATES VERY HIGH AT HIGH PRESSURE
- **EVOLUTION OF SOLID OR LIQUID TO GAS PHASE CONTROLS COMBUSTION RATE**
  - DETAILED PROCESS INVOLVES DIFFUSION OF HEAT AND SPECIES
  - CAN BE CHARACTERIZED BY A TIME OR LENGTH SCALE TYPICALLY MUCH SMALLER THAN DIMENSIONS OF COMPUTATIONAL CONTROL VOLUME
  - SURFACE AREA DEPENDENT
- **REPRESENTATIONS IN A COMPUTATIONAL CONTROL VOLUME**
  - VOLUME AT P,T CONTAINS UNBURNED AND BURNED PROPELLANT
  - BURN RATE GIVEN BY EXPERIMENTAL PRESSURE OR TEMPERATURE CRITERION
  - MASS AND HEAT TRANSPORT ACROSS CONTROL VOLUME SURFACES STRONGLY AFFECT COMBUSTION INSIDE CONTROL VOLUME
- **MASS AND ENERGY TRANSPORT GOVERNED BY MIXING LENGTH TURBULENCE MODEL**

## **ARC HEAT INPUT**

---

- **KILOAMP DISCHARGE AT KILOBAR PRESSURES HAVE VERY SMALL RADIUS**
  - **RADIUS GIVEN BY PRESSURE AND ENERGY BALANCE ACROSS ARC TO FLUID BOUNDARY**
  - **TYPICAL  $R < 0.5$  mm**
- **VERY SMALL VOLUME OF FLUID IS IONIZED**
- **INTENSE RADIATION FROM ARC IS TRAPPED IN VERY SMALL DISTANCE**
- **IONIZED FLUID RECOMBINES RAPIDLY AT KILOBAR PRESSURES**
- **EXPECT VERY LITTLE EFFECT ON CHEMISTRY FROM IONS**
- **TREAT ARC AS LOCALIZED HEAT SOURCE**

## **STATUS**

---

- **APPROACH**

- 2D CODES DEVELOPED BY LOS ALAMOS NATIONAL LABORATORIES UNDER CONTRACT TO ROCKET RESEARCH COMPANY/OLIN DEFENSE SYSTEMS GROUP
- IN HOUSE MODIFICATION FOR SPECIFIC APPLICATIONS

- **LIQUID PROPELLANT 2D MODEL**

- OPERATIONAL
- MULTIPHASE, SINGLE VELOCITY & TEMPERATURE
- VALIDATION WITH EXOTHERMIC PROPELLANTS UNDERWAY



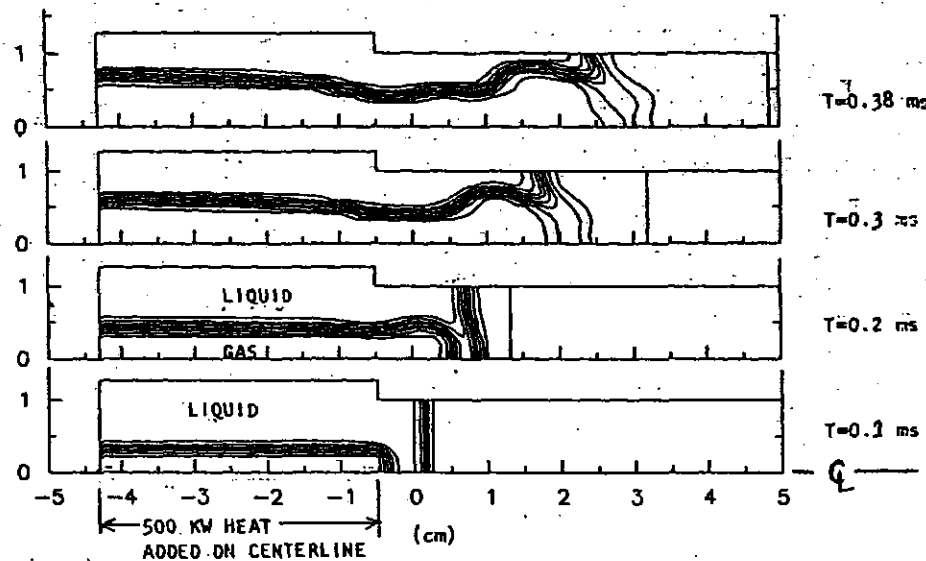
**STATUS (CONTINUED)**

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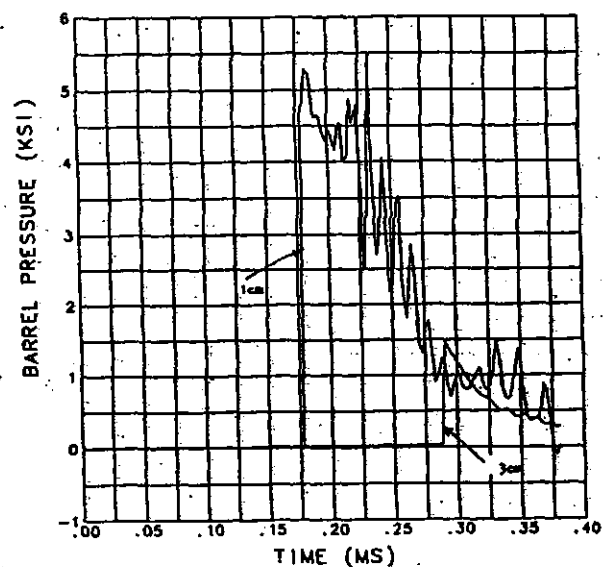
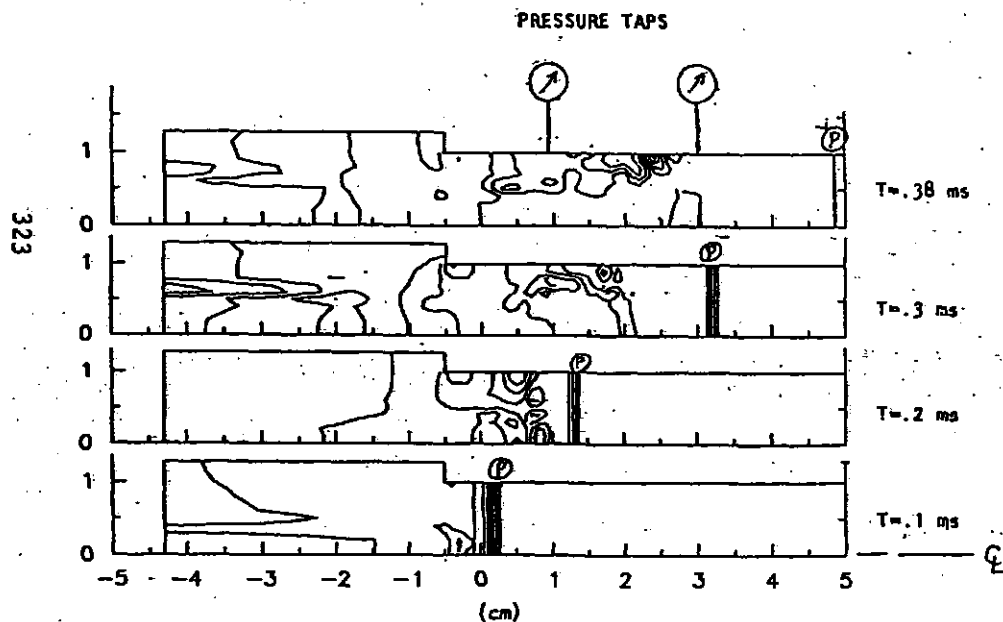
- **SOLID PROPELLANT 2D MODEL**
  - **READY FOR INITIAL TESTING**
  - **MULTIFLUID - SEPARATE TEMPERATURES & VELOCITIES FOR GAS AND SOLID FLUIDS**
  - **HANDLES SOLID PROPELLANT AND FRACTURED PIECES OR "RUBBLE" WITH CLOSE PACKED BED**

# ELECTROTHERMAL-CHEMICAL GUN MODELING

## EXAMPLE CALCULATION - STEAM GUN WITH CENTERLINE HEATING DENSITY CONTOURS



**EXAMPLE CALCULATION - STEAM GUN WITH CENTERLINE HEATING  
PRESSURE CONTOURS**



## **APPLICATIONS**

- **GAS GENERATORS**
- **ET-C MODELING**
  - **VARIOUS GEOMETRIES**
  - **ALTERNATE ELECTRODE CONFIGURATIONS**

## **CONCLUSIONS**

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- LIQUID & SOLID PROPELLANT MODELS ARE OPERATIONAL AND VALIDATION IS UNDERWAY
- APPROACH YIELDS A CAPABILITY THAT IS EASILY ADAPTED TO PROBLEM SPECIFIC SPECIALIZATIONS

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## RAILGUN RESEARCH RELEVANT TO ELECTROTHERMAL GUNS

Jad H. Batteh  
Science Applications International Corporation  
Marietta, GA 30062

### ABSTRACT

Some aspects of the modeling and diagnostics of electrothermal guns are common to railguns, as well. The objective of this presentation is to compare and contrast the two technologies and to provide a reference guide to the recent relevant literature describing railgun research. Particular emphasis is placed on the following areas - the calculation of thermodynamic and transport properties in very dense, relatively low temperature plasma; on-board projectile diagnostics; spectroscopic analysis; and the confinement and stability of high-pressure arc discharges.

# **Railgun Research Relevant to Electrothermal Guns**

**Jad H. Batteh  
Science Applications International Corporation  
1519 Johnson Ferry Road  
Suite 300  
Marietta, Georgia 30062  
(404)973-8935**

**Presented at JANNAF Workshop on  
ETC Modeling and Diagnostics  
July 9 - 11, 1991  
Aberdeen Proving Ground, MD**



# Objective

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- Review railgun research relevant to ETC technology
  - Analysis of plasma jets
  - Diagnostics
- Provide references to the relevant literature

# Basic References for Railgun Physics

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- **Proceedings of the Symposia on Electromagnetic Launcher Technology published by IEEE Transactions on Magnetics**
  1. Vol. 18, January 1982
  2. Vol. 20, March 1984
  3. Vol. 22, November 1986
  4. Vol. 25, January 1989
  5. Vol. 27, January 1991
- **Special Issue on Electromagnetic Launchers, IEEE Transactions on Plasma Science. Vol. 17, June 1989.**
- **“Proceedings of the Electromagnetic Launcher Workshop II - Diagnostic Techniques”, AFATL-TR-87-65, January 1988.**

# Comparison of Plasma Flows

|                            | v(km/s) | P(atm)   | T(K)          | $\beta^*$ | Length Scale (m) | Flow Character | Elect. Cond. ( $10^4$ mhos/m) |
|----------------------------|---------|----------|---------------|-----------|------------------|----------------|-------------------------------|
| <b>MHD Generator</b>       | 1       | 1        | $10^3$        | 0.1       | 1 - 10           | Channel        | 0.01 - 0.1                    |
| <b>High-Speed Re-entry</b> | 1 - 10  | $\leq 1$ | $10^3 - 10^4$ | $\infty$  | 1 - 10           | Free           | 0.01                          |
| <b>MPD Thrusters</b>       | 10      | 1 - 10   | $10^4$        | 1         | 1 - 10           | Channel        | 0.01                          |
| <b>Plasma Armature</b>     | 10      | $10^3$   | $10^4$        | 1         | 0.1              | Slug           | 1                             |
| <b>ETC Plasma</b>          | 10      | $10^3$   | $10^4$        | 10        | 0.1              | Channel        | 1                             |

$\beta^* = \frac{\text{thermodynamic pressure}}{\text{magnetic pressure}}$



# INCOMPLETE UNDERSTANDING LIMITS OUR ABILITY TO CONTROL ARMATURE PERFORMANCE

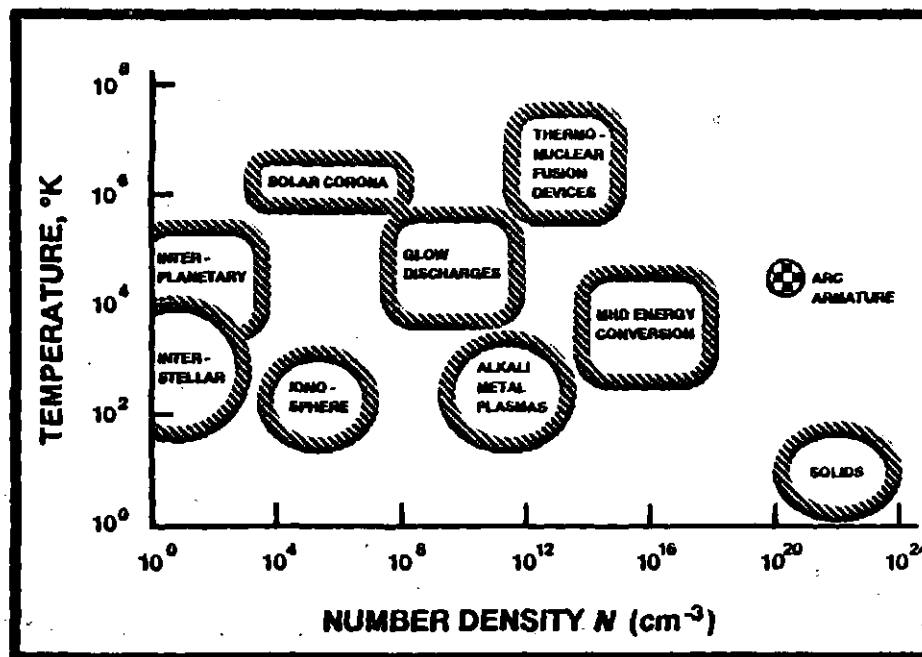


## MODELING DIFFICULTIES

- MECHANISMS WHICH ARE CONTROL ARC MASS AND COMPOSITION ARE NOT WELL UNDERSTOOD
  - COMPLEX INITIATION PHYSICS
  - ARMATURE EXCHANGES MATERIAL WITH BORE THROUGH ABLATION AND PLATING
- CONVENTIONAL ELECTRIC AND THERMAL TRANSPORT MODELS ARE INADEQUATE (NONIDEAL PLASMA)
- PLASMA REPRESENTS A NON - STEADY, 3 - D, TURBULENT, POSSIBLY MULTI - PHASE MHD FLOW
- PLASMA MAY BE SUSCEPTIBLE TO INSTABILITIES

## DIAGNOSTIC DIFFICULTIES

- LIMITED DIAGNOSTICS CURRENTLY AVAILABLE
- RELIABLE, HIGH FIDELITY, CONTINUOUS MEASUREMENTS OF ACCELERATION ARE UNAVAILABLE
- HIGH PRESSURES IMPEDE OPTICAL DIAGNOSTICS OF PLASMA CORE
- PRESENCE OF STRONG TRANSIENT FIELDS



# PLASMA PARAMETERS

- NONIDEAL PARAMETER

$$\gamma \equiv \frac{\text{Colomb Energy}}{\text{Thermal Energy}} = \left[ \left( \frac{4\pi}{9} \right)^{1/3} \frac{e^2}{4\pi\epsilon_0 k} \right] \left[ \frac{\alpha(1+z)}{(1+\alpha)^{2/3}} \right] \frac{n^{1/3}}{T}$$

- NUMBER OF PARTICLES IN A DEBYE SPHERE

$$N_D \propto \left( \frac{1}{\gamma} \right)^{3/2}$$

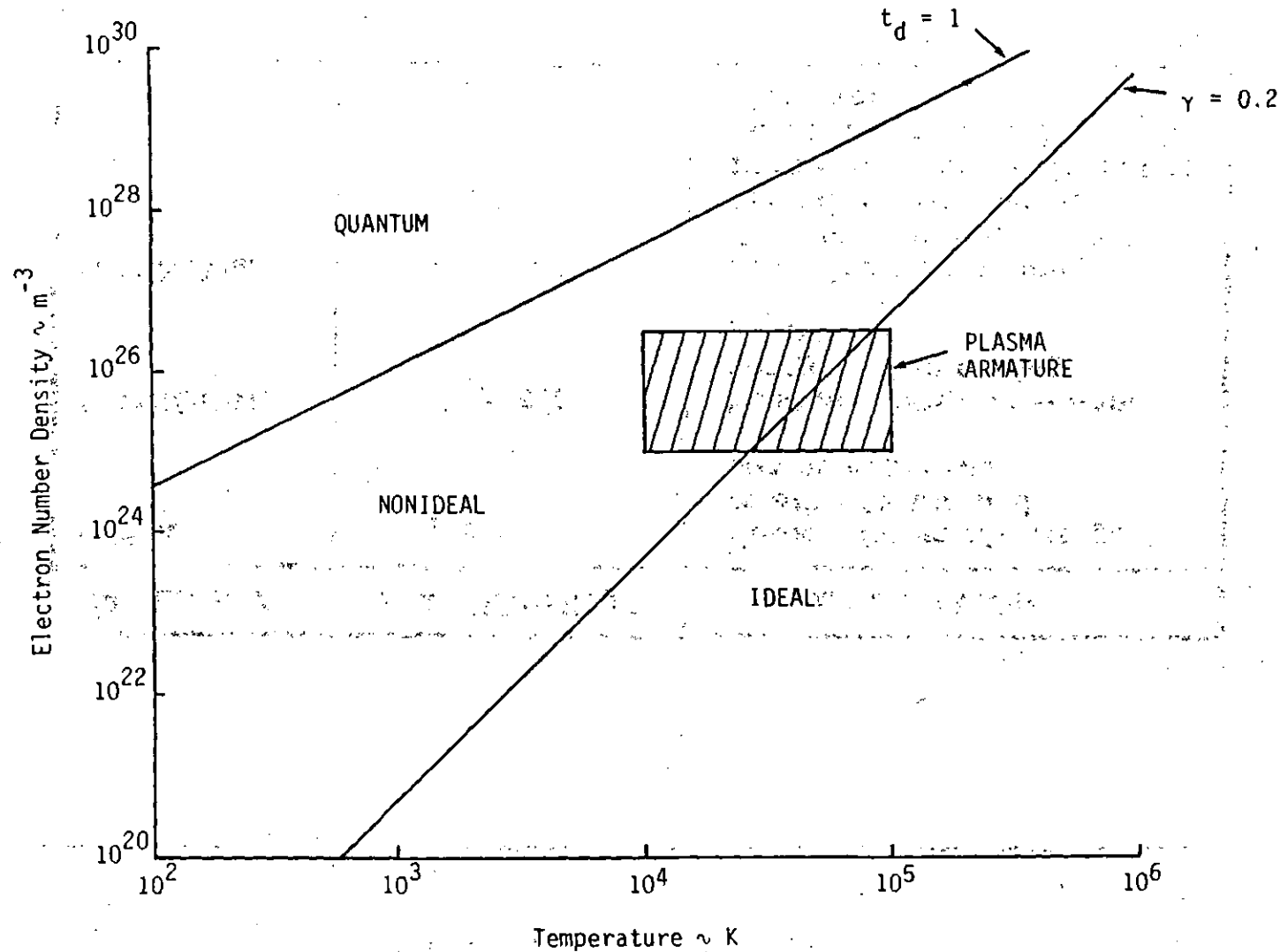
- DEGENERACY TEMPERATURE RATIO

$$t_D = \frac{T_0}{T} = \left[ \left( \frac{3}{4\pi} \right)^{2/3} \frac{h^2}{m_e k} \right] \alpha^{2/3} \frac{n^{2/3}}{T}$$

# TYPES OF PLASMAS

| CATEGORY | REQUIREMENT          | IMPLICATION                                                                                                                       |
|----------|----------------------|-----------------------------------------------------------------------------------------------------------------------------------|
| IDEAL    | $\gamma \ll 1$       | Neglect Coulomb energy relative to thermal energy in plasma                                                                       |
| NONIDEAL | $\gamma \gtrsim 0.2$ | Must account for Coulomb energy in determining properties                                                                         |
| QUANTUM  | $t_D \gtrsim 1$      | Free electrons no longer described by Boltzmann statistics, and plasma properties must be based on Fermi-Dirac quantum statistics |

# METAL-PLASMA ARMATURES ARE TYPICALLY NONIDEAL



Assumes Singly Ionized Plasma

**SAIC**

Science Applications International Corporation

# IMPACT OF NONIDEAL PLASMA BEHAVIOR

- SIGNIFICANT DECREASE IN THE PLASMA CONDUCTIVITY BELOW THAT PREDICTED BY SPITZER'S FORMULA
- LOWERING OF THE IONIZATION POTENTIAL
- DECREASE IN GAS PRESSURE WHEN COMPARED TO THE IDEAL GAS EQUATION OF STATE



# Selected References for Nonideal Plasma Properties

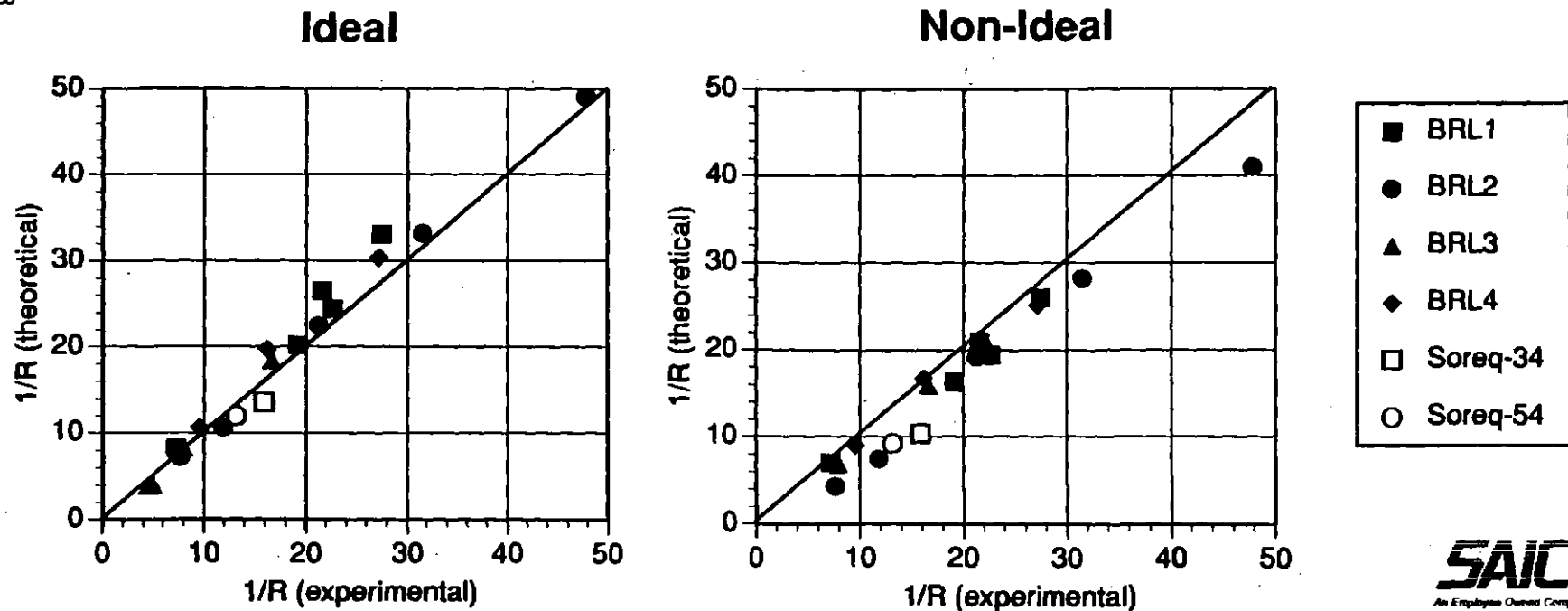
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- "Electrical Conductivity of Nonideal Quasi - Metallic Plasmas," A.H. Khalfaoui, IEEE Trans. on Plasma Science *PS-12*, 179 (1984)
- "The Electrical Conductivity of Plasma in a Wide Range of Charge Densities," Yu. K. Kurilenkov and A.A. Valuev, Beitr. Plasma phys. *24*, 161 (1984).
- "Physical Properties of High-Pressure Plasmas of Hydrogen and Copper in the Temperature Regime 5000 - 60000 K, "P. Kovitya, IEEE Trans. on Plasma Science *PS-13*, 587 (1985).
- "Electrical Conductivity of Nonideal Plasmas," R.J. Zollweg and R.W. Liebermann, J. Appl. Phys. *62*, 3621 (1987).
- "Thermodynamic and Electrical Properties of Railgun Plasma Armatures," G.E. Rolander and J.H. Batteh, IEEE Trans. on Plasma Science *17*, 439 (1989)
- "Electrical Conductivity and Thermodynamic Functions of Weakly Nonideal Plasma," R.B. Mohanti and J.G. Gilligan, J. Appl. Phys. *68*, 5044 (1990).

# Comparison of Measured and Predicted Conductance for Plasma Capillaries

- Based on quasi-steady model of Powell (in Technology Efforts in ET Gun Propulsion, Vol. 2, 1989)
- Predictions assume choked flow
- Measured values denote conductance in units of mhos
- Non-ideal model based on Kurilenkov and Valuev

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# Factors That Influence Current Distributions in Confined and Unconfined Discharges

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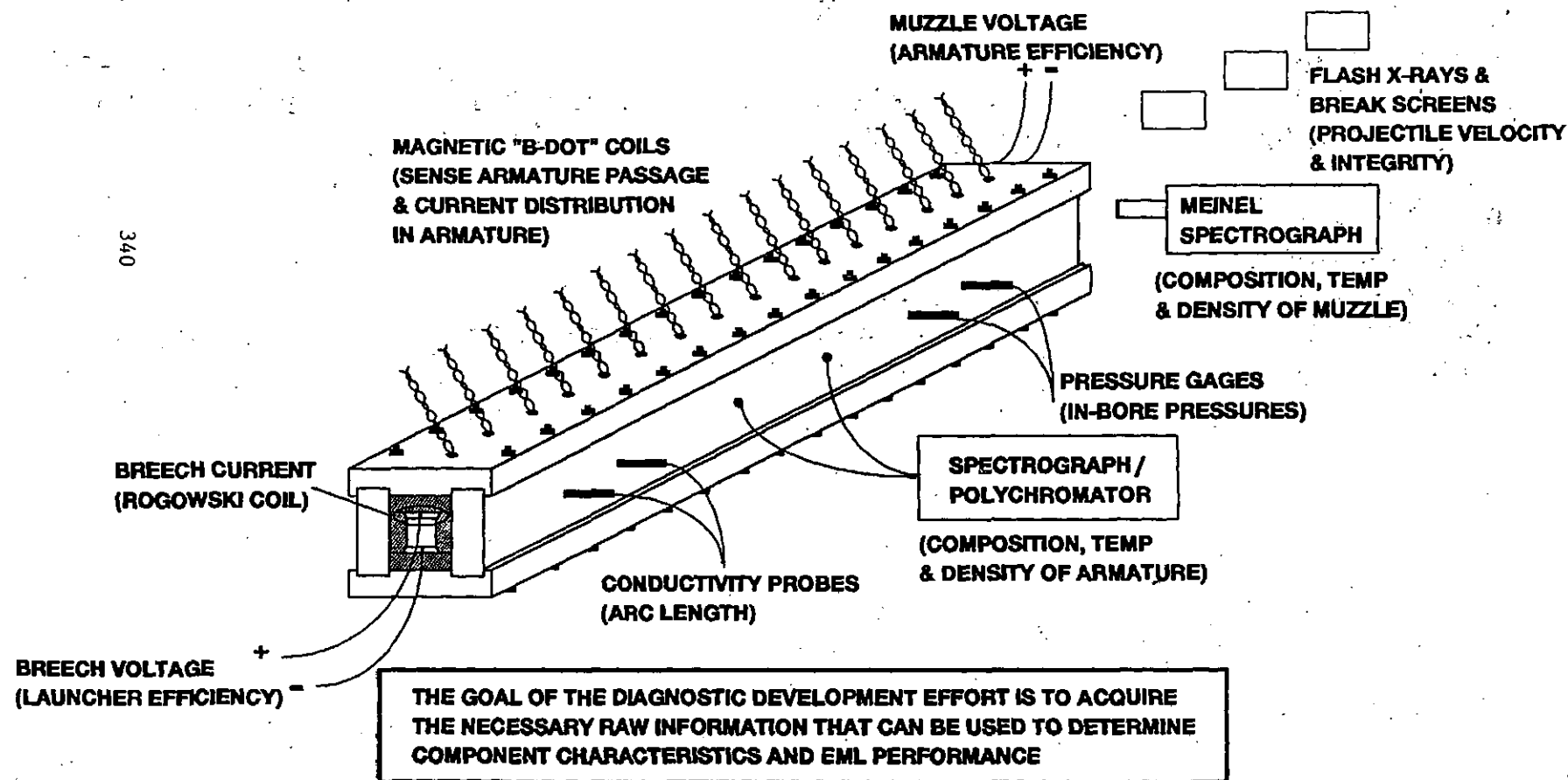
- Solid boundaries
  - railgun bore
  - capillary wall
- Dynamic (pressure) equilibrium
  - discharge into liquid
- Electric field distribution
- Conductivity distribution
- Flowfield
$$\mathbf{J} = \sigma (\mathbf{E} + \mathbf{V} \times \mathbf{B})$$
- Magnetic confinement
  - $\beta \leq 1$
- Instabilities



# HRP PHASE I DIAGNOSTIC DEVELOPMENT



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# Overview of Advanced Railgun Diagnostics

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| Diagnostics                         | Measured or Inferred Parameters                                                                              | Issues                                                                                                                                     | Selected References                                                                                                                                                                                                 |
|-------------------------------------|--------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Spectroscopy of plasma armatures    | <ul style="list-style-type: none"><li>• Composition</li><li>• Temperature</li><li>• Flow Structure</li></ul> | <ul style="list-style-type: none"><li>• Short optical depths</li><li>• Data interpretation transient</li><li>• Coating/shielding</li></ul> | Keefer, et al. <ul style="list-style-type: none"><li>- Ref. 1, p 217</li><li>- Ref. 2, p. 295</li><li>- Ref. 3, p. 360</li></ul> Clothiaux, et al. <ul style="list-style-type: none"><li>- Ref. 1, p. 199</li></ul> |
| X-ray absorption of plasma armature | <ul style="list-style-type: none"><li>• Density</li><li>• Composition</li></ul>                              | <ul style="list-style-type: none"><li>• Initial estimate of components</li></ul>                                                           | Clothiaux, et al. <ul style="list-style-type: none"><li>- Ref. 1, p. 139</li><li>- Ref. 1, p. 165</li></ul>                                                                                                         |

# Overview of Advanced Railgun Diagnostics

| Diagnostics          | Measured or Inferred Parameters                                                                                | Issues                                                                                                                       | Selected References                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|----------------------|----------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Magnetic B-dots      | <ul style="list-style-type: none"> <li>• Armature current distribution</li> <li>• Armature location</li> </ul> | <ul style="list-style-type: none"> <li>• 3-D structure</li> <li>• Quasi-steady assumptions</li> <li>• Orientation</li> </ul> | <p>Cobb, et al.</p> <ul style="list-style-type: none"> <li>- Ref. 1, p. 189</li> <li>- Ref. 3, p. 507</li> </ul> <p>Jamison, et al.</p> <ul style="list-style-type: none"> <li>- Ref. 2, p. 256</li> </ul> <p>Parker</p> <ul style="list-style-type: none"> <li>- Ref. 3, p. 487</li> </ul> <p>Smith, et al.</p> <ul style="list-style-type: none"> <li>-Ref. 3, p. 501</li> </ul> <p>Bouvier</p> <ul style="list-style-type: none"> <li>- Ref. 3, p. 516</li> </ul> |
| On-board diagnostics | <ul style="list-style-type: none"> <li>• Projectile acceleration and velocity profiles</li> </ul>              | <ul style="list-style-type: none"> <li>• Soft-catch</li> <li>• Vibrations</li> <li>• Mass/volume of package</li> </ul>       | <p>Fernandez, et al</p> <ul style="list-style-type: none"> <li>-Ref. 1, p. 185</li> </ul> <p>Littrell, et al.</p> <ul style="list-style-type: none"> <li>- Ref 4</li> </ul> <p>Grzesik, et al.</p> <ul style="list-style-type: none"> <li>- Ref. 1, p. 147</li> </ul>                                                                                                                                                                                                |

# Overview of Advanced Railgun Diagnostics

---

| Diagnostics | Measured or Inferred Parameters                                                             | Issues                                                                                                                                                                                                                | Selected References                 |
|-------------|---------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------|
| Visar       | <ul style="list-style-type: none"><li>• Velocity profiles</li></ul>                         | <ul style="list-style-type: none"><li>• Shock heating of ambient gas</li><li>• Vaporization of projectile/bore</li><li>• Blowby</li><li>• Projectile deflection/deformation</li><li>• Mechanical vibrations</li></ul> | Asay, et al.<br>- Ref. 2, p. 46     |
| Calorimetry | <ul style="list-style-type: none"><li>• Total thermal energy delivered to surface</li></ul> | <ul style="list-style-type: none"><li>• High powers</li></ul>                                                                                                                                                         | Derbidge, et al.<br>-Ref. 1, p. 202 |
| Radiometry  | <ul style="list-style-type: none"><li>• Heat flux</li></ul>                                 | <ul style="list-style-type: none"><li>• High powers</li><li>• Vibration sensitivity</li></ul>                                                                                                                         | Ibrahim<br>- Ref 5, p. 2045         |

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# Reference List for Diagnostics Table

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1. IEEE Trans. on Magnetics 27, Jan. 1991
2. IEEE Trans. on Magnetics 25, Jan. 1989
3. IEEE Trans. on Plasma Science, June 1989
4. Third European Symposium on EML Technology
5. J. Phys. D: Appl. Phys. 13, (1980)



# Summary

---

- **Some railgun research is relevant to ETC technology**
  - **Plasma physics**
  - **Plasma/solid/liquid interactions**
  - **Diagnostics**
  - **Data analysis**
- **Railgun literature is well-documented and readily available**
- **Expect surprises**

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IN-BORE POSITION AND VELOCITY  
MEASUREMENT TECHNIQUES

R. Richard Bartsch and Harold A. Davis  
Los Alamos National Laboratory  
Los Alamos, NM 87544

ABSTRACT

A mode-launcher has been developed which permits in-bore microwave interferometry in the lowest propagating mode ( $TE_{11}$ ). This technique eliminates multipath and multiple mode problems which can occur with a launcher external to the gun barrel, and may result in position data which is clean enough to look at details of the acceleration of the projectile. Tests with a 20mm steam gun will be discussed.

This work performed under the auspices of the U.S. Department of Energy.

R. Richard Bartsch  
and Harold A. Davis  
Los Alamos National Laboratory

# In-Bore Position and Velocity Measurement Techniques

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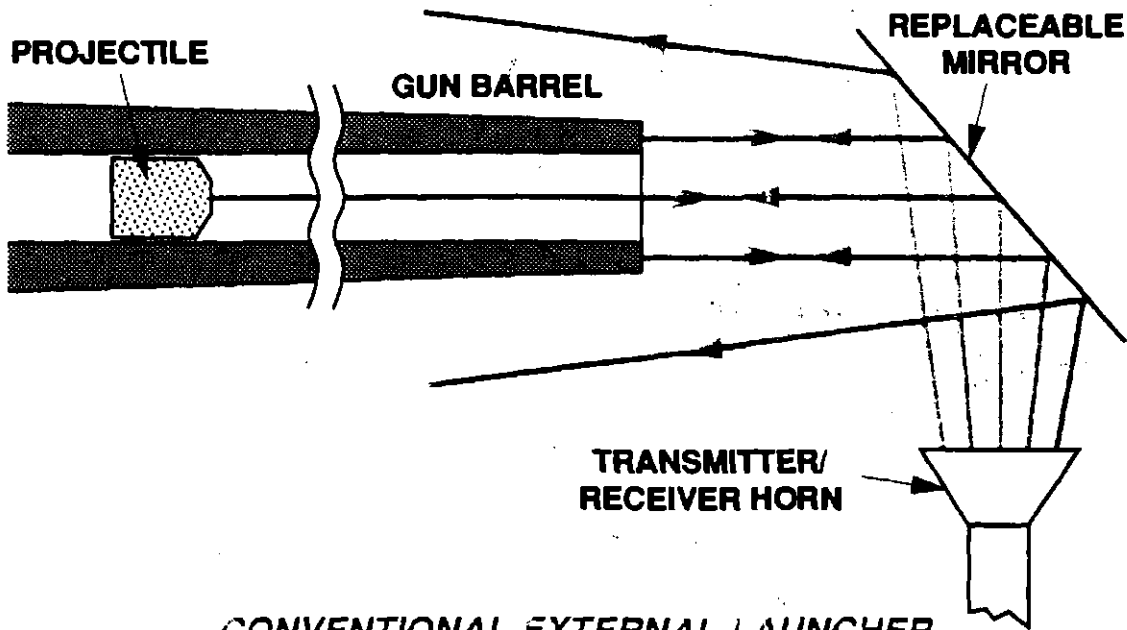
JANNAF Workshop  
9-11 July, 1991  
Aberdeen, Md

# Outline

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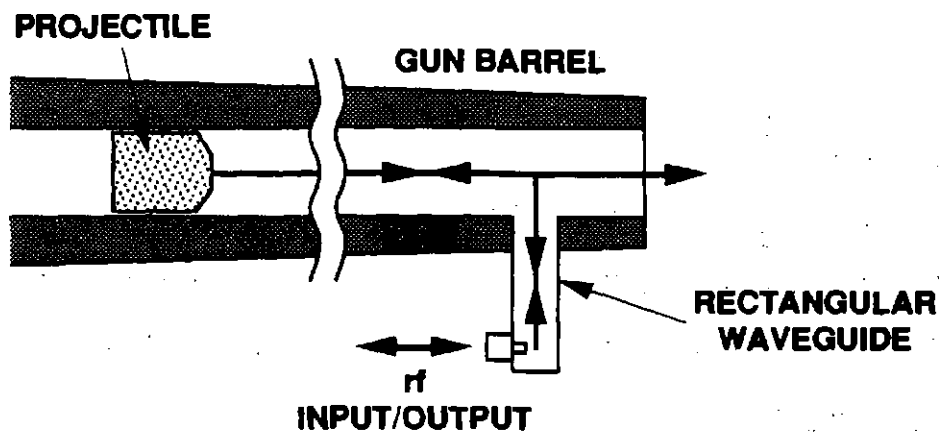
- Fundamental Mode Microwave Interferometer (20 mm Test Gun)
  - ✓ Developed and Demonstrated
  - ✓ Position Measurement
- R.F. Modulated Laser Radar
  - ✓ Developed and Demonstrated @ 500 MHz
  - ✓ Designed 1 GHz System
  - ✓ Position Measurement
- VISAR (Velocity Interferometer System for Any Reflector)
  - ✓ Developed at SNL
  - ✓ Refined and Extended at LANL
  - ✓ Velocity Measurement

Los Alamos



### CONVENTIONAL EXTERNAL LAUNCHER

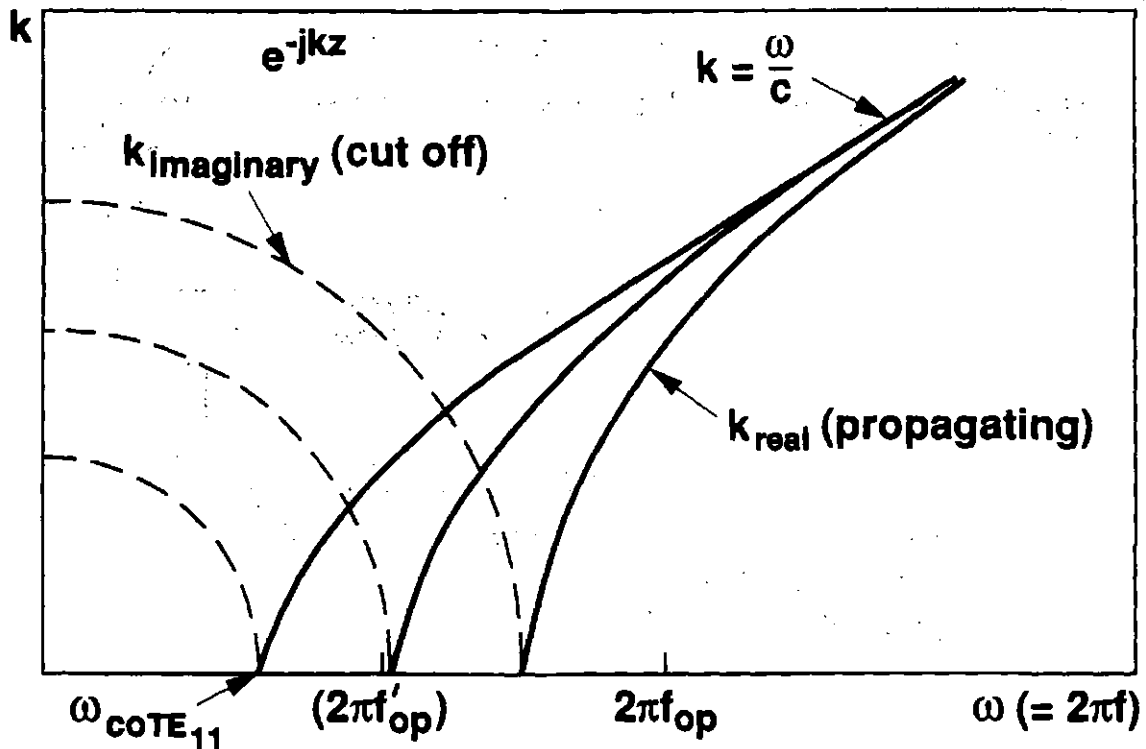
- a) INEFFICIENT
- b) MULTIPLE PATHS
- c) MULTIPLE MODES
- d) EASY TO SETUP



### FUNDAMENTAL MODE LAUNCHER

- a) MECHANICAL DESIGN TO WITHSTAND BLAST
- b) SINGLE MODE
- c) EFFICIENT

Los Alamos



$f$  = Frequency

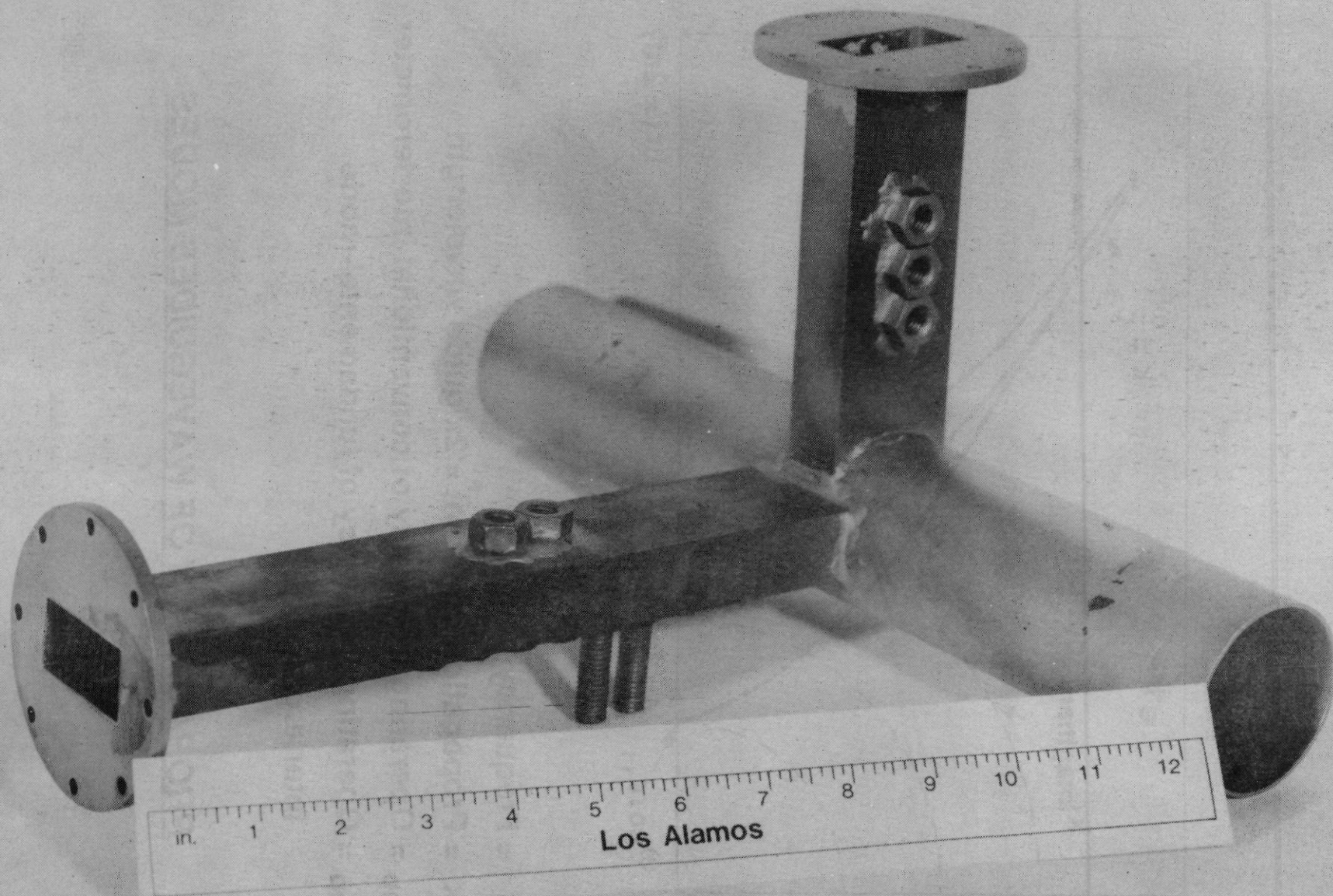
$k$  = Propagation constant =  $2\pi/\text{guide wavelength}$

$f_{op}$  = Operating frequency of conventional interferometer

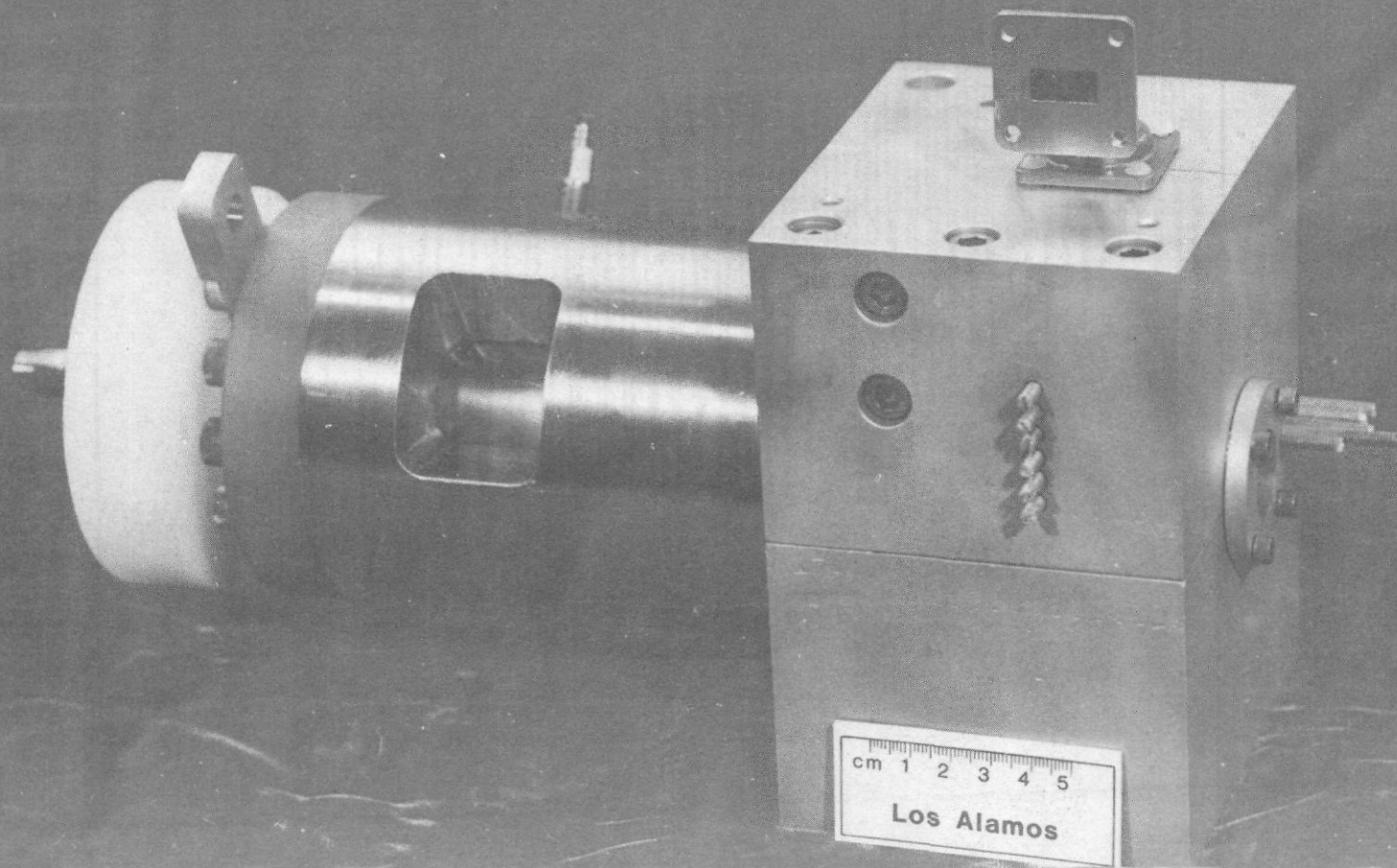
$f'_{op}$  = Operating frequency of fundamental-mode  
Interferometer

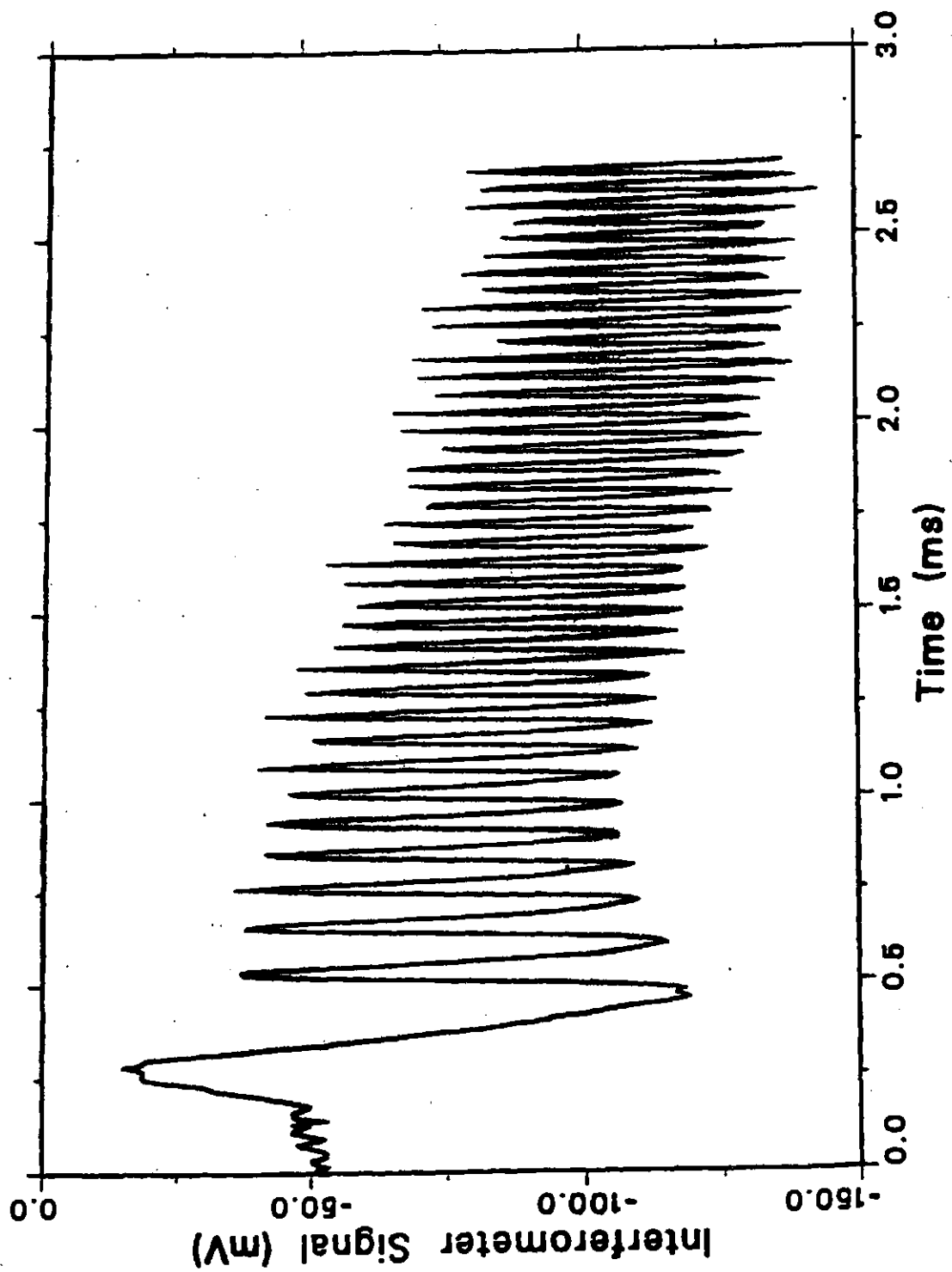
### **PROPAGATION OF WAVEGUIDES MODES**

Los Alamos

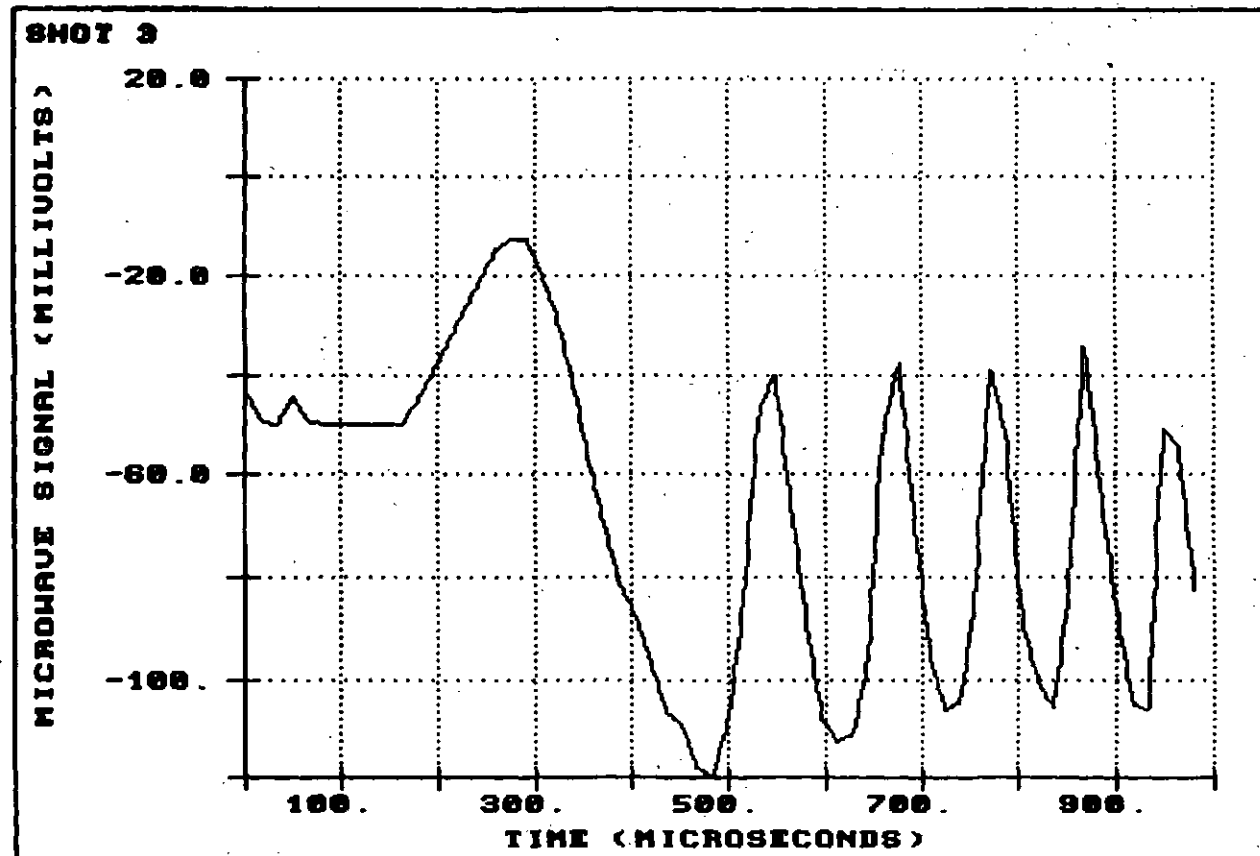








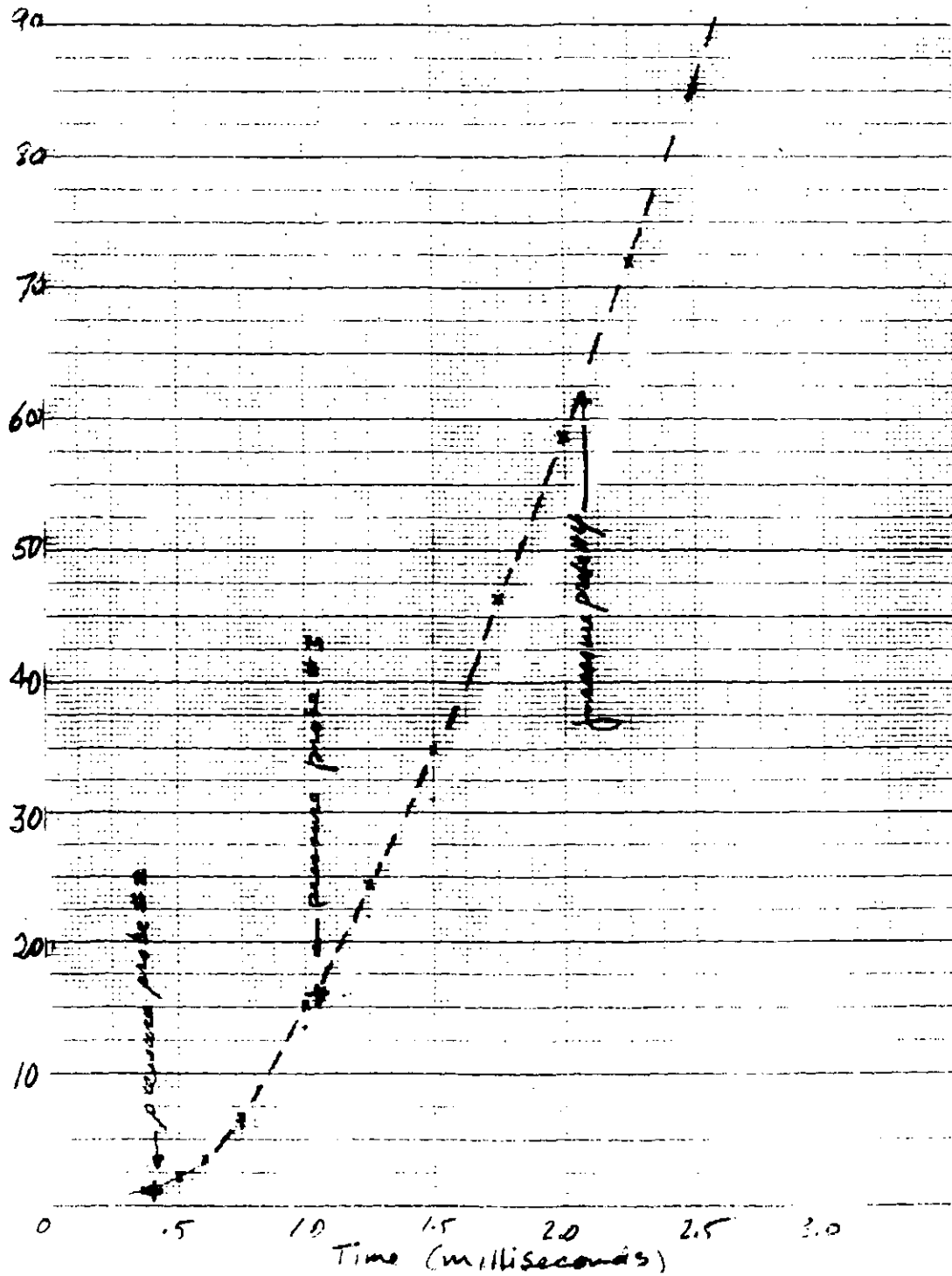
# Microwave Interferometer Signal

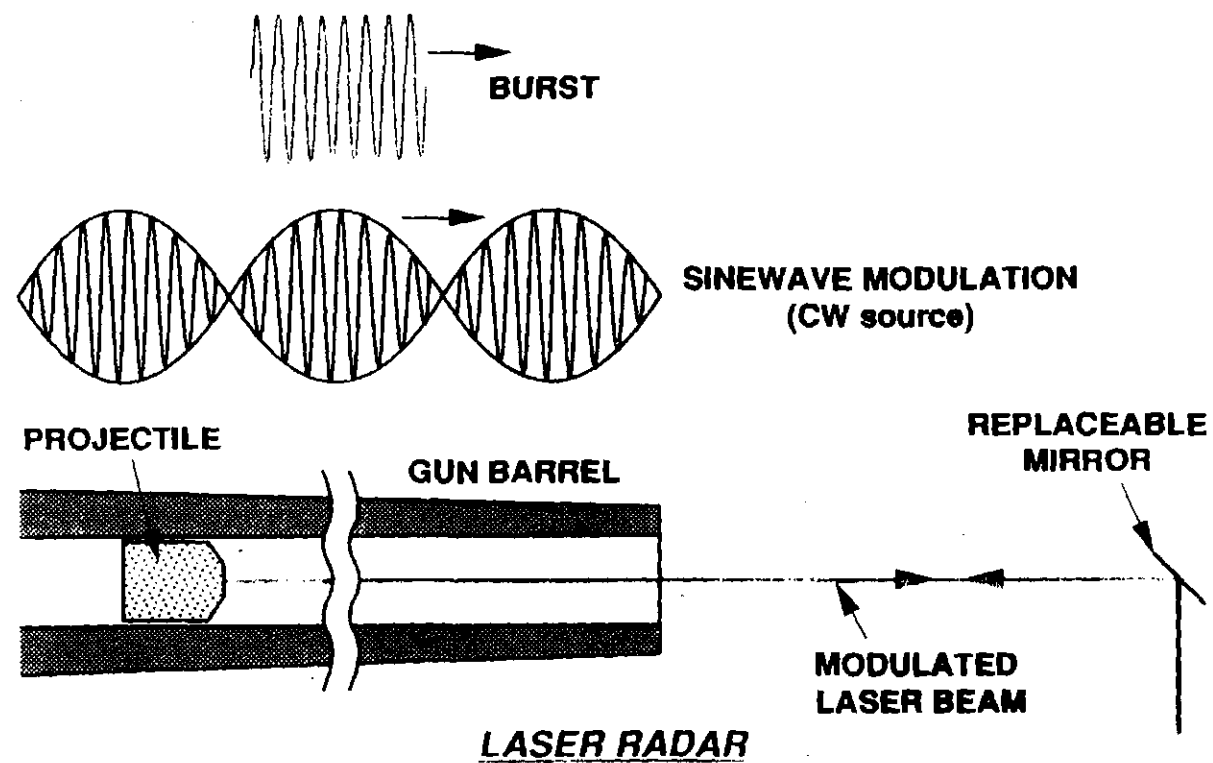


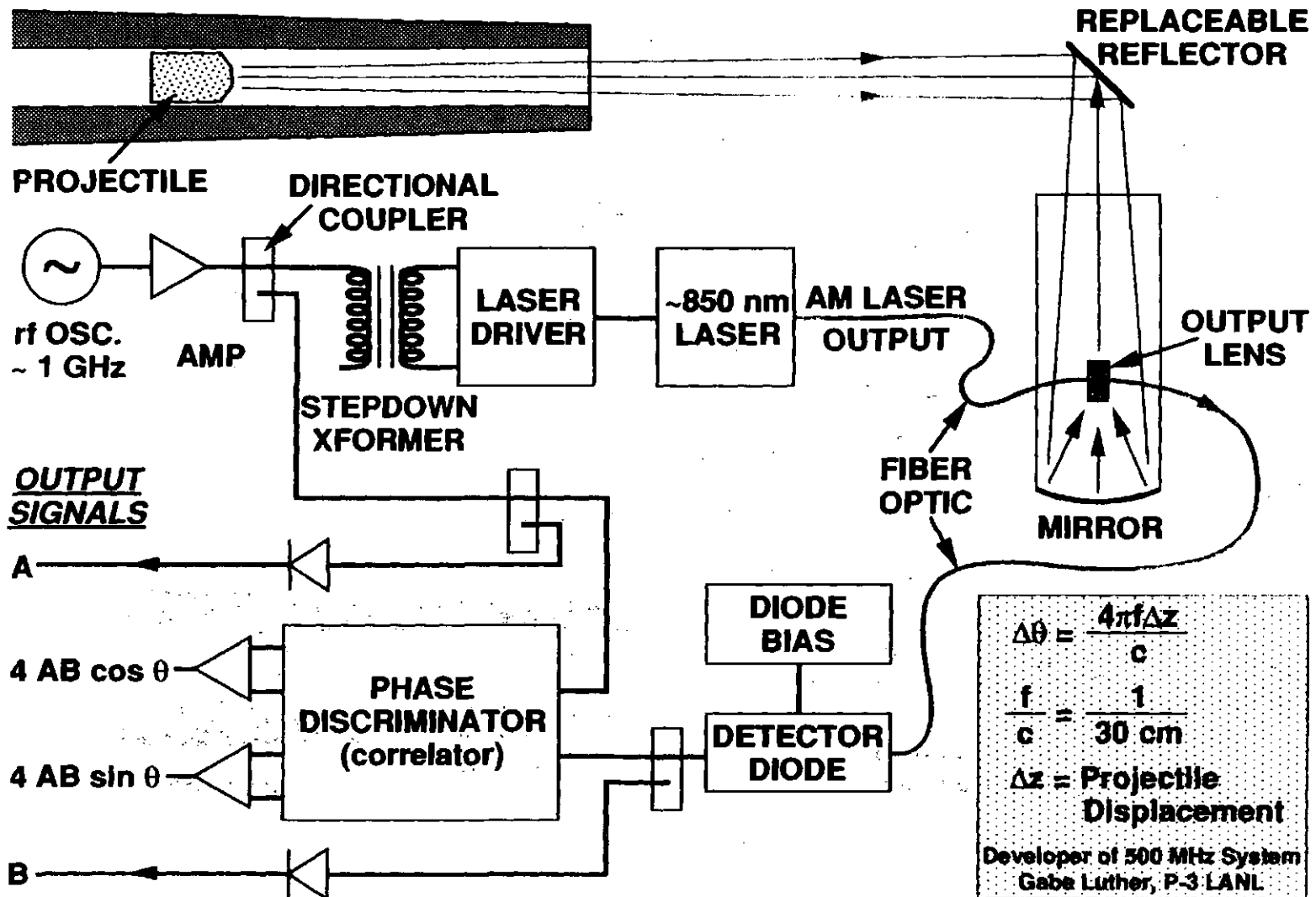
Los Alamos

100 cma

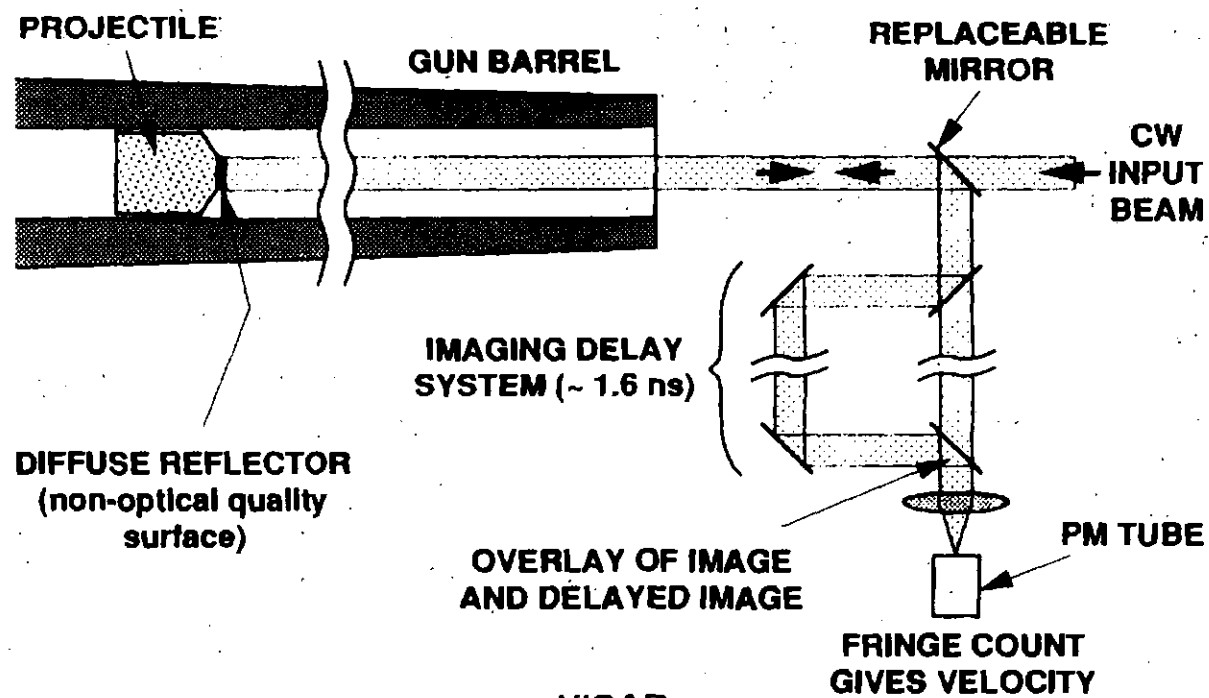
# Interferometer Shot 04





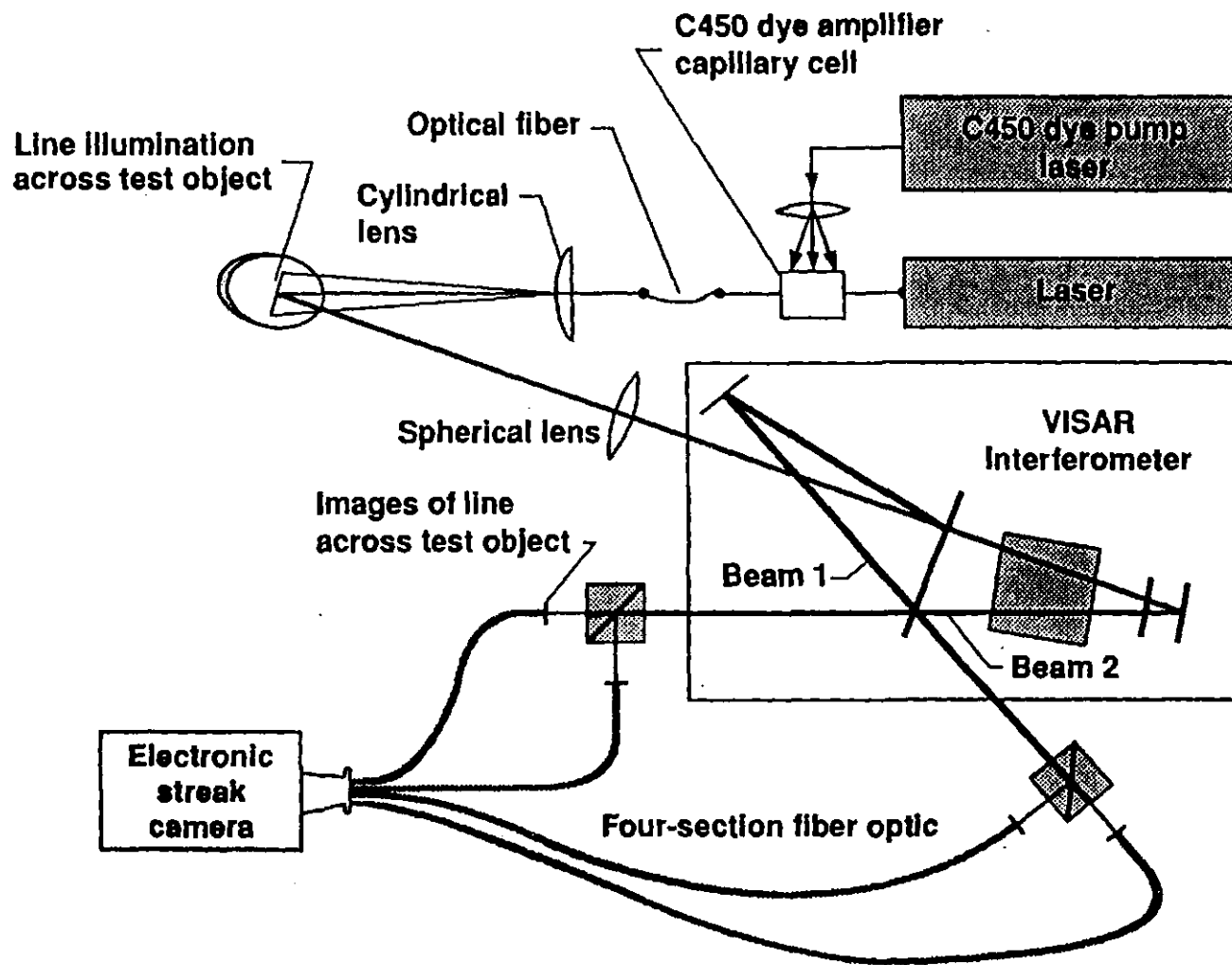


**rf MODULATED-LASER-BEAM POSITION SENSOR**



VISAR

Los Alamos



360

c/o Will Hemsing  
M-4  
LANL





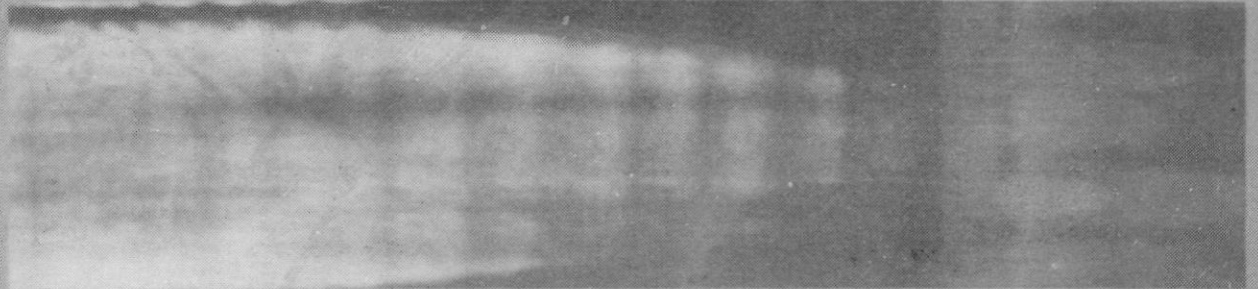
SIN - (-SIN)

This image shows a complex interference pattern with multiple overlapping wave-like fringes, creating a moiré effect. The pattern is centered and occupies the upper portion of the frame.



COS - (-COS)

This image displays a similar interference pattern to the one above, but with a different phase or frequency, resulting in a slightly different arrangement of the wave-like fringes.



SUM SIGNAL

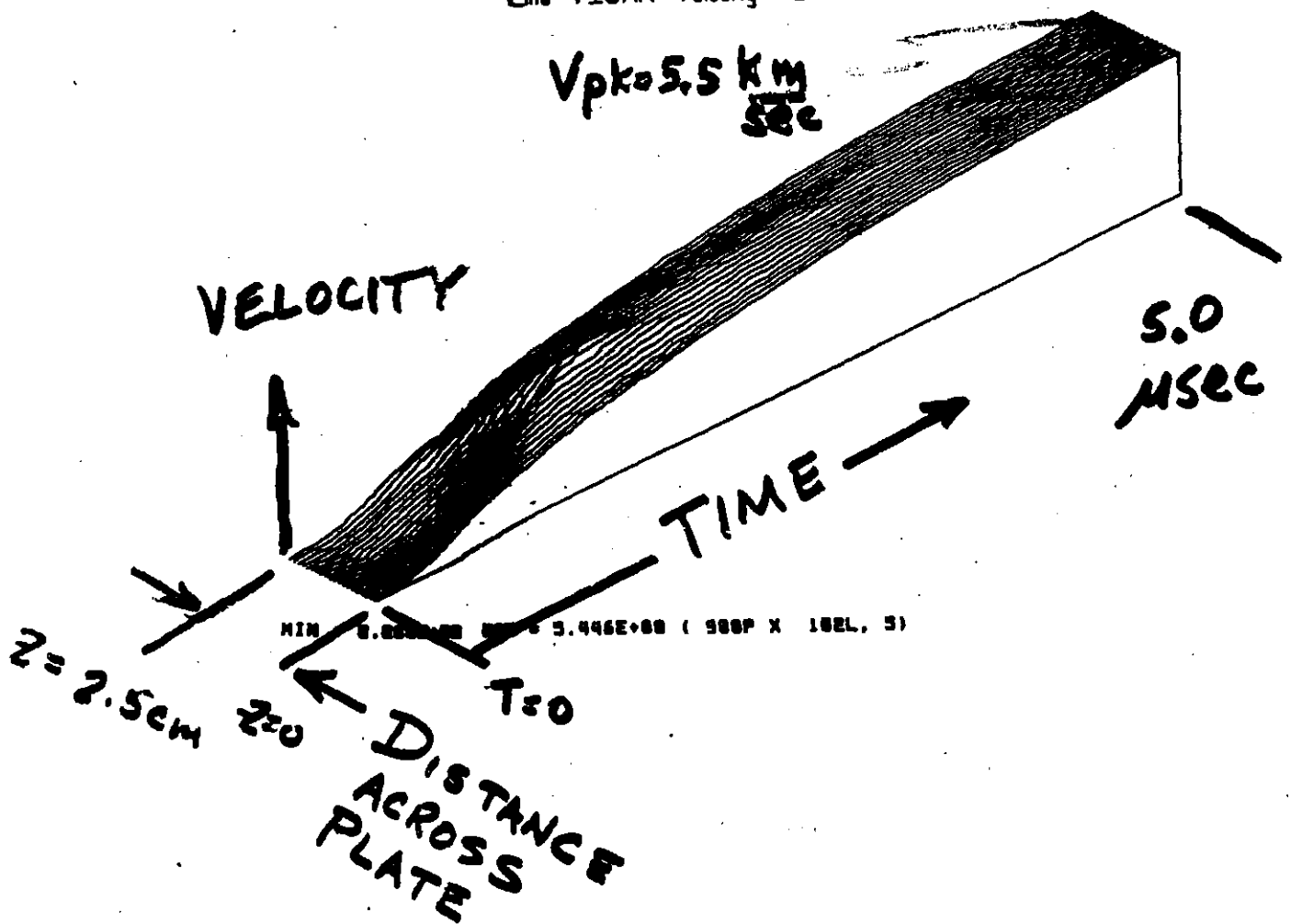
This image shows the result of summing the two signals above. The interference pattern is significantly different, appearing as a series of more uniform, horizontal bands with some internal structure.

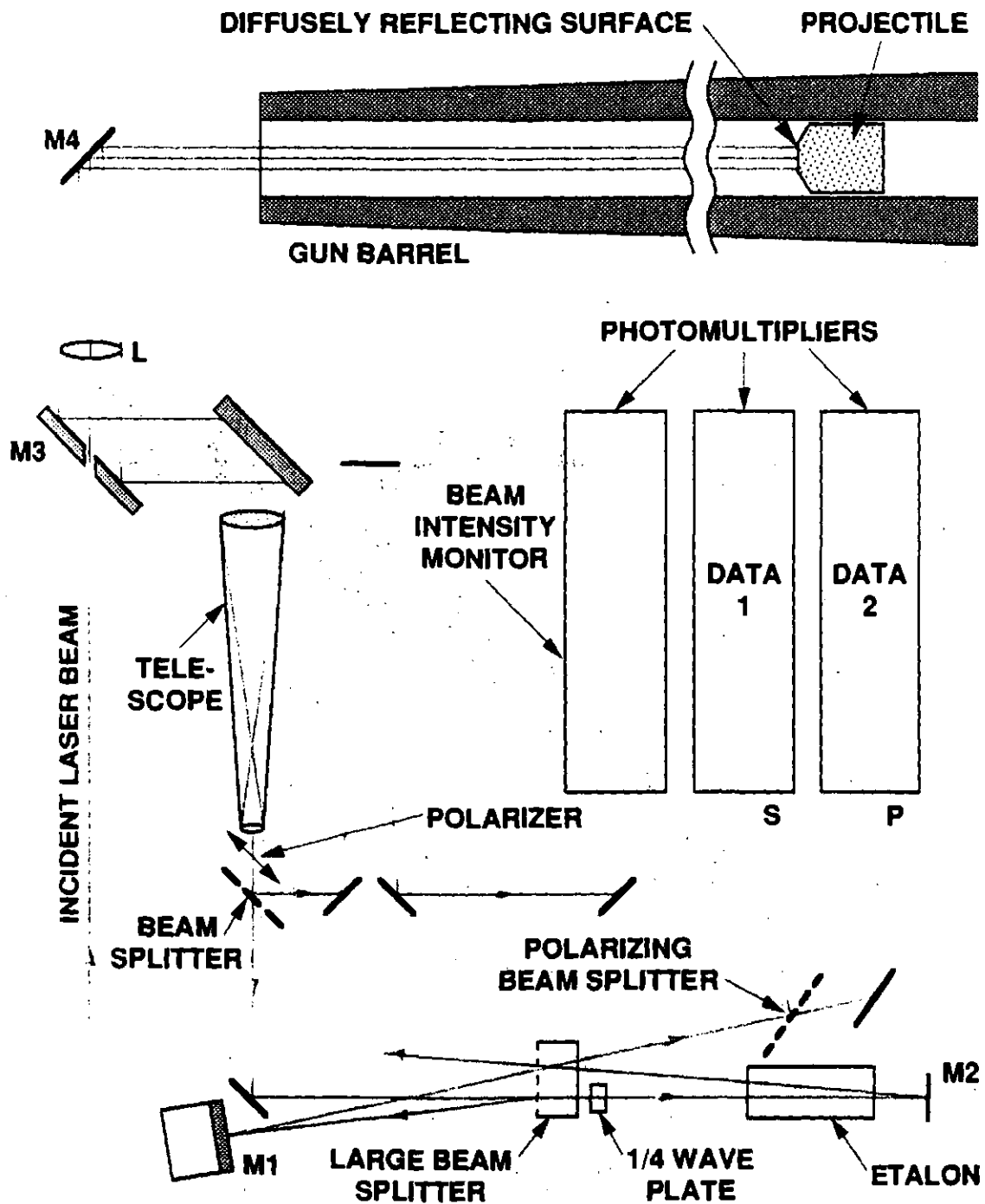
\*H1434 LINE-VISAR

Line VISAR Velocity H1434

20-JUN-91 12:00:27

$V_{pk} = 5.5 \frac{\text{km}}{\text{sec}}$

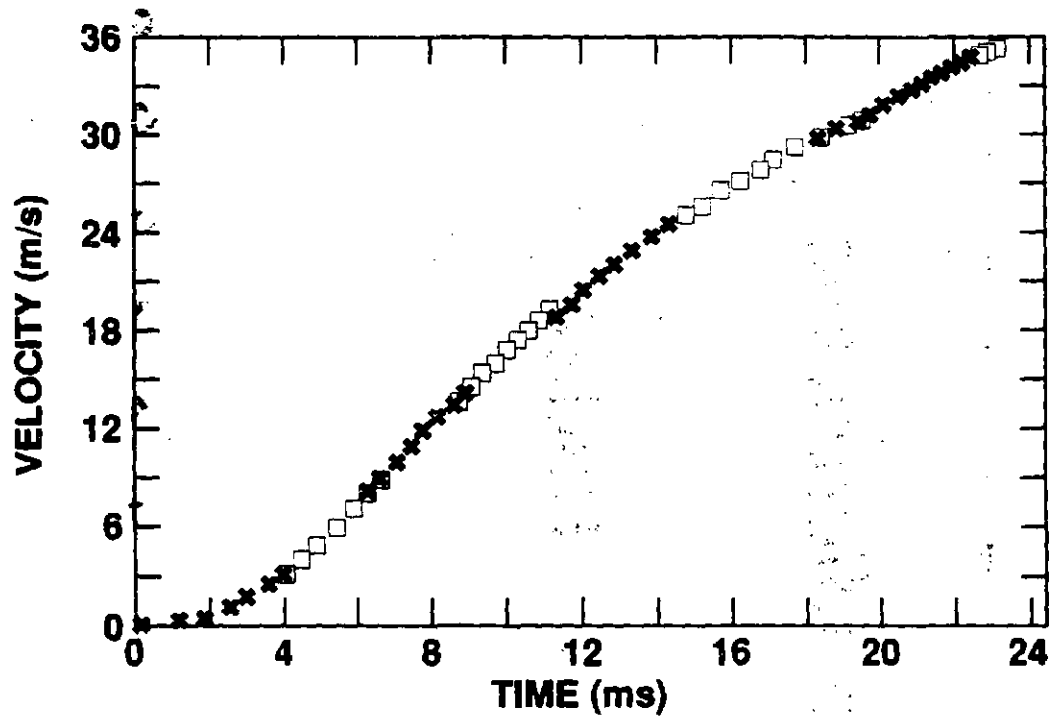
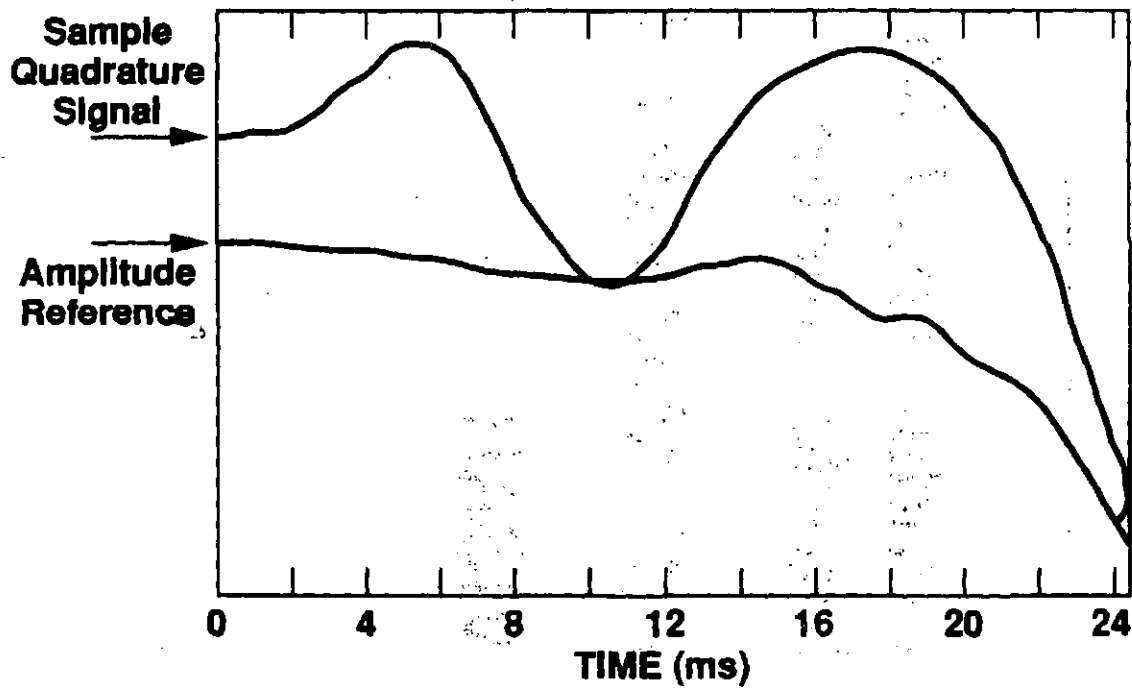




SCHEMATIC OF A VISAR SYSTEM

ref. Barker and Hollenbach,  
J. Appl. Phys. Vol. 43, No.11, 4669

Los Alamos

**PROJECTILE VELOCITY vs TIME****FRINGE DATA FOR PROJECTILE MOTION**

ref. Barker and Hollenbach,  
J. Appl. Phys. Vol. 43, No.11, 4669

Los Alamos

# Summary

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- Fundamental-Mode Microwave Interferometer
- R.F. Modulated Laser Radar
- VISAR

Los Alamos

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**IN-BORE ACCELERATION MEASUREMENTS WITH AN  
INSTRUMENTED RAILGUN PROJECTILE**

Donald M. Littrell, Keith A. Jamison and Glenn E. Rolader  
U.S. Air Force Armament Directorate  
Eglin AFB, FL 32542-5434

**ABSTRACT**

An instrumented package has been accelerated in an electromagnetic launcher to measure the in-bore acceleration as a function of time. Direct, continuous acceleration profiles of the launch show the gas injection phase, electromagnetic propulsion, and downrange deceleration in a softcatch recovery system. These proof-of-principle experiments were conducted in a 50 mm square bore railgun and utilized off-the-shelf components for the in situ measurement, digitization, and storage of acceleration data. The 1.2 kg launch package was subject to peak accelerations of nearly 30 kilogeeks ( $2.8 \times 10^5 \text{ m/s}^2$ ) in the electromagnetic propulsion phase of the launch. Velocity and position data obtained through integration of this data are correlated with velocity data derived from conventional static diagnostics (e.g., magnetic flux loops) to validate the technique. The peak acceleration was slightly more than anticipated from the electrical current delivered to the railgun, and this deviation is examined. The presentation includes a description of the experimental apparatus, acquired data, a comparison of the data with code simulations, and suggestions for further application of this diagnostic for in-bore ballistic measurements.



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# **IN-BORE ACCELERATION MEASUREMENTS WITH AN INSTRUMENTED RAILGUN PROJECTILE**

368

**PRESENTED AT**

**JANNAF Workshop on Electrothermal-Chemical Modeling and Diagnostics**

**Aberdeen Proving Ground, MD**

**July 9-11, 1991**

**PRESENTER**

**Donald M. Littrell, USAF, WL/MNSH**

**CONTRIBUTORS**

**Keith A. Jamison, SAIC**

**Glenn E. Rolader, SAIC**



# PRESENTATION OUTLINE

---

- PROGRAM OVERVIEW
- EQUIPMENT
- PRELIMINARY TESTS
- EML TESTS
- DATA ANALYSIS
- SUMMARY

# PROGRAM DEFINITION

## *In-Bore Instrumentation/Diagnostics (IBID)*

---

- 370 The use of self-contained, on-board instrumentation to measure and explore the projectile environment within an electromagnetic gun during launch.

# PROGRAM GOALS

---

- CONSTRUCT A PROJECTILE TO ACQUIRE AND STORE DATA DURING ACCELERATION BY AN ELECTROMAGNETIC LAUNCHER
- EXPAND THE KNOWLEDGE BASE ON PROJECTILE ACCELERATION VIA THE APPLICATION OF MAGNETIC FORCES
- FURTHER THE DEVELOPMENT OF GUN-LAUNCHED, SMART PROJECTILES TO VERY HIGH VELOCITIES

# IBID CRITICAL ISSUES

---

- SURVIVABILITY OF ELECTRICAL COMPONENTS AND SENSORS IN THE EML'S TRANSIENT ELECTROMAGNETIC FIELDS
- ELECTRONIC HARDENING AGAINST THE EML'S HIGH ACCELERATION (G) AND TIME RATE OF CHANGE OF ACCELERATION (G-DOT)
- DEVELOPMENT OF A SOFT CATCH SYSTEM TO STOP A HIGH VELOCITY PROJECTILE WITHOUT DAMAGE

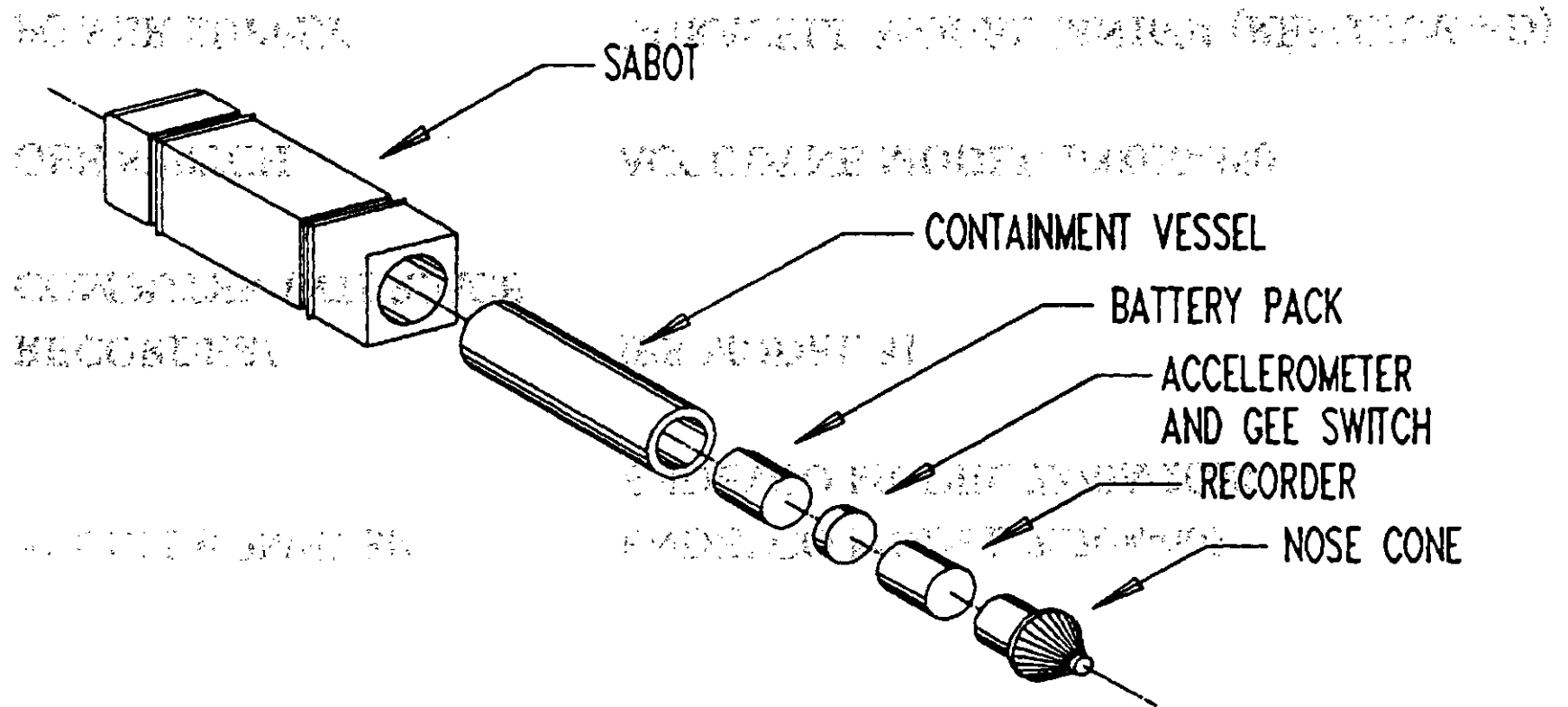
# PROJECTILE/EML INTERFACE ISSUES

---

## CHARACTERIZATION OF IN-BORE GUN ENVIRONMENT

- JERK (G-DOT) DURING CURRENT RISE
- MAGNETIC FIELDS
- BALLOTING, EXCESSIVE LATERAL GEES
- NEGATIVE G-DOT IN FORCING CONE
- NEGATIVE G-DOT AT CROWBAR AND EXIT
- MUZZLE WHIP

# LAUNCH PACKAGE SCHEMATIC



# INSTRUMENTATION

---

ACCELEROMETER

ENDEVCO MODEL 7270A-60K

ENDEVCO MODEL 7270A-200K

REORDER/

IES MODEL 31

COMPUTER INTERFACE

GEE SWITCH

ACCUDYNE MODEL 100050-350

POWER SUPPLY

DURACELL MODEL MN1604 (REPACKAGED)

# ACCELEROMETER SPECIFICATIONS

---

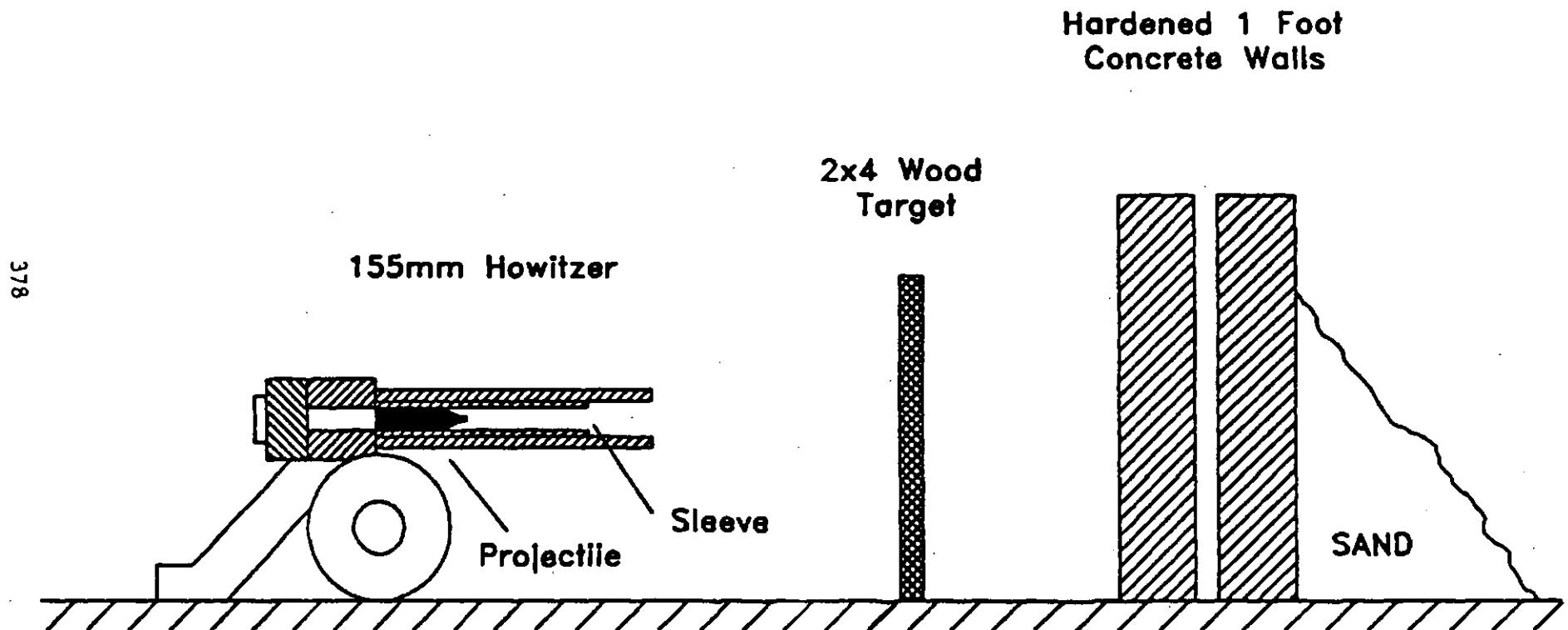
| Model #                          | 7270A-60K | 7270A-200K |
|----------------------------------|-----------|------------|
| Range (kgees)                    | 60        | 200        |
| Overrange Limits (kgees)         | 180       | 200        |
| Non-Linearity & Hysteresis (%)   | $\pm 2$   | $\pm 2$    |
| Transverse Sensitivity (%)       | 5         | 5          |
| Frequency Response (kHz)         | DC to 100 | DC to 150  |
| Mounted Resonant Frequency (kHz) | 700       | 1200       |
| Mass (grams)                     | 1.5       | 1.5        |

376



# HOWITZER TEST SETUP

---

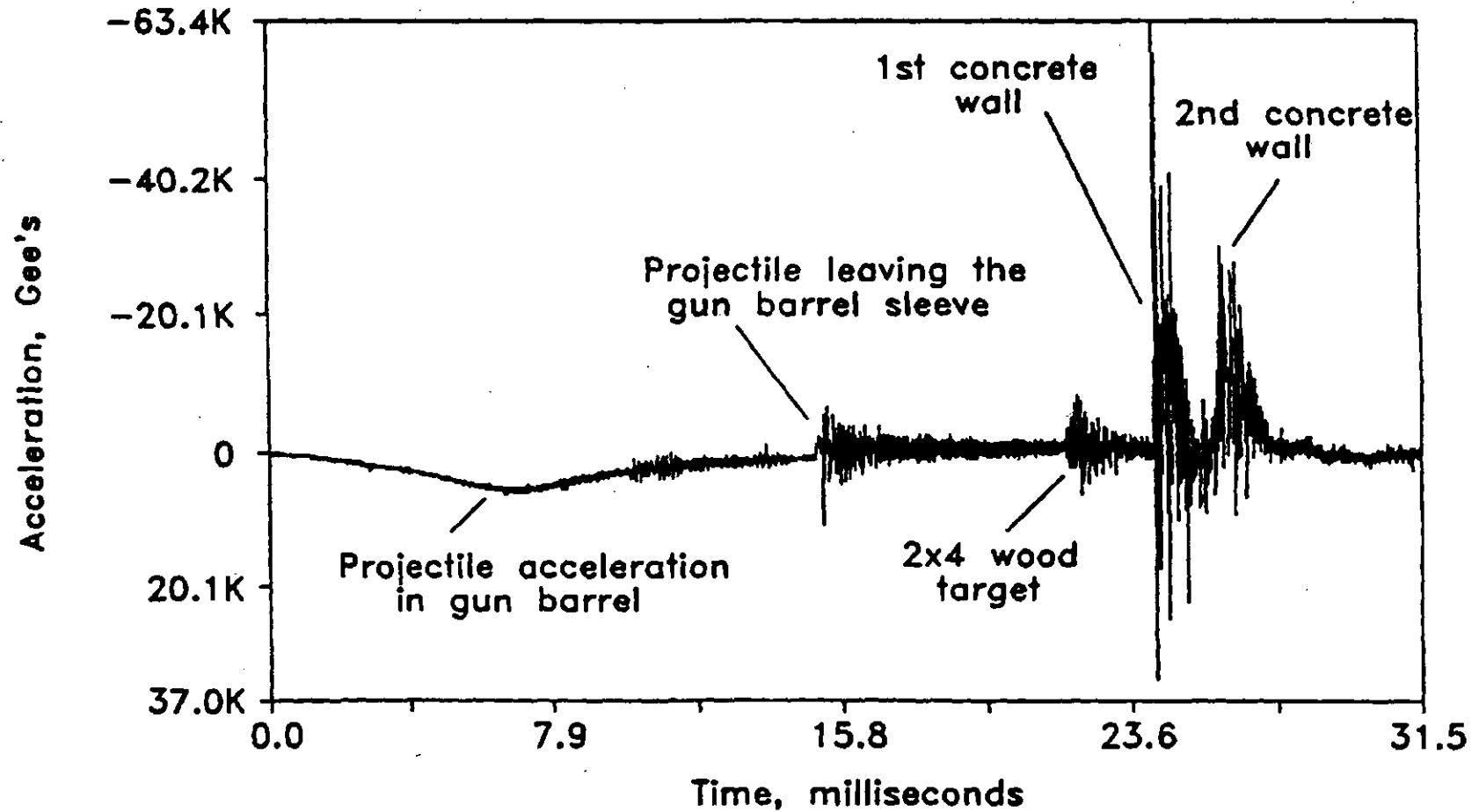


# RECORDER SPECIFICATIONS

|                            |                                |
|----------------------------|--------------------------------|
| Number of Channels .....   | 1                              |
| Bandwidth .....            | DC to 300 KHz*                 |
| Input .....                | Instrumentation Amplifier      |
| Filter .....               | 4 Pole Butterworth*            |
| Amplitude Resolution ..... | 8 Bits (256 digital steps)     |
| Storage Capacity .....     | 32K Bytes (32K x 8)*           |
| Sample Rate .....          | Up to 2.5 MHz*                 |
| Pre-trigger Storage .....  | 1762 Bytes                     |
| Triggers .....             | Switch Closure or 5 Volt Pulse |
| Supply Voltage .....       | 8 to 15 Volts                  |
| Supply Current             |                                |
| Standby .....              | 40 microamps (typical)         |
| Data Acquisition .....     | 60 milliamps (typical)         |
| Data Retention .....       | 40 microamps (typical)         |
| *Selectable at Factory     |                                |

# HOWITZER ACCELERATION DATA

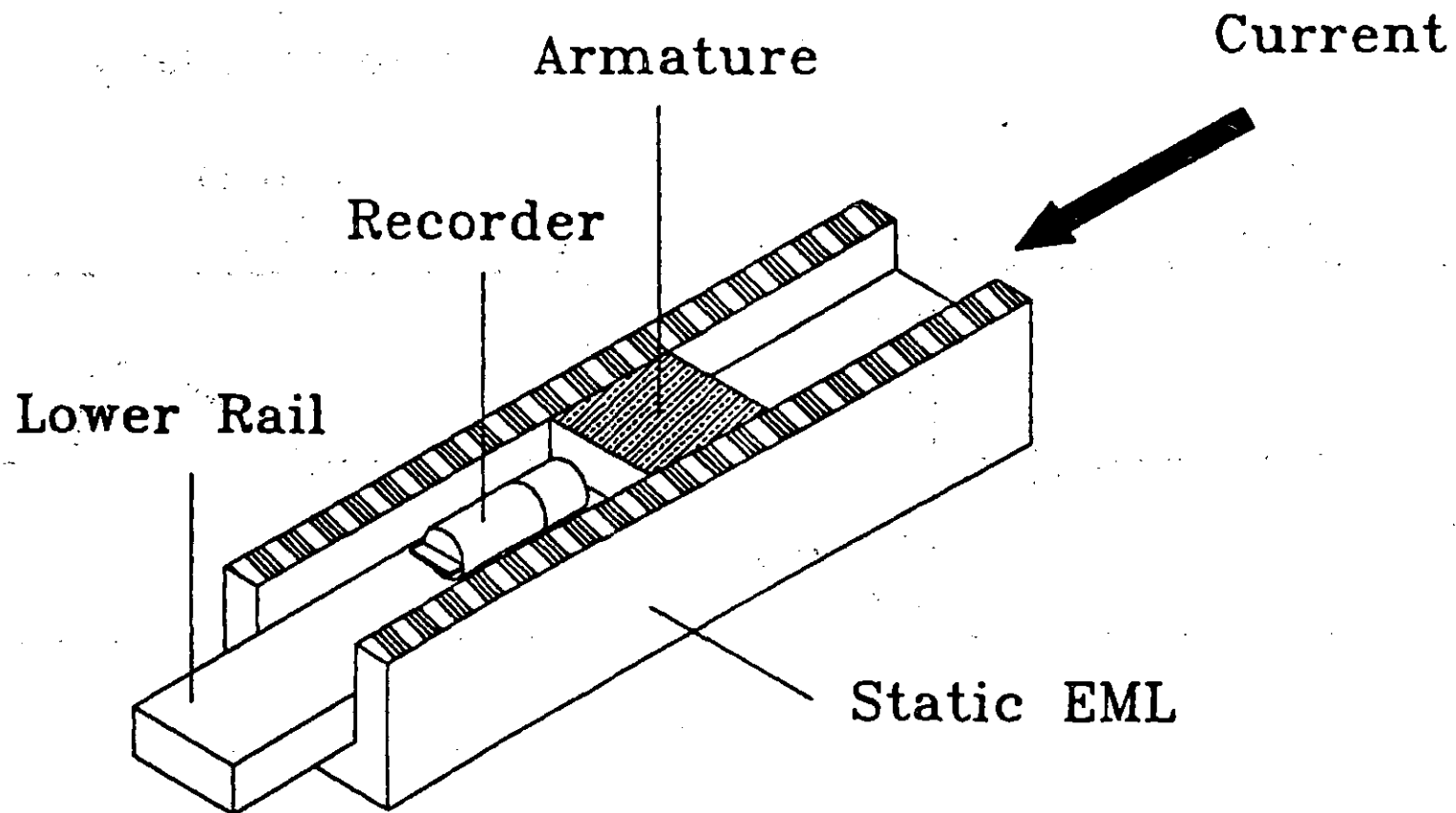
379



# STATIC EML SETUP

## *Transient Field Effects Analysis*

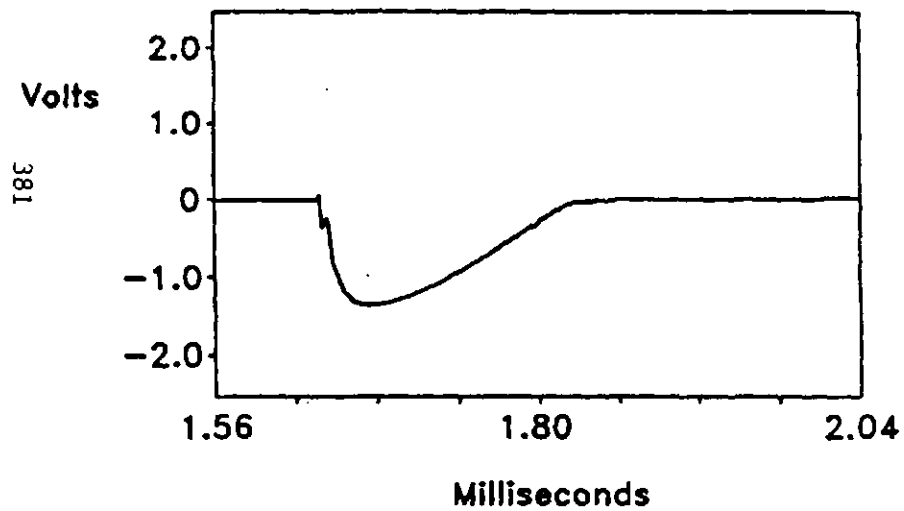
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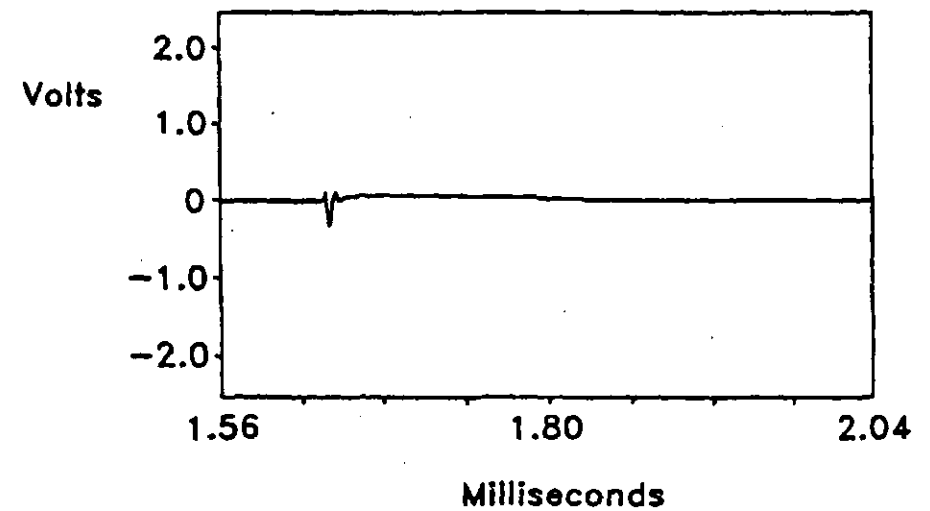
# EM INDUCED NOISE

## *With Respect to Circuit Board Orientation*

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"Perpendicular"



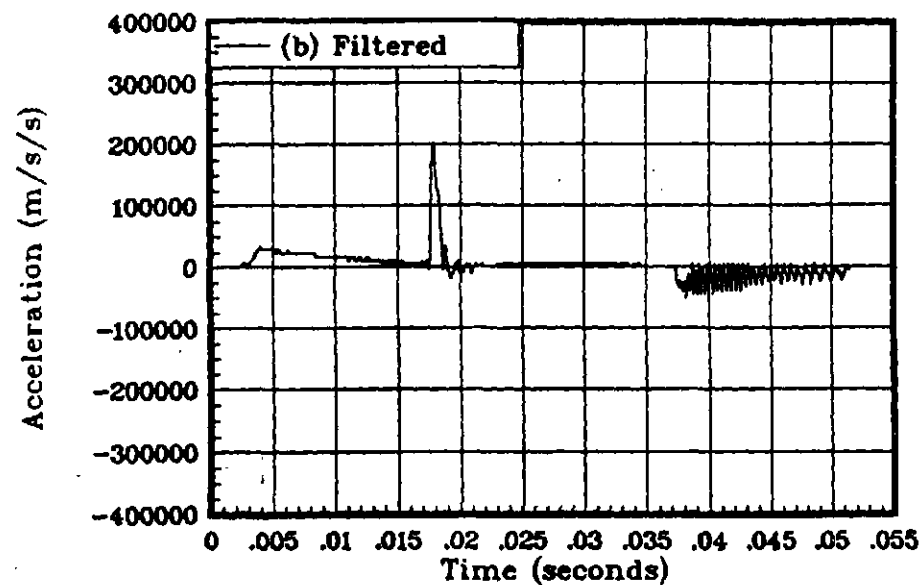
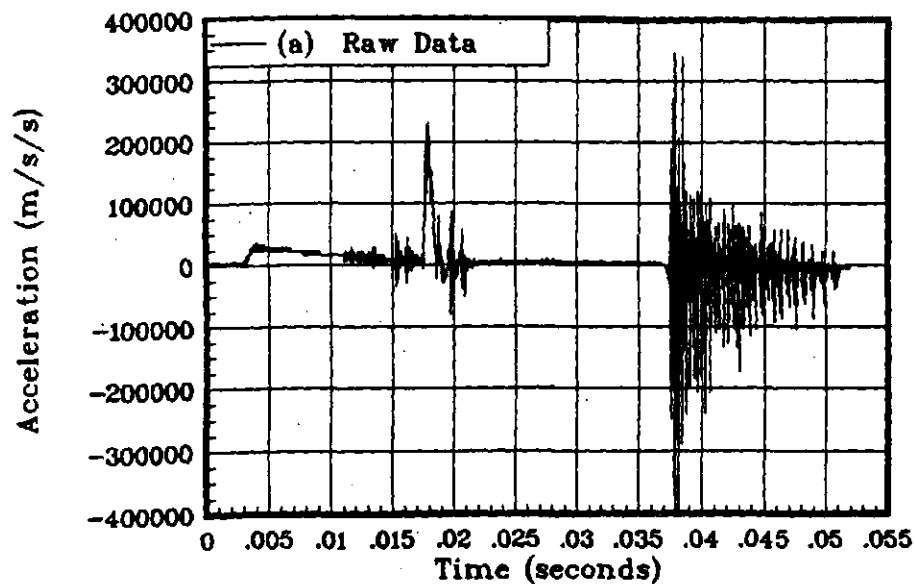
"Parallel"

# SUMMARY OF EML ACCELEROMETER TESTS

| <u>Test Conditions</u>       | <u>PKD</u> | <u>Boeing</u> | <u>IBID197</u> | <u>IBID235</u> |
|------------------------------|------------|---------------|----------------|----------------|
| Maximum current (kA)         | 550        | 150           | 821            | 941            |
| Distance traveled (m)        | <1.3       | <0.18         | >7             | >7             |
| Injection velocity (m/s)     | —          | 0             | 149            | 162            |
| EML velocity (m/s)           | <300       | —             | 264            | 360            |
| Injector acceleration (kgee) | 18         | N/A           | 3.5            | 3.5            |
| EML peak acceleration (kgee) | 12         | 15            | 20             | 28             |
| Projectile mass (kg)         | —          | —             | 1.17           | 1.15           |
| Kinetic energy (kJ)          | —          | —             | 48             | 74             |
| Bore size (mm)               | 50         | 25            | 51             | 51             |
| Armature type                | —          | —             | plasma         | plasma         |

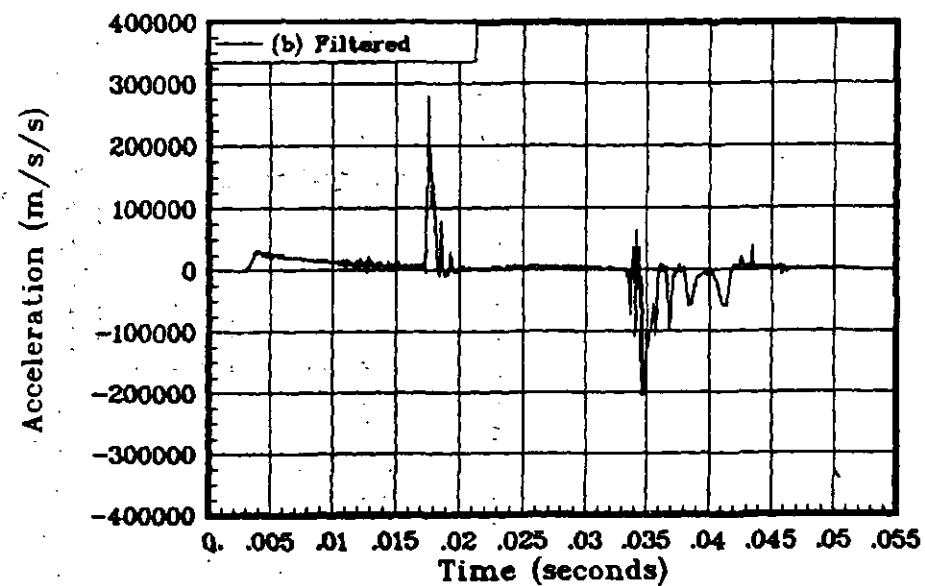
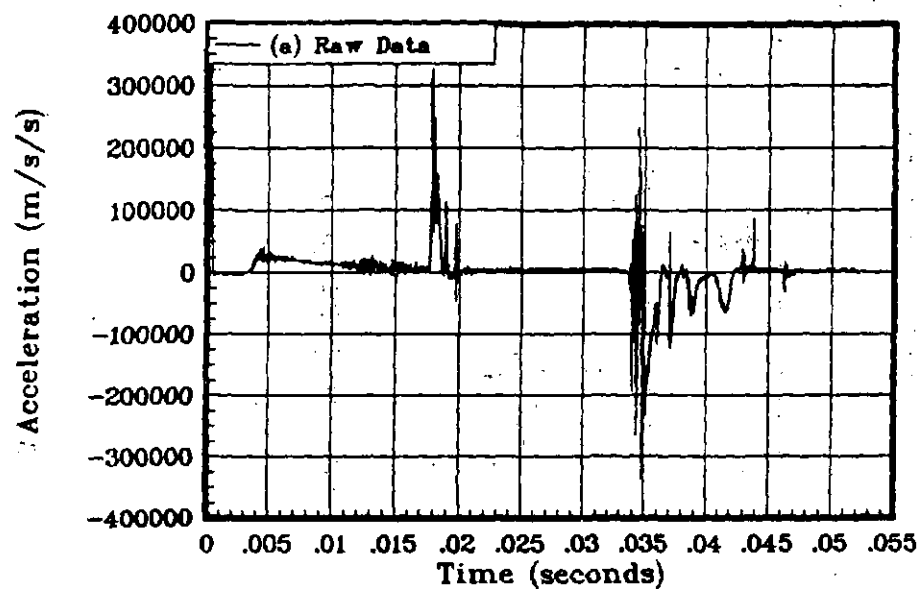
# IBID197 ACCELERATION RECORD

*(a) Raw Data and (b) Filtered Data (12 kHz)*



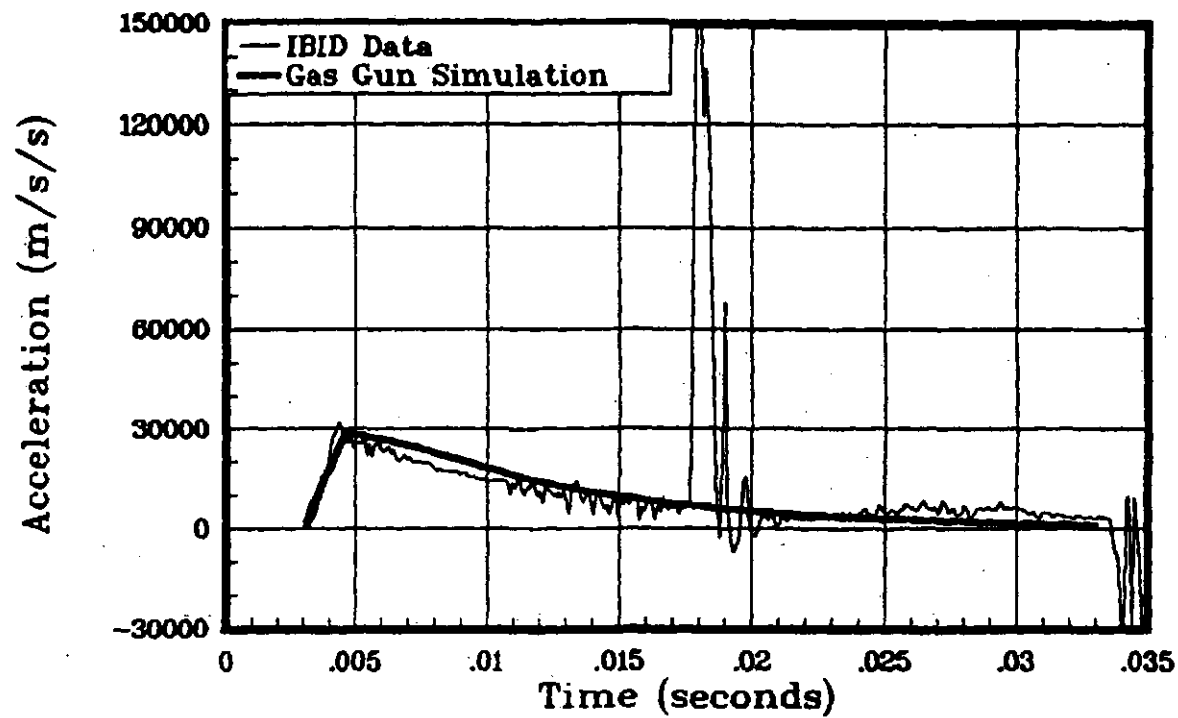
# IBID235 ACCELERATION RECORD

(a) *Raw Data* and (b) *Filtered Data (12 kHz)*





# COMPARISON OF IBID235 ACCELERATION WITH GAS GUN SIMULATION

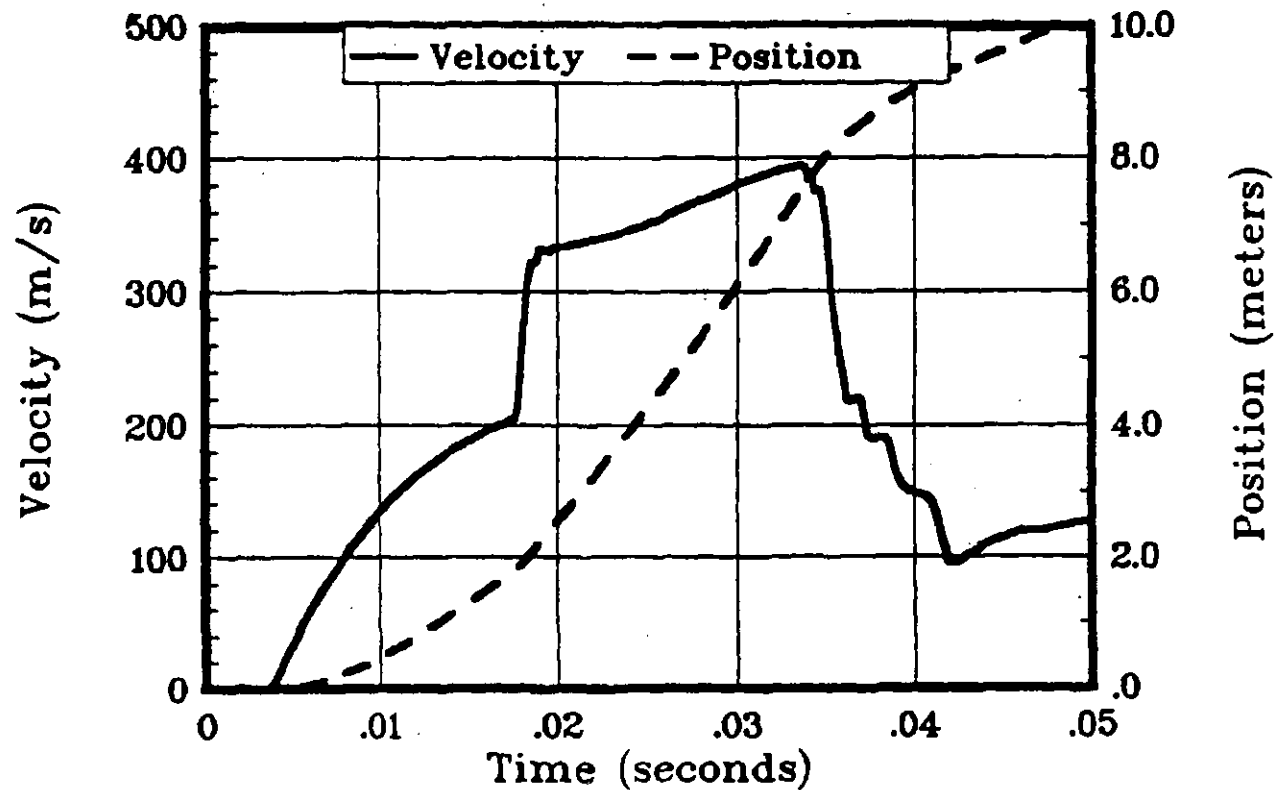


385

# VELOCITY AND POSITION VERSUS TIME

## OBTAINED VIA INTEGRATION OF IBID235 DATA

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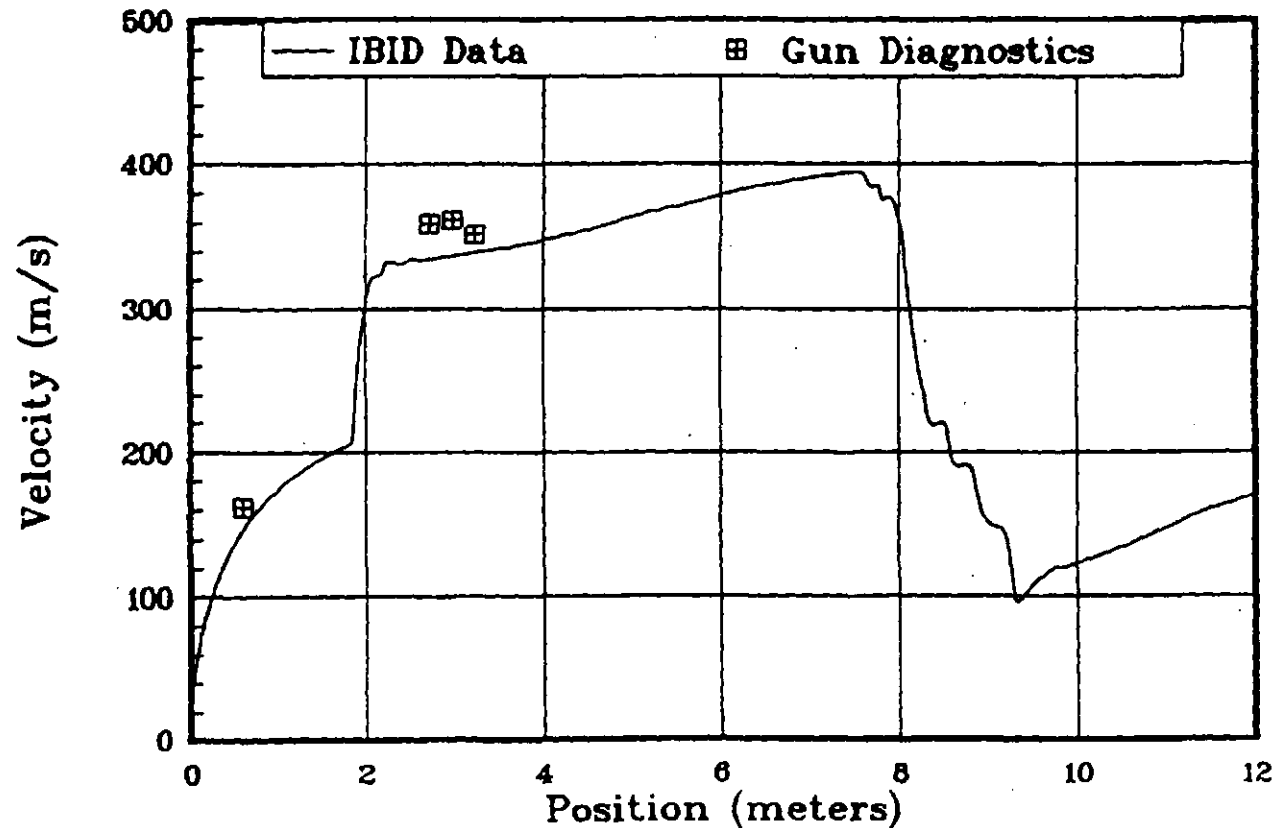
386

# COMPARISON OF VELOCITY MEASUREMENT TECHNIQUES

## IBID235

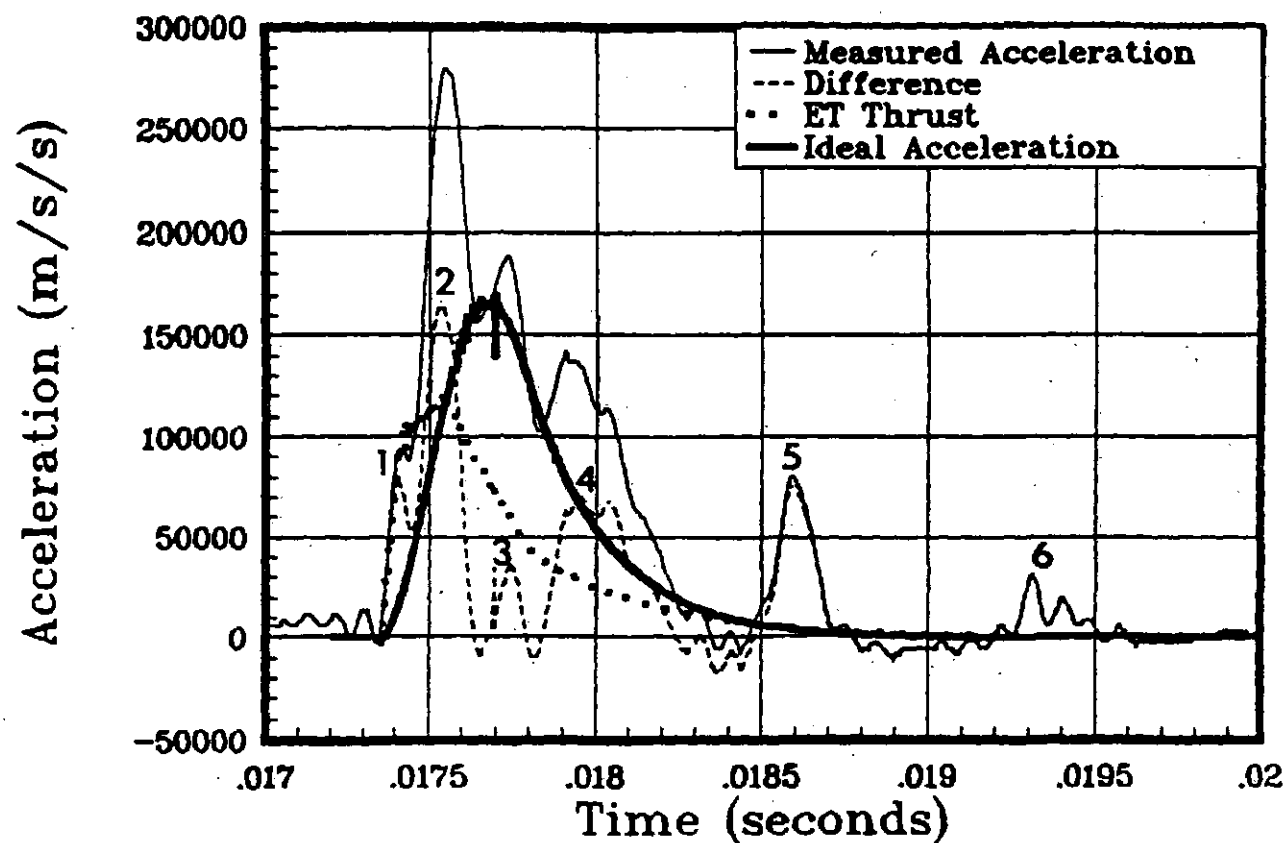
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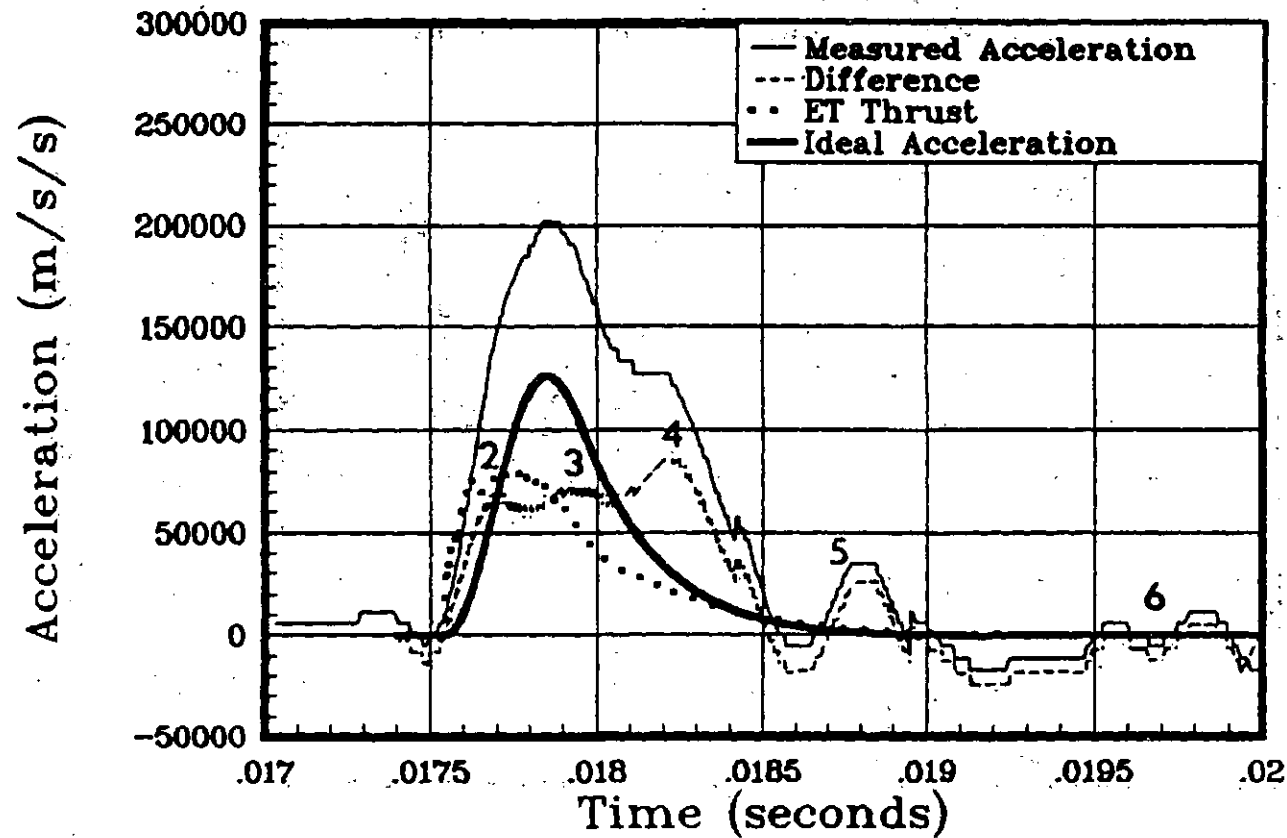
# COMPARISON OF MEASURED AND IDEAL ACCELERATION

## IBID235



# COMPARISON OF MEASURED AND IDEAL ACCELERATION

## IBID197

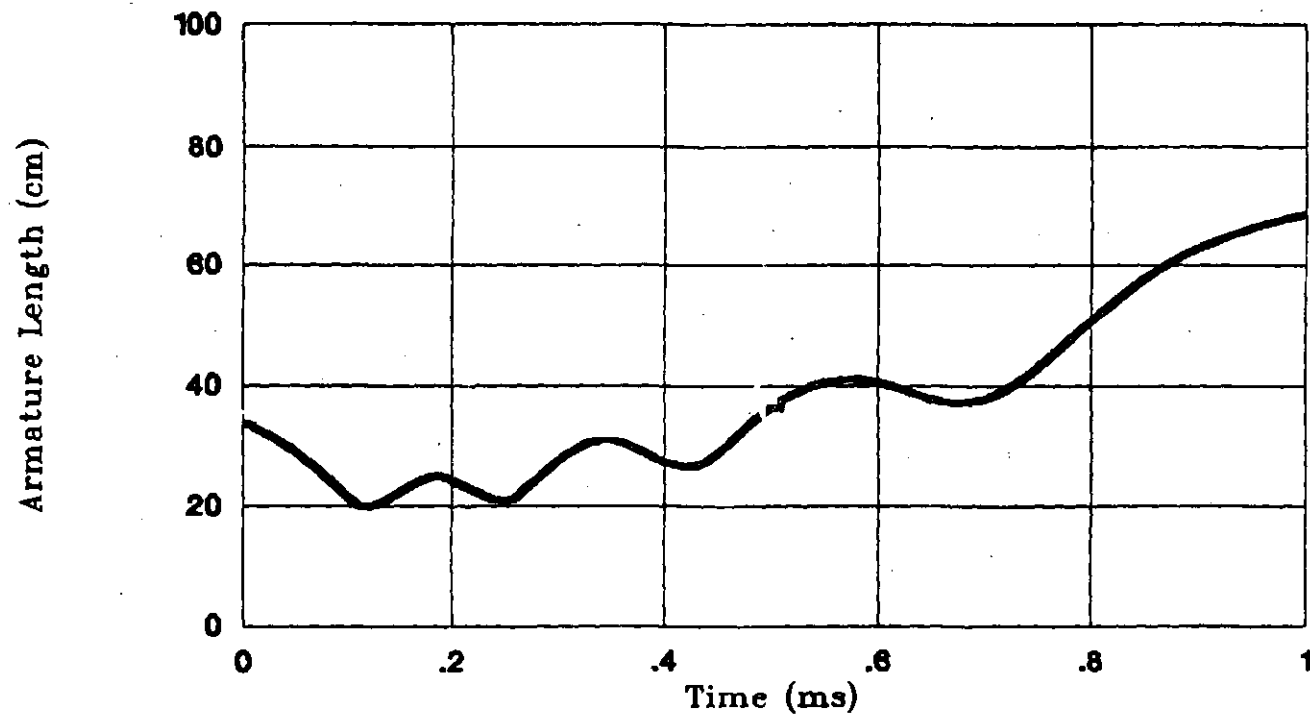


# THEORETICAL ARMATURE RESPONSE TO VARIABLE CURRENT

## *1-Dimensional, Transient Plasma Armature Model*

---

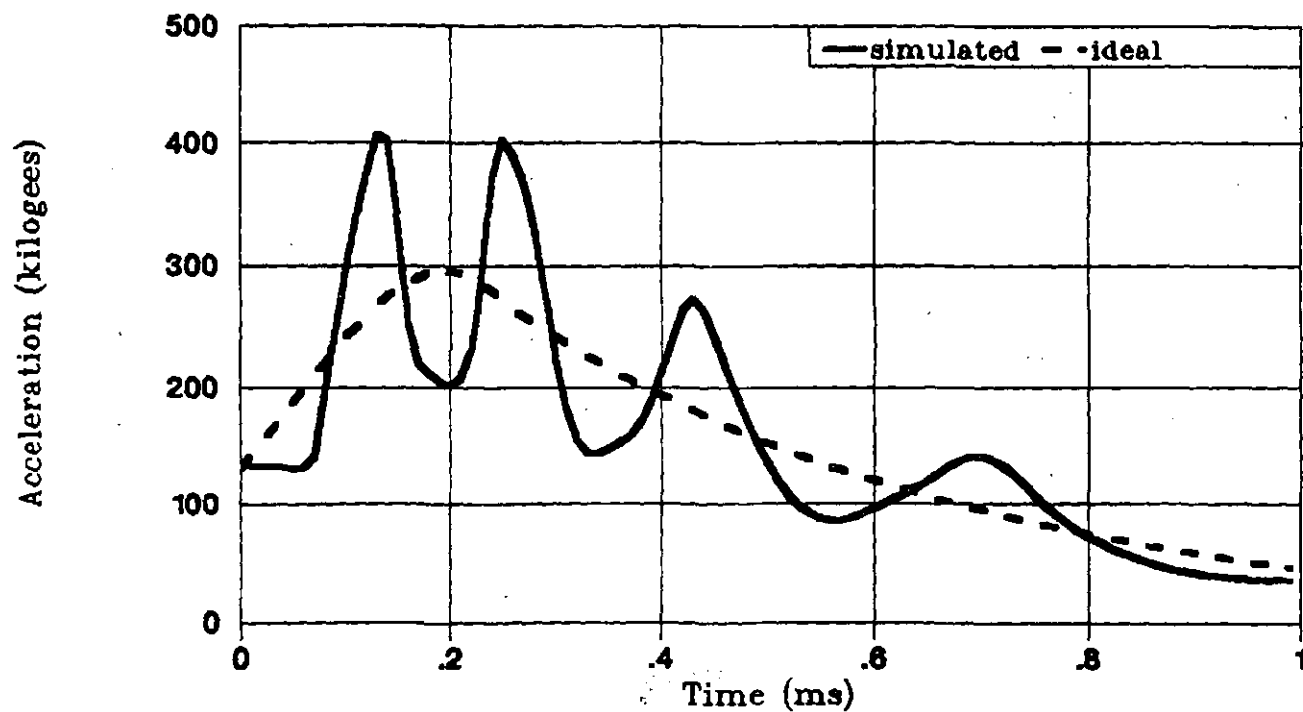
Armature Length



# THEORETICAL PROJECTILE ACCELERATION DUE TO VARIABLE CURRENT

## *1-Dimensional, Transient Plasma Armature Model*

---

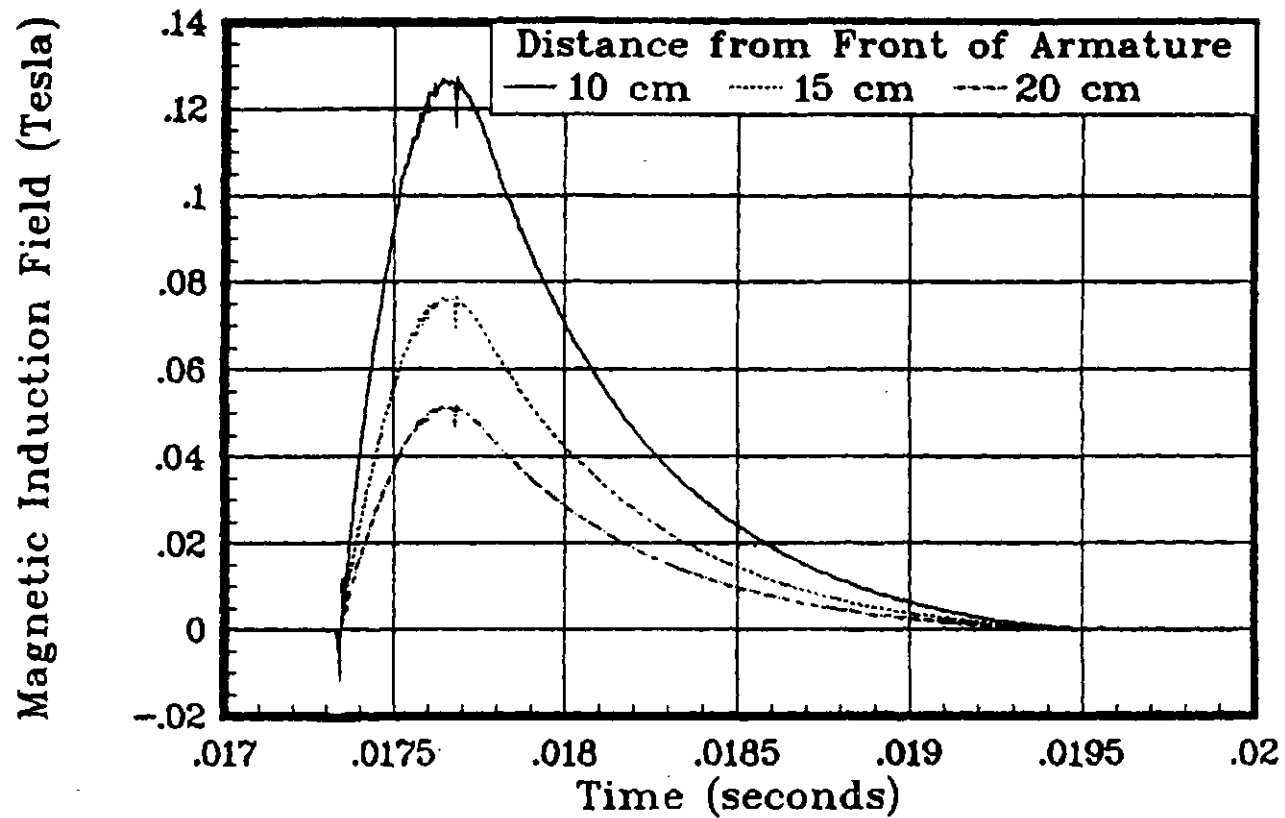


# PROJECTILE ENVIRONMENT

## CALCULATED MAGNETIC FIELD INTENSITY

*IBID235*

---

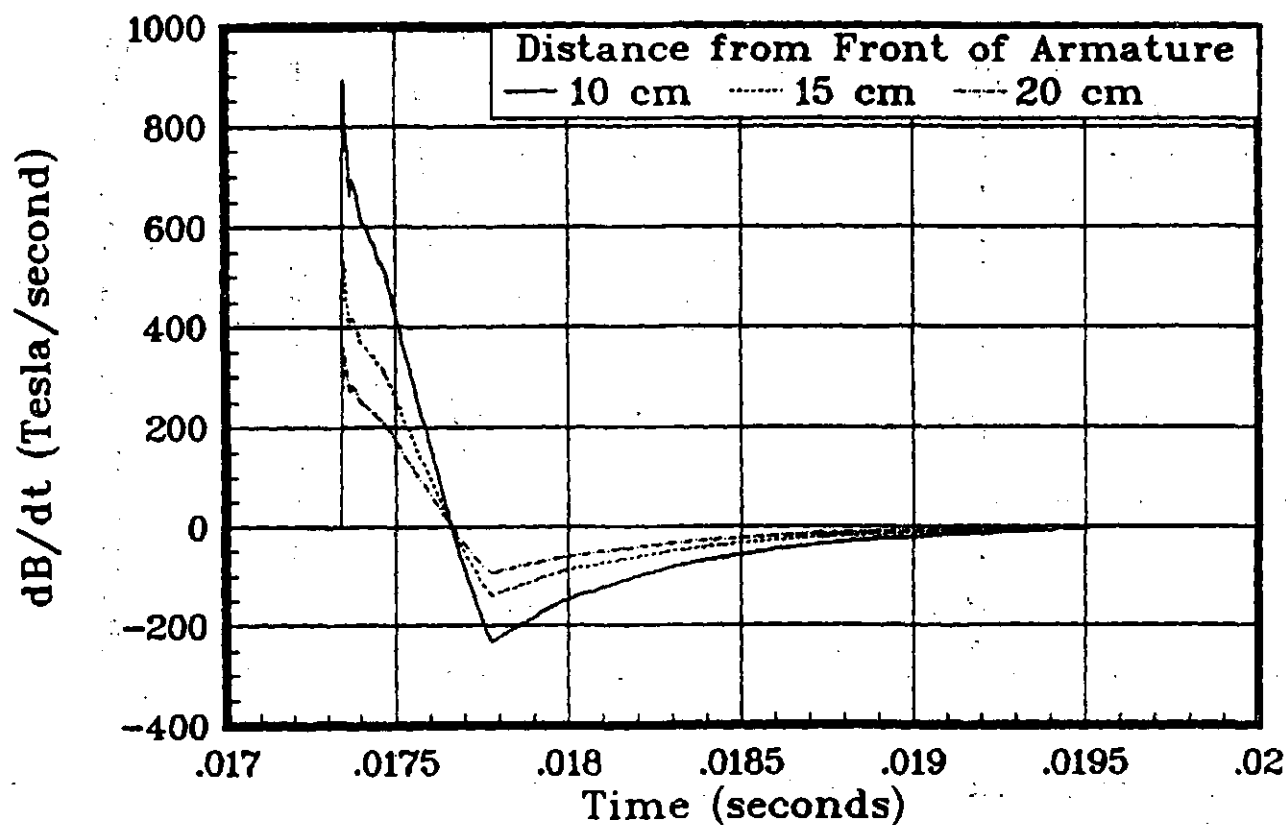




# PROJECTILE ENVIRONMENT

## CALCULATED TIME RATE OF CHANGE OF MAGNETIC FIELD INTENSITY

IBID235



# CONCLUSIONS

---

## SUMMARY

- TWO GOOD DATA SETS
- AGREEMENT WITH GAS GUN SIMULATION
- AGREEMENT WITH PROBE VELOCITY AND POSITION MEASUREMENTS
- POTENTIAL FOR STUDY OF ARMATURE DYNAMICS

## FUTURE PLANS

- NEAR TERM      MEASURE ACCELERATION AT CONSTANT CURRENT
- MID TERM      DEVELOP MORE ADVANCED PAYLOADS WHICH  
MEASURE OTHER IN-BORE PHENOMENA
- FAR TERM      DEMONSTRATE A HIGHLY INSTRUMENTED PACKAGE TO  
SIMULTANEOUSLY MEASURE AND RECORD MULTIPLE  
CRITICAL PARAMETERS RELATING TO SMART  
PROJECTILES

# SUGGESTED READING

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D.M. Littrell, K.A. Jamison, R.D. Hudson, M.J. Fernández, and S.A. Ager, "Measurement of Acceleration Using an Instrumented Railgun Projectile," Proceedings of the 3rd European EML Symposium on EML Technology, London England, April 16-18, 1991.

395 M.J. Fernandez, S.A. Ager, and R.D. Hudson, "In-Bore Instrumentation/Diagnostics for Large-Bore EMLs," IEEE Transactions on Magnetics, 27(1), pp. 185-188, January 1991.

J. Thoman, "Rail Gun Material Survey Summary and Launch Environment Simulator Description," 2nd Electromagnetic Launcher Association meeting, Pomona CA, July 1986.

J. Thompson, "Component Testing and Launch Environment Diagnostics," 3rd Electromagnetic Launcher Association meeting, Tamarron CO, March 1987.

R.G. Grzesik, D.E. Mitchell, J.H. Sebastian, I.W. Chin, and S.A. Kostakis, "E/M Launcher Vibration and Acceleration Data Analysis," IEEE Transactions on Magnetics, 27(1), pp. 147-151, January 1991.

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**APPENDIX A:**  
**FINAL AGENDAS**

**JANNAF Workshop on**

***Electrothermal-Chemical Modeling  
and Diagnostics***

**July 9-11, 1991**

***Ballistic Research Laboratory  
Aberdeen Proving Ground, MD***

**Workshop Chairman: Ms. Gloria P. Wren  
Workshop Co-Chairman: Dr. Arpad A. Juhasz**

# A G E N D A

Tuesday, July 9, 1991

8:30 Registration

8:45 Welcome  
Administrative Remarks

I. May  
G. Wren

## SESSION I: SERVICE USES OF ETC GUNS & PLASMAS Chairman: W. Morelli, EAPO

9:00 "National Electric Gun Reviews and Implications  
for the Army's ETC Gun Technology Program"

W. Oberle

9:30 "Electrothermal Gun Demonstration Program"

C. Dampier

10:15 "Electrothermal (ET) Gun Program"

S. Fowler

10:35 Break

10:50 "Plasma Discharge in the Electrothermal Gun"

J. Powell

11:15 "Diagnostics and Modeling of an Electrothermal  
Plasma Source Experiment (SIRENS)"

J. Gilligan  
O. Hankins

11:40 "Finite Element Analysis of Engineering  
Electromagnetics of ETC Guns"

R. Boggavarapu

12:05 Lunch

## SESSION II: PROPELLANTS Chairman: C. Dampier, NSSC

1:15 "Army Alternate ETC Propellant Program"

D. Downs

1:30 "Overview of Solid Propellant ETC Guns"

A. Juhasz

1:45 "Overview of Gel/Slurry Propellant"

A. Bracuti

2:15 Break

2:30 "Electrothermal-Chemical (ET-C) Alternate  
Propellant Systems Investigation and Study  
Effort"

H. McElroy

3:00 "What's Wrong with Thermochemical Codes  
Applied to ETC Systems?"

E. Freedman

3:30 "Assessing ETC Performance for  
Systems Integration"

L. Harris

4:00 Adjourn

Wednesday, July 10, 1991

**SESSION III: MIXING & CONTROL**  
Chairman: D. Downs, ARDEC

|       |                                                                                              |                     |
|-------|----------------------------------------------------------------------------------------------|---------------------|
| 8:00  | Administrative Remarks                                                                       | G. Wren             |
| 8:05  | "Electrothermal-Chemical Gun Program"                                                        | R. Woodfin          |
| 8:35  | "Diagnostics Development for the ETC Program"                                                | D. Sweeney          |
| 9:05  | "Development of an Upwind/Implicit Computational Model for the Advancement of Army ETC Guns" | S. Dash             |
| 9:40  | Break                                                                                        |                     |
| 9:55  | "Recent Advances in CAP <sub>tm</sub> Gun Modeling"                                          | D. Cook             |
| 10:25 | "30-MM ETC Ballistic Diagnostic Facility"                                                    | K. White            |
| 10:45 | "Numerical Simulation of the Interior Ballistic Processes in an ETC Gun"                     | K. Kuo<br>F. Cheung |
| 11:15 | Lunch                                                                                        |                     |

**SESSION IV: MIXING & CONTROL**  
Chairman: S. Vosen, SNLL

|       |                                                                         |               |
|-------|-------------------------------------------------------------------------|---------------|
| 12:15 | "Finite-Element Modeling of Electrothermal-Chemical Guns"               | N. Winsor     |
| 12:45 | "Special Diagnostics and Instrumentation"                               | R. Richardson |
| 1:15  | Break                                                                   |               |
| 1:30  | "First Principles Modeling of a DNA 60mm ETC Gun Design"                | CC. Hsiao     |
| 2:00  | "Physics of ETC Plasma-Fluid Interactions"                              | B. Kashiwa    |
| 2:30  | "Observations and Modeling of Fundamental Electrothermal Gun Phenomena" | H. Davis      |
| 3:00  | Adjourn                                                                 |               |
| 4:00  | Bus leaves from Sheraton Inn to the Inner Harbor                        |               |



Thursday, July 11, 1991

**SESSION V: LESSONS LEARNED FROM OTHER FIELDS**

Chairman: J. Gilligan, NC State U.

|       |                                                                                |             |
|-------|--------------------------------------------------------------------------------|-------------|
| 8:00  | "Electrothermal-Chemical Gun Modeling"                                         | D. King     |
| 8:30  | "Railgun Research Relevant to Electrothermal Guns"                             | J. Batteh   |
| 9:00  | "In-Bore Position and Velocity<br>Measurement Techniques"                      | R. Bartsch  |
| 9:30  | Break                                                                          |             |
| 9:45  | "In-Bore Acceleration Measurements with an<br>Instrumented Railgun Projectile" | D. Littrell |
| 10:15 | Group Discussion and Wrap-up                                                   | G. Wren     |
| 12:00 | Adjourn                                                                        |             |

**APPENDIX B:**  
**ATTENDEES**

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JANNAF Workshop on  
Electrothermal-Chemical Modeling and Diagnostics

July 9-11, 1991

Attendees

Dr. Robert Armstrong  
Sandia National Laboratories  
Energetic Materials Division, 8357  
Combustion Research Facility  
Livermore, CA 94551-0969  
(415) 294-2470

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

Dr. R. Richard Bartsch  
Los Alamos National Laboratory  
Mail Stop E526 (Group P-1)  
Los Alamos, NM 87545  
(505) 667-9977

Dr. Rao L. Boggavarapu  
General Dynamics Land Systems  
Division  
PO Box 2074  
Warren, MI 48090-2074  
(313) 825-5350

Dr. Mohamed Bourham  
Department of Nuclear Engineering  
Box 7909  
North Carolina State University  
Raleigh, NC 27695  
(919) 737-7662

Dr. Arthur Bracuti  
US Army Armament Research, and  
Development & Engineering Center  
ATTN: SMCAR-AEE  
Picatinny Arsenal, NJ 07806-5000  
(201) 724-5759

Mr. Henry Burden  
Ballistic Research Laboratory  
ATTN: SLCBR-TB  
Aberdeen Proving Ground, MD  
21005-5066  
(301) 278-4363

Mr. Donald Chiu  
US Army Armament Research, and  
Development & Engineering Center  
ATTN: SMCAR-AEE  
Picatinny Arsenal, NJ 07806-5000  
(201) 724-5759

Dr. David Cook  
FMC Corporation  
Naval Systems Division - M170  
4800 E. River Road  
Minneapolis, MN 55421-1498  
(612) 572-4744

CDR Craig Dampier  
Naval Sea Systems Command  
Dept. of the Navy  
CSEA 06 KR12  
Washington, DC 20362-5101  
(703) 602-2941

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

Dr. Harold Davis  
Los Alamos National Laboratory  
P-1, MS E526  
Los Alamos, NM 87545  
(505) 667-8373

Mr. James DeSpirito  
Ballistic Research Laboratory  
ATTN: SLCBR-IB-B  
Aberdeen Proving Ground, MD  
21005-5066  
(301) 278-6104

Mr. Thomas E. Doran  
Code G33  
Naval Surface Warfare Center  
Dalgren, VA 22448-5000  
(703) 663-8188

Dr. David S. Downs  
US Army Armament Research, and  
Development and Engineering Center  
ATTN: SMCAR-AEE-B, Bldg 382  
Picatinny Arsenal, NJ 07806-5000  
(201) 724-2219

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

Mr. Stuart Fowler  
Laser Radar Branch  
Optical Systems Dept.  
Teledyne Brown Engineering  
Cummings Research Park  
300 Sparkman Drive, NW  
PO Box 070007 / MS 19  
Huntsville, AL 35807-7007  
(205) 726-2576

Dr. Eli Freedman  
Eli Freedman & Associates  
2411 Diana Road  
Baltimore, MD 21209-1525  
(301) 484-0632

Dr. John Gilligan  
North Carolina State University  
Department of Nuclear Engineering  
Box 7909  
Raleigh, NC 27695  
(919) 737-2301

Dr. Paul S. Gough  
Paul Gough Associates, Inc.  
1048 South Street  
Portsmouth, NH 03801  
(603) 436-5172

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

Dr. Orlando Hankins  
Department of Nuclear Engineering  
Box 7909  
North Carolina State University  
Raleigh, NC 27695  
(919) 737-2301

Dr. Lee E. Harris  
US Army Armament Research, and  
Development and Engineering Center  
ATTN: SMCAR-AEE-BR, Bldg 382  
Picatinny Arsenal, NJ 07806-5000  
(201) 724-4535

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

Mr. CC. Hsiao  
Science Applications Int'l Corp.  
10210 Campus Point Drive  
San Diego, CA 92121  
(619) 458-5058

Dr. Arpad A. Juhasz  
Ballistic Research Laboratory  
ATTN: SLCBR-IB-B  
Aberdeen Proving Ground, MD  
21005-5066  
(301) 278-6158

Mr. Gary Katulka  
Ballistic Research Laboratory  
ATTN: SLCBR-IB-B  
Aberdeen Proving Ground, MD  
21005-5066  
(301) 278-6184

Dr. Dennis Keefer  
University of Tennessee Space  
Institute  
Center for Laser Applications, MS-14  
Tullahoma, TN 37388-8897  
(615) 455-0631

Mr. John Knapton  
Ballistic Research Laboratory  
ATTN: SLCBR-IB-B  
Aberdeen Proving Ground, MD  
21005-5066  
(301) 278-6170

CPT Kevin Nekula  
Ballistic Research Laboratory  
ATTN: SLCBR-IB-B  
Aberdeen Proving Ground, MD  
21005-5066  
(301) 278-6856

Professor Kenneth K. Kuo  
The Pennsylvania State University  
Propulsion Engr Rsch Ctr/Mech Engr  
Dept  
140 Research Building "E"  
University Park, PA 16802  
(814) 863-6270

Mr. Donald M. Littrell  
WL/MNSH  
Electromagnetic Launcher Tech Branch  
Hypervelocity Research Complex  
Wright Laboratory//Armament  
Directorate  
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