ELECTROTHERMAL-CHEMICAL MODELING
AND DIAGNOSTICS WORKSHOP,
VOLUME 2

GLORIA P. WREN
SHARON L. RICHARDSON

OCTOBER 1991

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND
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Electrothermal-Chemical Modeling and Diagnostics Workshop, Vol. 2

Gloria P. Wren and Sharon L. Richardson

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

This report contains the abstracts and viewgraphs of the papers presented at the JANNAF workshop on Electrothermal-Chemical Modeling and Diagnostics, 9–11 July 1991, held at the U.S. Army Ballistic Research Laboratory.
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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.
Electrothermal-Chemical Gun Program

Dr. Ronald L. Woodfin
Advanced Projects Division V
(505) 844-3111  AV 244-3111
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:
* 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
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
Integrated experimental & analytical effort

Produces & verifies detailed physical models

Supports Army modeling of interior ballistics

Develops new diagnostics for mixing & combustion
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
ETC Gun

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

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

SIMPLIFIED GUN DESIGN

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 cm$^3$
  Arc Length 4.3 cm
  Capillary Inside Dia. 0.58 cm
  Max. Pressure 100 kpsi
Effect of Capillary Efflux on Accumulator Mixing

\[ \left( \frac{dM}{dt} \right)_{\text{mixing}} \]

\[ \left( \frac{dM}{dt} \right)_{\text{cap}} \]
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 nitratred polyethylene materials (PEVN) for liners
- Demonstrated enhanced arc induced ablation with PEVN liners

![Graph of arc power dissipated over time (μs)]

![Graph of accumulator chamber pressure over time (ms)]
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⁺, C²⁺, H, H⁺
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:
  - 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

• 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

\[
\frac{\partial f}{\partial t} + u \frac{\partial f}{\partial x} = 0
\]
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 (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**

<table>
<thead>
<tr>
<th>Process/Location</th>
<th>Diagnostic Technique</th>
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<tbody>
<tr>
<td>Gas Generation/</td>
<td>Photography and image processing</td>
</tr>
<tr>
<td>Mixing Chamber</td>
<td>• Develop image processing techniques, similar to those</td>
</tr>
<tr>
<td></td>
<td>developed for liquid propellants, to quantify images of</td>
</tr>
<tr>
<td></td>
<td>full flow-field mixing</td>
</tr>
<tr>
<td></td>
<td>• Vary energy and mixing fluid.</td>
</tr>
<tr>
<td></td>
<td>• Determine effect of energy and fluid on evolution of</td>
</tr>
<tr>
<td></td>
<td>mixing region.</td>
</tr>
<tr>
<td>Plasma Formation/</td>
<td>n.a.</td>
</tr>
<tr>
<td>Plasma Cartridge</td>
<td>(explosive charge)</td>
</tr>
</tbody>
</table>
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 cartridges release 200 Joules in 1 - 2 milliseconds

Discharge of a 180 mg pressure cartridge into a 10 cc volume
10 E VS Photographs of Burning LP 1846
Velocity of the Gas/Liquid Interface Profile
 Relevant gas generation mechanisms and plasma behavior will be studied at medium pressure

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<thead>
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<th>Process/Location</th>
<th>Diagnostic Technique</th>
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<td>Gas Generation/Mixing Chamber</td>
<td>Photography/image processing</td>
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<tr>
<td></td>
<td>- Characterize mixing over a range of conditions.</td>
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<tr>
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<td>(Maximum pressure overlaps with high pressure studies)</td>
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<tr>
<td>Plasma Formation/Plasma Cartridge</td>
<td>Time resolved emission</td>
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<tr>
<td></td>
<td>- Plasma stability</td>
</tr>
<tr>
<td></td>
<td>Spectrally resolved emission</td>
</tr>
<tr>
<td></td>
<td>- Plasma temperature</td>
</tr>
<tr>
<td></td>
<td>- Electron density</td>
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<tr>
<td></td>
<td>- Sheath temperature</td>
</tr>
<tr>
<td></td>
<td>- Identify Species</td>
</tr>
<tr>
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<td>Heat transfer probes</td>
</tr>
<tr>
<td></td>
<td>- Radiative heat transfer</td>
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<tr>
<td></td>
<td>- Conductive heat transfer</td>
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A Medium Pressure Apparatus will be used to study plasma characteristics and flow-field mixing

Schematic of medium pressure apparatus

Electrodes

Transparent Accumulator Chamber

Fiber Optic Probe

Pressure Transducers

10 cm
The transparent chamber with corrective optics will allow for Schlieren photographic measurements.

End View of Chamber:

Transparent Chamber

Light Ray Paths

Corrective Optics
Fiber-optic probes will provide spectral information from the plasma cartridge and in high pressure experiments.

Fiber Optic Probes have been designed and used to measure light emission from the Sandia Liquid Propellant Injectors 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.

- Temp
  - $T \sim 4000\text{K}$
  - $P \sim 5\text{ atm}$

- Convective flow of gas species

- Ablated products

- Thermal boundary layer $\sim 100\ \mu\text{m}$

- Test surface

- Full gas-phase and surface chemistry (CHEMKIN)
Chemical ablation is initiated by seeding the shock tube

\[ \text{N}_2 \text{O} \rightarrow \text{N}_2 + \text{O} \]

The O-atoms attack the surface and generate OH

\[ \text{O} + (-\text{CH}_2-)_n \rightarrow \text{OH} + (-\text{CHCH}_2-)_n \]

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.
ETC Combustion is being studied using Laser - Plasma Ablation

- Spectroscopy
- Imaging
Laser-induced plasmas help discern various ETC processes
Variations in Test Conditions

- Plasma power density ranges from $10^8$ to $10^{11}$ W/cm$^3$
- 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

Polyethylene

PEVN
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 ($\geq 10^{10} \text{W/cm}^3$)
- 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

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
  - ADAPTATION 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

Model/Diagnostics

Goals

- Support cartridge design
- Fundamental understanding of ETC process

Freedman Assoc
  - Thermochemistry

Sandia Nat Lab
  - Diagnostics
  - Improved capillaries
  - Fundamental submodels

BRL
  - 30mm diagnostics
  - Plasma/WF diagnostics
  - Engineering models
    - Lumped parameter
    - Plasma capillary
    - Inverse
    - Power system
  - Applications/Analysis

SAIC
  - Model development
    - 2D, fundamental

PCRL
  - Power Model
    - System studies
    - End-to-end

NC State
  - Model development
    - Plasma/WF physics

Gun Propulsion Technology
  - Gun test data
  - Diagnostics
  - Contractor models

PGA
  - Model development
    - Lumped parameter
    - 1D

ETC Propulsion

mod/diag.may91
<table>
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<tr>
<th>FEATURE</th>
<th>ADVANTAGE</th>
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<td>1D/2D/AXI/3D RUN OPTIONS</td>
<td>CAN DO FAST PRELIMINARY DESIGN STUDIES (1D) AND DETAILED SIMULATION (2D/AXI/3D) IN SINGLE CODE</td>
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<td>FINITE-VOLUME IMPLICIT CONSERVATIVE FORMULATION</td>
<td>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</td>
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<td>ROE/TVD UPWIND NUMERICS</td>
<td>ROE IS REIMANN BASED DIFFERENCING FOR ACCURATE CONVECTIVE/WAVE TRACKING; TVD IS HIGHER-ORDER EXTENSION; NO ARTIFICIAL DISSIPATION REQUIRED FOR STABILITY</td>
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<td>BLOCK MATRIX INVERSION WITH INNER NEWTON ITERATION</td>
<td>ROBUST INVERSION PROCEDURE PERMITS TAKING LARGE TIME-STEP; INNER ITERATIONS PERMITS ELIMINATING ALL FACTORIZATION/LINEARIZATION ERRORS WITHIN STEP</td>
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<td>CHEMICAL SPECIES ARE PART OF COUPLED EQUATION SET FOR ACCURACY/ROBUSTNESS; CHEMICAL SOURCE TERMS TREATED FULLY-IMPLICITLY TO ELIMINATE STIFFNESS</td>
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<tr>
<td>STRONGLY-COUPLED, FULLY-IMPLICIT TURBULENCE MODELS</td>
<td>TURBULENCE MODEL EQUATIONS ARE PART OF COUPLED EQUATION SET FOR ACCURACY/ROBUSTNESS; TURBULENCE SOURCE TERMS TREATED FULLY-IMPLICITLY TO ELIMINATE STIFFNESS</td>
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<tr>
<td>IMPLICIT/UPWIND DISPERSED PHASE SOLVER</td>
<td>PARTICULATE EQUATIONS SOLVER ON SAME GRID AS FLUID PHASE USING SAME IMPLICIT/UPWIND NUMERICS; STRONG FLUID/PARTICLE COUPLING AND IMPLICIT SOURCE TERM TREATMENT</td>
</tr>
<tr>
<td>DYNAMIC GRID, SOLUTION ADAPTIVE MODULE</td>
<td>GRID MOVES/DEFORMS IN ACCORDANCE WITH BOUNDARY MOTION (PROJECTILE) AND REDISTRIBUTES USING NASA/AMES SAGE MODULE</td>
</tr>
</tbody>
</table>
EVOLUTION OF METHODOLOGY IN CRAFT CODE


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

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

\[ \frac{\partial}{\partial t} \iiint QdV + \iiint (E_{1_{-1/2}} - E_{1_{-1/2}}) d\eta d\zeta \]

\[ + \iiint (F_{1_{-1/2}} - F_{1_{-1/2}}) d\xi d\zeta + \iiint (G_{k_{-1/2}} - G_{k_{-1/2}}) d\xi d\eta \]

\[ = \frac{1}{Re} \iiint (R_{1_{+1/2}} - R_{1_{-1/2}}) d\eta d\zeta + \iiint (S_{1_{+1/2}} - S_{1_{-1/2}}) d\xi d\zeta \]

\[ + \frac{1}{Re} \iiint (T_{k_{+1/2}} - T_{k_{-1/2}}) d\xi d\eta + \iiint DdV \]

\[
Q = \begin{pmatrix}
\rho \\
\rho u \\
\rho v \\
\rho w \\
\rho e \\
\rho_1 \\
\rho_2 \\
\rho_{a-1} \\
\rho k \\
\rho e
\end{pmatrix} \quad E = \begin{pmatrix}
\rho \dot{U} \\
\rho U + \rho x P \\
\rho \dot{V} + \rho y P \\
\rho \dot{W} + \rho z P \\
(e + P) \dot{U} \\
\rho_1 \dot{U} \\
\rho_2 \dot{U} \\
\rho_{a-1} \dot{U} \\
\rho k \dot{U} \\
\rho e \dot{U}
\end{pmatrix} \quad D = \begin{pmatrix}
0 \\
0 \\
0 \\
0 \\
\omega_1 \\
\omega_2 \\
\vdots \\
\omega_{a-1} \\
\omega_k \\
\frac{e}{k(CP - C_P e)}
\end{pmatrix} \quad R = \begin{pmatrix}
0 \\
\mu(l_x p_{ix} + m_y p_{iy} + n_z p_{iz}) \\
\mu(l_x p_{ix} + m_y p_{iy} + n_z p_{iz}) \\
\mu(l_x p_{ix} + m_y p_{iy} + n_z p_{iz}) \\
\mu(l_x p_{ix} + m_y p_{iy} + n_z p_{iz}) \\
\mu(l_x p_{ix} + m_y p_{iy} + n_z p_{iz})
\end{pmatrix}
**DYNAMIC GRID COMPUTATIONS**

<table>
<thead>
<tr>
<th>EQUATIONS</th>
<th>Term I</th>
<th>Term II</th>
<th>Term III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Term I: PRIMARY CONSERVED VARIABLES</td>
<td>PRIMARY CONSERVED VARIABLES</td>
<td>PRIMARY CONSERVED VARIABLES</td>
<td>PRIMARY CONSERVED VARIABLES</td>
</tr>
<tr>
<td>Term II: FLUX TERMS</td>
<td>FLUX TERMS</td>
<td>FLUX TERMS</td>
<td>FLUX TERMS</td>
</tr>
<tr>
<td>Term III: SOURCE TERMS</td>
<td>SOURCE TERMS</td>
<td>SOURCE TERMS</td>
<td>SOURCE TERMS</td>
</tr>
<tr>
<td>V(t): TIME VARYING VOLUME</td>
<td>TIME VARYING VOLUME</td>
<td>TIME VARYING VOLUME</td>
<td>TIME VARYING VOLUME</td>
</tr>
</tbody>
</table>

**METHODOLOGY**

TREAT GRID AS PURELY GEOMETRIC QUANTITY, i.e., DEFINITION OF CONTRAVARIANT VELOCITY UNCHANGED

EVALUATE FLUX TERM BY ASSUMING GRID IS HELD CONSTANT AT TIME-AVERAGED VALUE

EVALUATE SOURCE TERM FOR THE GRID AT THE NEW TIME LEVEL, THUS GIVING:

\[
\left(\frac{Q^{n+1} - Q^n}{\Delta t}\right) V^{n+1} + Q^n \left(\frac{V^{n+1} - V^n}{\Delta t}\right) + F_n^{n+1} \tilde{S} \Delta t = \rho^n V^{n+1}
\]

\( F_n = \vec{n} \cdot \vec{F} \), and \( \tilde{S} \) is the time averaged metric

**NUMERICS**

- SPECIFY GRID MOVEMENT AS A FUNCTION OF TIME
- EVALUATE \( F_n \) AS A THIRD-ORDER UPWIND BASE FLUX
- SOLVE LINEARIZED IMPLICIT OPERATOR USING ADI PROCEDURE
- USE NEWTON ITERATION FOR HIGHER ORDER ACCURACY IN TIME
SOLUTION ADAPTIVE GRID GENERATION

- NASA/AMES RESEARCH CENTER SAGE 2D/3D CODE

- 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 PROPORTIONAL TO LOCAL FLOW GRADIENT AND FINDING EQUILIBRIUM (REDISTRIBUTED) POSITION OF THE RESULTING SYSTEM OF GRID POINTS

- USER-DEFINED WEIGHTED COMBINATION OF ADAPTATION VARIABLES

- CURRENTLY SAGE BEING OPTIMIZED FOR ETC PROBLEMS TO YIELD "BEST" COMBINATION OF ORTHOGONALITY, SMOOTHNESS AND CLUSTERING
TRANSIENT UNDEREXPANDED JET INJECTION INTO MIXING CHAMBER
INITIAL PRESSURE RATIO = 5
JET INTO CHAMBER WITH MOVING WALLS
PRESSURE SNAPSHOTs
## Features of the Particle-Cloud Solver

<table>
<thead>
<tr>
<th>Features</th>
<th>Particle Cloud Solver</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Equations</strong></td>
<td>• 1D/2D/3D time marching particle-cloud equations</td>
</tr>
<tr>
<td></td>
<td>• Fully coupled particle density, velocity, and temperature equations</td>
</tr>
<tr>
<td></td>
<td>• Drag terms modeled for non-equilibrium particle interactions</td>
</tr>
<tr>
<td></td>
<td>• Drag relations of Hermsef and Henderson available</td>
</tr>
<tr>
<td></td>
<td>• Phase change of particles incorporated</td>
</tr>
<tr>
<td><strong>Numerics</strong></td>
<td>• Limiting particle streamline captured as a discontinuity in the particle-cloud density</td>
</tr>
<tr>
<td></td>
<td>• Roe TVD upwind algorithm fully consistent with gas phase numerics</td>
</tr>
<tr>
<td></td>
<td>• Implicit treatment of particle source and flux terms</td>
</tr>
<tr>
<td></td>
<td>• ADI block inversion</td>
</tr>
<tr>
<td></td>
<td>• Time accurate/time asymptotic numerics</td>
</tr>
<tr>
<td></td>
<td>• Newton iteration to remove approximate factorization errors</td>
</tr>
<tr>
<td><strong>Boundary Conditions</strong></td>
<td>• Wall with particles sticking</td>
</tr>
<tr>
<td></td>
<td>• Wall with particles slipping</td>
</tr>
<tr>
<td></td>
<td>• Inflow</td>
</tr>
<tr>
<td></td>
<td>• Outflow</td>
</tr>
</tbody>
</table>
6μm Finite-Duration Transverse Particle Injection: Density Contours of Particle Packet at Four Time Intervals
MULTI-PHASE PERPENDICULAR JET INJECTION
PARAMETRIC VARIATION OF PARTICLE-SIZE

GAS FLOW

M = 2
P = 1 atm
T = 500°K

50% MASS LOADING OF PARTICLES IN JET

25μ, 5μ, 2.2μ PARTICLES RESPECTIVELY

GAS/PARTICLE INJECTION

M = 1
P = 2 atm
T = 1000°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-COUPLLED 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
   - HOMOGENEOUS vs NON-HOMOGENEOUS 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
- 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


ALTERNATIVE RIEMANN SOLVERS


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
\[ \rho = V^{-\gamma} \]

SAIC Science Applications International Corporation
2D Greenfarm Simulation

- 120mm

- Experimental data exhibits pressure waves
PRESSURE VS X AT 0.76 MS

TEMPERATURE VS X AT 0.76 MS
BASE PRESSURE VS TIME

TIME (MS)

PRESS (PSI)
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™ 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\textsuperscript{tm} Gun Modeling

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\textsuperscript{tm} 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.
30-mm DNA SHOT 2
30-mm 2-D CALCULATIONS

Time (SEC) *10^-4

Pressure (KPSI)
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.
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

INJECTOR  PROPELLANT  PROJECTILE
CAP 1-D PRESSURE DISTRIBUTION

TIME = 1.65ms  
TRAVEL = 11.61cm
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.
60-mm DNA SHOT #1

PRESSURE (psi)

TIME (msec)

SOLID LINE - DATA
DASHED LINE - CALCULATION
CAP 1-D PRESSURE DISTRIBUTION

TIME = 1.15 ms
TRAVEL = 7.06 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 on/off 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.
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.
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
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.
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.
Scaling: \((30/120)^3 = 1/64\)

<table>
<thead>
<tr>
<th></th>
<th>120-mm</th>
<th>30-mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical energy</td>
<td>4.5 MJ</td>
<td>70 kJ</td>
</tr>
<tr>
<td>Chamber volume</td>
<td>9.95 l</td>
<td>155 cc</td>
</tr>
<tr>
<td>Projectile mass</td>
<td>11.4 kg</td>
<td>178 g</td>
</tr>
</tbody>
</table>

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.
V1 + V2 = 547.4 - 100 = 447.4 cm$^3$
V2 = 247 - 100 = 147 cm$^3$
V3 = 100 cm$^3$ (Styrofoam)

V2 = 138 cm$^3$

M256 (120 mm)
\[ V = 9950 \text{ cm}^3 \]
Chamber length = 555 mm
Chamber Diameter = 158 mm

Scaled Value
\[ V = 9950 \left( \frac{30}{120} \right) \]
\[ V = 155 \text{ cm}^3 \]
Modified BRL five module pulse forming network (135kj at 10kV)
<table>
<thead>
<tr>
<th>Radial</th>
<th>Axial W Liner</th>
<th>Axial W/O Liner</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/O Liner</td>
<td>070291</td>
<td>061991</td>
</tr>
<tr>
<td>P1 kHz</td>
<td>P1 kHz</td>
<td>P1 kHz</td>
</tr>
<tr>
<td>10.7</td>
<td>(2.3)</td>
<td>(3.1)</td>
</tr>
<tr>
<td>P2 kHz</td>
<td>P2 kHz</td>
<td>P2 kHz</td>
</tr>
<tr>
<td>12.6</td>
<td>(2.1)</td>
<td>(2.2)</td>
</tr>
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<td>5.7</td>
<td>(12.5)</td>
<td>18.4</td>
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<td>(8.8)</td>
<td></td>
<td>4.2</td>
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<tr>
<td>14.4</td>
<td></td>
<td>19.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(15.9)</td>
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<tr>
<td></td>
<td></td>
<td>20.9</td>
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<tr>
<td></td>
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<td>(23.2)</td>
</tr>
</tbody>
</table>
RADIAL INJECTION
WITHOUT LINER

SET2 070291, P1

SET4 070291, P2
AXIAL INJECTION
WITH LINER

Set1 061991, P1

Set3 061991, P2
AXIAL INJECTION
WITHOUT LINER

Set1 062091, P1

Set3 062091, P2

MPa

0.8s  500.8us  1.8ms  1.5ms TIME
FOURIER ANALYSIS

BALLISTIC RESEARCH LABORATORY

Radial
W/O Liner
070291

Axial
W Liner
061991

Axial
W/O Liner
062091
### RESULTS

Radial Injection (Center Core)

<table>
<thead>
<tr>
<th>ID</th>
<th>P2 MPa</th>
<th>Vol cc</th>
<th>v m/s</th>
<th>liner</th>
<th>ME kJ</th>
<th>EE kJ</th>
<th>Sam. μs</th>
<th>Disp @1ms mm</th>
<th>P MW</th>
<th>Star μs</th>
</tr>
</thead>
<tbody>
<tr>
<td>053091</td>
<td>50</td>
<td>154</td>
<td>73</td>
<td>Y</td>
<td>0.48</td>
<td>-</td>
<td>10</td>
<td>10</td>
<td>-</td>
<td>400</td>
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<tr>
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<td>70</td>
<td>131</td>
<td>79</td>
<td>Y</td>
<td>0.56</td>
<td>67</td>
<td>10</td>
<td>12</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>062591</td>
<td>&gt;150</td>
<td>423</td>
<td>65</td>
<td>N</td>
<td>0.38</td>
<td>67</td>
<td>2</td>
<td>33.5</td>
<td>300</td>
<td>500</td>
</tr>
<tr>
<td>070291</td>
<td>80</td>
<td>383</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>64</td>
<td>2</td>
<td>-</td>
<td>270</td>
<td>-</td>
</tr>
</tbody>
</table>

Axial Injection

<table>
<thead>
<tr>
<th>ID</th>
<th>P2 MPa</th>
<th>Vol cc</th>
<th>v m/s</th>
<th>liner</th>
<th>ME kJ</th>
<th>EE kJ</th>
<th>Sam. μs</th>
<th>Disp @1ms mm</th>
<th>P MW</th>
<th>Star μs</th>
</tr>
</thead>
<tbody>
<tr>
<td>061991</td>
<td>&gt;150</td>
<td>136</td>
<td>202</td>
<td>Y</td>
<td>3.63</td>
<td>69</td>
<td>2</td>
<td>85</td>
<td>300</td>
<td>310</td>
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<tr>
<td>062091</td>
<td>200</td>
<td>&gt;500</td>
<td>182</td>
<td>N</td>
<td>2.95</td>
<td>68</td>
<td>2</td>
<td>-</td>
<td>300</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: Water leakage around projectile in test ID 062591.
CONCLUSIONS

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

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 + H2O,
safe & available,
difficult to ignite,
bulk loaded firing data,
mono-propellant.
INTERFEROMETER DATA
& DISPLACEMENT

Volts

8.0s 250.0us 500.0us 750.0us

Set 06/1991, INTERFEROMETER

TIME

75.0
50.0
25.0
0.0

Set 3 Set 3

TIME, μs

Set 3
INTENTIONALLY LEFT BLANK.
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

Control Volume for Gas
= Total Control Volume
- Volume Occupied by Droplets

Motion of Droplet

Control Volume for Liquid Phase

Projectile Dynamics

Resistant Forces

P_{proj} = \frac{u_p}{-P_{amp}}
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, $\varepsilon$ Two Equation Model
Gas Phase

Continuity Equation

\[
\frac{\partial (p_g \phi)}{\partial t} + \frac{\partial (p_g \phi u_g)}{\partial x} + \frac{\partial (p_g \phi v_g r)}{r \partial r} = S_{gm}
\]

x-Momentum Equation

\[
\frac{\partial (p_g \phi \tilde{u}_g)}{\partial t} + \frac{\partial (p_g \phi \tilde{u}_g \tilde{u}_g)}{\partial x} + \frac{\partial (p_g \phi \tilde{u}_g \tilde{v}_g r)}{r \partial r} \\
= - \frac{\partial (P \phi)}{\partial x} + \frac{\partial}{\partial x} \left[ \phi \mu_{\text{eff}} \left( \frac{4 \partial \tilde{u}_g}{3 \partial x} - \frac{2 \partial \tilde{v}_g}{3 \partial r} - \frac{2 \tilde{v}_g}{3 r} \right) \right] \\
+ \frac{\partial}{r \partial r} \left[ \phi \mu_{\text{eff}} \frac{\partial \tilde{u}_g}{\partial r} + \frac{\partial \tilde{v}_g}{\partial x} \right] - S_{dx} + S_{g x}
\]

r-Momentum Equation

\[
\frac{\partial (p_g \phi \tilde{v}_g)}{\partial t} + \frac{\partial (p_g \phi \tilde{v}_g \tilde{u}_g)}{\partial x} + \frac{\partial (p_g \phi \tilde{v}_g \tilde{v}_g r)}{r \partial r} \\
= - \frac{\partial (P \phi)}{\partial r} + \frac{\partial}{\partial x} \left[ \phi \mu_{\text{eff}} \left( \frac{\partial \tilde{u}_g}{\partial r} + \frac{\partial \tilde{v}_g}{\partial x} \right) \right] \\
+ \frac{\partial}{r \partial r} \left[ \phi \mu_{\text{eff}} \left( \frac{4 \partial \tilde{v}_g}{3 \partial r} - \frac{2 \tilde{v}_g}{3 \partial r} - \frac{2 \partial \tilde{u}_g}{3 \partial x} \right) \right] - S_{dr} + S_{g r}
\]
Gas Phase

Energy Equation

\[
\frac{\partial (p_g \tilde{\phi} \tilde{H})}{\partial t} + \frac{\partial (p_g \tilde{\phi} \tilde{H} \tilde{u}_g)}{\partial x} + \frac{\partial (p_g \tilde{\phi} \tilde{H} \tilde{v}_g r)}{\partial r} = \frac{\partial}{\partial x} \left[ \phi \lambda_{ef} \left( \frac{\partial \tilde{T}_g}{\partial x} \right) \right] + \frac{\partial}{\partial r} \left[ r \phi \lambda_{ef} \left( \frac{\partial \tilde{T}_g}{\partial r} \right) \right] \\
+ \frac{\tilde{a}_d}{\tilde{a}_k} \tilde{S}_p - \tilde{S}_t - \tilde{S}_d - \tilde{P} \frac{\partial \tilde{\phi}}{\partial t}
\]

Equation of State

\[
\tilde{P} = b_p \tilde{P} + R \rho_g \tilde{\tilde{T}}_g
\]
Gas Phase

* Turbulence Model

**k Equation**

\[
\frac{\partial (\rho_g k)}{\partial t} + \frac{\partial (\rho_g \bar{u}_g k)}{\partial x} + \frac{\partial (\rho_g \bar{v}_g kr)}{r \partial r} = \frac{\partial}{\partial x} \left[ \left( \frac{\mu_T}{\sigma_k} + \mu_g \right) \frac{\partial k}{\partial x} \right] + \frac{\partial}{r \partial r} \left[ r \left( \frac{\mu_T}{\sigma_k} + \mu_g \right) \frac{\partial k}{\partial r} \right] + G_k
\]

\[
= \frac{\mu_T}{\rho_g} \frac{\partial}{\partial r} \left( \frac{\partial P}{\partial r} \right) - \frac{\mu_T}{\rho_g} \frac{\partial}{\partial x} \frac{\partial P}{\partial x} - \frac{\partial}{\partial r} \frac{\partial}{\partial x} \frac{\partial P}{\partial x} - \rho_g e + A_s \bar{r}_b \rho_d k
\]

**ε Equation**

\[
\frac{\partial (\rho_g \bar{e})}{\partial t} + \frac{\partial (\rho_g \bar{u}_g \bar{e})}{\partial x} + \frac{\partial (\rho_g \bar{v}_g \bar{e} r)}{r \partial r} = \frac{\partial}{\partial x} \left[ \left( \frac{\mu_T}{\sigma_e} + \mu_g \right) \frac{\partial \bar{e}}{\partial x} \right] + \frac{\partial}{r \partial r} \left[ r \left( \frac{\mu_T}{\sigma_e} + \mu_g \right) \frac{\partial \bar{e}}{\partial r} \right]
\]

\[
+ C_{\varepsilon_1} \varepsilon \frac{\mu_T}{\rho_g} \frac{\partial}{\partial r} \frac{\partial P}{\partial r} \left( \frac{\partial}{\partial x} \frac{\partial P}{\partial x} - \frac{\partial}{\partial r} \frac{\partial}{\partial x} \frac{\partial P}{\partial x} \right) - C_{\varepsilon_2} \rho_g \frac{\varepsilon^2}{k} + A_s \bar{r}_b \rho_d \varepsilon
\]

with

\[
G_k = \frac{4}{3} \mu_T \left[ \left( \frac{\partial \bar{u}_g}{\partial x} \right)^2 - \frac{\partial \bar{u}_g}{\partial x} \left( \frac{\partial \bar{v}_g + \bar{v}_g}{\partial r} \right) \right] + \frac{\partial \bar{v}_g + \bar{v}_g}{\partial r} \frac{\partial \bar{v}_g + \bar{v}_g}{\partial r}
\]

\[
+ \mu_T \left( \frac{\partial \bar{u}_g}{\partial r} \right)^2 - \frac{2}{3} \rho_g k \left( \frac{\partial \bar{u}_g}{\partial x} + \frac{\partial \bar{v}_g + \bar{v}_g}{\partial x} \right)
\]

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Droplet Phase

Droplet Motion:

Small Droplets Follow Flow Motions

Number Density Equation for Group k

\[
\frac{\partial (n_k)}{\partial t} + \frac{\partial (n_k u_g)}{\partial x} + \frac{\partial (n_k v_g r)}{r \partial r} = -C_{1,k} n_k + \sum_{i=1}^{\infty} C_{2,i} n_k + \dot{n}_{k,ea}
\]

(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

\[P_{i,g} = P_{i,l} \text{ (at Ambient Pressure)}\]

\[f_{i,g} = f_{i,l} \text{ (at High Pressure), Equality of Fugacity}\]
Entrainment Mechanism

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

Entrainment Rate:

\[ R_A = K_A \left[ \frac{W_{LF} - W_{LF,C}}{P_e} \right] u_g^2 \rho_g^{1/2} \rho_l^{1/2} \]

- \( R_A \): 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

\[ \frac{d_{32}}{d_t} \left( \frac{\rho_g u_g f_s d_t}{2 \sigma} \right)^{1/2} = 2.3 \times 10^{-2} \]

- \( d_{32} \): Sauter mean diameter
- \( d_t \): hydraulic diameter of tube
- \( f_s \): friction factor for smooth pipe
- \( \sigma \): surface tension

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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

\[
\begin{align*}
ap &= \frac{R_p^* (P_B - P_w) A_{CS} (\cos \theta - C_f \sin \theta) - F_D}{W_p R_p^* (\cos \theta - C_f \sin \theta) + I_p K_p (\cos \theta + C_f \sin \theta)}
\end{align*}
\]
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: \( \tau, \eta, \zeta \)

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

\[
\frac{\partial (\Phi \psi \rho \theta)}{\partial t} = \frac{\partial (\Phi \psi \rho \theta)}{\partial \tau} + u_c \frac{\partial (\Phi \psi \rho \theta)}{\partial \eta} + v_w \frac{\partial (\Phi \psi \rho \theta)}{\partial \zeta}
\]
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

\[ a_p P' = a_E P'_E + a_W P'_W + a_N P'_N + a_S P'_S \]

\[ a_E = (\rho^*_e d_e - K u^*_e) A_\eta \]
\[ a_W = (\rho^*_w d_w - K u^*_w) A_\eta \]
\[ a_S = (\rho^*_s d_s - K u^*_s) A_\zeta \]
\[ a_N = (\rho^*_n d_n - K u^*_n) A_\zeta \]
\[ a_p = (\rho^*_n d_n + \rho^*_s d_s) A_\zeta + (\rho^*_e d_e + \rho^*_w d_w) A_\eta + \frac{K \Delta V}{\Delta t} \]
\[ d_j = \frac{A_j}{a_j} \quad j = e, w, s, n \]
\[ K = \frac{R T_g}{(P_b + R T_g)^2} \]
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
Figure: 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
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
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

<table>
<thead>
<tr>
<th>PPN Discharging Characteristics</th>
<th>Interior Ballistic Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power Time (ms)</td>
<td>Total Discharging Time (ms)</td>
</tr>
<tr>
<td>0.8</td>
<td>2.0</td>
</tr>
<tr>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>1.4</td>
<td>2.0</td>
</tr>
<tr>
<td>1.8</td>
<td>2.0</td>
</tr>
</tbody>
</table>

*Electrical Energy 0.7 MJ, Chemical Energy 0.4 MJ

Results from Numerical Analysis for Cases with Total Discharging Times

<table>
<thead>
<tr>
<th>PPN Discharging Characteristics</th>
<th>Interior Ballistic Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power Time (ms)</td>
<td>Total Discharging Time (ms)</td>
</tr>
<tr>
<td>1.2</td>
<td>1.4</td>
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<tr>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>1.8</td>
<td>2.0</td>
</tr>
</tbody>
</table>

*Electrical Energy 0.7 MJ, Chemical Energy 0.4 MJ
# Interior Ballistic Results from Present Work and Literature

## (a) Measured Results

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

* Data Unavailable  
+ Electrical Efficiency = Projectile Kinetic Energy / Input Electrical Energy  
Ballistic Efficiency = Projectile Kinetic Energy / Total Input Energy

## (b) Predicted Results

<table>
<thead>
<tr>
<th>Source</th>
<th>Gun (mm)</th>
<th>Barrel (caliber)</th>
<th>Projectile Mass (gm)</th>
<th>Muzzle Vel (km/s)</th>
<th>Working Fluid</th>
<th>Electrical Eng (kJ)</th>
<th>Total Eng (kJ)</th>
<th>Electrical Efficiency</th>
<th>Ballistic Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oberle (1988)</td>
<td>14</td>
<td>100</td>
<td>18</td>
<td>2.17</td>
<td>H₂O</td>
<td>447.8</td>
<td>368.6</td>
<td>9%</td>
<td>10.9%</td>
</tr>
<tr>
<td>Oberle (1988)</td>
<td>14</td>
<td>100</td>
<td>18</td>
<td>2.34</td>
<td>LiBH₄</td>
<td>449.8</td>
<td>406.4</td>
<td>10.9%</td>
<td>12.1%</td>
</tr>
<tr>
<td>Oberle (1988)</td>
<td>14</td>
<td>100</td>
<td>18</td>
<td>1.75</td>
<td>TiH₂/Al</td>
<td>77.9</td>
<td>222.2</td>
<td>35.6%</td>
<td>12.5%</td>
</tr>
<tr>
<td>Oberle (1988)</td>
<td>14</td>
<td>100</td>
<td>18</td>
<td>2.13</td>
<td>C₈H₁₈/H₂O₂</td>
<td>43.3</td>
<td>322.6</td>
<td>94.2%</td>
<td>12.6%</td>
</tr>
<tr>
<td>Present Work¹</td>
<td>25</td>
<td>100</td>
<td>70</td>
<td>1.94 - 2.05</td>
<td>C₈H₁₈/H₂O₂</td>
<td>700</td>
<td>1100</td>
<td>18.7%</td>
<td>10.6%</td>
</tr>
</tbody>
</table>

* Max Breech Pressure = 52,900 - 60,200 psi.  
Gun System Information: Projectile Mass = 70 gm, Residual Air = 3%, Chamber Length/Diameter = 3.5.  
Electrical Energy = 0.7 MJ, Total Energy = 1.1 MJ, Working Fluid = C₈H₁₈/H₂O₂
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.
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

Cartridge Case

Cartridge Interior

Stub Case Area

Projectile Tail

Obturator
OUTLINE

FINITE-ELEMENT MODEL
WATER HAMMER TESTS
CLOSED BOMB EXPTS.
IBHVG2 #6 SIMULATION
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!
FINITE-ELEMENT ETC MODEL (FETC)

NAVIER-STOKES EQ. OF MOTION
4th TIME, 2nd SPACE FCT ALG.
UNSTRUCTURED FINITE-ELT. GRID
DETALIED CARTRIDGE GEOMETRY
DETALIED PROPELLANT CHEMISTRY
NAVIER–STOKES

TRANSPORT EQUATIONS

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

STATE VECTOR AND FLUXES

\[
U = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho e \end{bmatrix}, \quad F_a^x = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho u v \\ uH \end{bmatrix}, \quad F_a^r = \begin{bmatrix} r \rho v \\ r \rho u v \\ r \rho v^2 + rp \\ rvH \end{bmatrix}, \quad H = \rho e + p
\]
SCHEMATIC GEOMETRY
BASIC GRID STRUCTURE
SELECTIVELY-REFINED GRID
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

Pressure = 0.2 kBar
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
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

IBHVGS2 AND FETC PROJECTILE TRAVEL

DISTANCE (M) vs TIME (MS)
120 MM IBHVG2 SIMULATION

STUB AND PROJECTILE BASE PRESSURES

Graph showing pressure over time for stub and projectile base pressures.
120 MM FETC SIMULATION
STUB AND PROJECTILE BASE PRESSURES

Pressure (Atmospheres)
(Thousands)

Time, milliseconds

0 1 2 3 4 5 6
120 MM FETC SIMULATION

DETAIL OF PROJECTILE BASE PRESSURE

![Graph showing pressure vs. time for 120 MM FETC simulation.](image)
120 MM FETC GRID
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!
INTENTIONALLY LEFT BLANK.
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™ 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
rangedfinder 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.
SPECIAL DIAGNOSTICS AND INSTRUMENTATION

Prepared by

Dr. Rex D. Richardson

Science Applications International Corporation
Albuquerque, New Mexico

A WORK SUPPORTED BY THE DEFENSE NUCLEAR AGENCY
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

ANODE

COMBUSTION CHAMBER

PROJECTILE

PLASMA JET

PLASMA INJECTOR

TURBULENT ZONE
ENTRAINMENT & MIXING

TAYLOR CAVITY
- Volume
- Density

JET FRONT
PROPAGATION

SAIC
Science Applications
International Corporation
An Employee-Owned Company

RR 91/7974a
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 µS CAP DISCHARGES

DIGITIZE FILM USING CCD VIDEO CAMERA AND FG-BOARD

USE COMPUTER IMAGE PROCESSOR TO EXTRACT AND ENHANCE DENSITOMETRIC DATA
BURN RATE FIXTURE MODIFICATION FOR X-RAY RADIOGRAPHY

SECTION A

CAP OR SFI CLOSURE PLUG

STEEL TUBE

B

CARBON COMPOSITE CYLINDER

BARREL

SECTION B

A

120° SLOTS

213
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

THICK TARGET BREM MODEL → SYNTHESIZE X-RAY SPECTRA FOR HP 150 AND 300 kV TUBES → TUBE VOLTAGE WAVEFORMS OBTAINED FROM HP

SELECT SPECTRUM

SELECT LAYER GEOMETRY HIGH-Z DOPANT, AND DOPANT LOADING FOR BACKGROUND AND TEST ZONES

IMAGE PROCESSOR DYNAMIC RANGE

RUN FSCATT CODE ON BOTH ZONE LAYERS

FILM RESPONSE DATA

NO → CONTRAST ≥ MIN?

YES → XMISSION OK?

CANDIDATE FOR TEST
Abbreviations

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

W   Tungsten
Ba  Barium
Au  Gold

Case 1

Case 2

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

$2t$

$t = 0.5, 0.75, 1.0$

$1.65$

layer thickness (inches)

$2t$
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

- Fill
  - Tap water
  - 20% WC doped gelled water

- 9 mm OD, 7 mm ID Glass Rod
  - Empty
  - 20% WC doped, gelled water

- Graphite Cylinder
  - 1.65" ID
  - 3/4" wall
  - 1/2" wall

- Fill and vent ports
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 TI-3
B-SCREEN TI-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 TI-3
B-SCREEN TI-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 TI-3
B-SCREEN TI-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

- LASER
- DETECTOR
- TARGET
- Transmitted Signal
- Received Signal

\[ L_1 + L_2 = c\tau \]
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Laser Wavelength</td>
<td>820 nm</td>
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<tr>
<td>Laser Pulse Width</td>
<td>50 ps</td>
</tr>
<tr>
<td>Collimated Laser Beam Divergence</td>
<td>0.15 mrad</td>
</tr>
<tr>
<td>Absolute Position Accuracy</td>
<td>2 cm</td>
</tr>
<tr>
<td>Position Jitter</td>
<td>≤ 1.5 cm</td>
</tr>
<tr>
<td>Photodetector Signal Strength</td>
<td>1.0 V</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>40 kHz - 1MHz</td>
</tr>
<tr>
<td></td>
<td>(A/D board options)</td>
</tr>
<tr>
<td>PART</td>
<td>MANUFACTURER</td>
</tr>
<tr>
<td>--------------------------------------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>150mW, 50ps, 1MHz laser diode @ 820nm with collimator</td>
<td>Hamamatsu</td>
</tr>
<tr>
<td>35ps photodetector</td>
<td>Opto-Electronics</td>
</tr>
<tr>
<td>Vibration isolated optical bench</td>
<td>Newport</td>
</tr>
<tr>
<td>Optical components and hardware</td>
<td>Newport/Melles Griot</td>
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<tr>
<td>Analog timing electronics</td>
<td>EG&amp;G/ORTEC</td>
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<tr>
<td>1Mhz, 16 Bit, A/D DAS board</td>
<td>Analogic</td>
</tr>
<tr>
<td>Rack mount PC system</td>
<td>Cyber Research</td>
</tr>
<tr>
<td>DAS software (snapshot)</td>
<td>Cyber Research</td>
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</tbody>
</table>

**Total:** $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
INTENTIONALLY LEFT BLANK.
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 advective 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-ω) 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
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
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

Flexible Boundary Conditions
- Can be coupled to PFN
- Specify equipotential surfaces or current density

Table Driven Material Properties
- Real EOS table
- Conductivity table
Assumption: Time scale to reach thermodynamic equilibrium is smaller than computational time step.

- 4th order FCT
- High order multi-species & energy transport
- Non-iterative scheme for multi-species mixture
- Real EOS for all species including phase transitions
- Molecular + eddy diffusivities
- Multi-species density & energy diffusion
- Chemical reaction

chemistry & reaction rate model
Non-equilibrium two-phase interactions
mass, momentum & energy transfer through drag, heat transfer & droplet evaporation/combustion

Stochastic droplet size distribution
\[ \frac{N_k}{\sum_{1}^{k} N_k} = \int_{D_k}^{D_{k+1}} f(D) \, d(D) \]

Stochastic droplet generation
\[ \dot{m} = F(\tau) \]
Real EOS determine post-reaction thermodynamic states and heat releases

Single Step Chemical Reaction
Fuel + Oxidizer → Products + ΔH

Chemical Kinetics
Arrhenius form "Bulk Burn" rate

Effective Reaction Rate Model
Chemical reaction time scale
Turbulent mixing time scale
Effective reaction rate \( \tau = f(\tau_c, \tau_t) \)

Turbulence Model
Eddy Breakup Time
Turbulent Energy & Dissipation Rate Equations

\[
\begin{align*}
\frac{\partial (\rho \kappa)}{\partial t} + \frac{\partial (\rho u_j \kappa)}{\partial x_j} & = \left( \alpha^* \rho \bar{S} - \beta^* \rho w \right) \kappa \xi^* \rho \frac{\partial u_k}{\partial x_j} \frac{\partial}{\partial x_j} \left[ \mu + \sigma^* \rho e \right] \\
\frac{\partial (\rho w^2)}{\partial t} + \frac{\partial (\rho u_j w^2)}{\partial x_j} & = \alpha^* \rho \bar{S} \left[ \beta + 2 \sigma \left( \frac{\partial l}{\partial x_j} \right)^2 \right] w^2 + \frac{\partial}{\partial x_j} \left[ \mu + \sigma^* \rho e \right] \frac{\partial w^2}{\partial x_j}
\end{align*}
\]

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
Real Equations-of-State

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
- 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

- data calculated from NASA-CET89 code

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

- Gain an understanding of plasma/fluid interactions
- Allow computation of gas generation rates
- Provide data input for model verification
- Provide fuel-oxidizer chemical kinetic data
- Provide ignition delay time and temperature at high P
- Provide data for chemical reaction computer sub-model
- 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
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: $\text{C}_8\text{H}_{18}$, $\text{H}_2\text{O}_2$, $\text{H}_2\text{O}$, $\text{CO}_2$, 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
- 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
- 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
- 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
July 9, 1991

Pressure Waveform Comparison

P1

Model prediction
FMC data

Pressure (kPa)

Time (msec)
PHYSICS OF ETC PLASMA-FLUID INTERACTIONS

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

- End-to-end modeling tools
- Understanding of Fundamental Phenomena
- Diagnostic Capability

Predictive Capability for Design
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 -- Dick Bartsch
tomorrow AM

This talk
Hal Davis
next talk

Los Alamos
Los Alamos ETC Code Uses
Multidimensional Hydrocode Library

- 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:
Los Alamos 20 mm ET Gun

_Used For Code Benchmarking_

<table>
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<tr>
<th>Voltage</th>
<th>4 kV</th>
<th>Energy</th>
<th>22 kJ</th>
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</thead>
<tbody>
<tr>
<td>Current</td>
<td>10 kA</td>
<td>Impedance</td>
<td>0.2 Ω</td>
</tr>
<tr>
<td>Power</td>
<td>22 MW</td>
<td>Max. velocity</td>
<td>0.6 km/s</td>
</tr>
<tr>
<td>Rise time</td>
<td>0.6 ms</td>
<td>Max. pressure</td>
<td>6 kpsi</td>
</tr>
</tbody>
</table>

Los Alamos
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 Interacterion Chamber

- Insulator
- Electrodes
- Projectile
- Liquid Filled Transparent Chamber
- Wire
- Window
- Steel Housing

Los Alamos
ELECTROTHERMAL GUN
WITH TRANSPARENT CHAMBER

- Fiber Glass
- Stainless Steel Body
- Lexan Chamber (liquid filled)
- Lexan Bullet
- Wire
- Spoked Electrode
Electrical Drive Circuit

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
Plasma/Working-Fluid Interacterion Experiment

Flash X-ray Source (200 kV)

Lead Mask

Pressure Probes

Laser Break

Film

Breech Voltage

Breech Current

Los Alamos
Load Voltage Waveform
Load Current Waveform

Los Alamos
Load Electrical Power

Diagram of electrical power over time for Shot 12.
Load Resistance

![Graph showing impedance over time for Shot 12. The graph displays a peak in impedance at around 100 microseconds and a steady increase over time.](image-url)
Chamber Pressure

![Graph showing chamber pressure over time.](image)

Los Alamos
Radiographic Configuration
Copper Fiber - 0.33 mm Diameter

Orientation

Top

2.5 cm

Projectile

4.0 cm

Time

Los Alamos
Static Chamber
Copper - 150 microsec
Copper - 215 microsec
Copper - 385 microsec
RADIOPHASIC CONFIGURATION
Carbon Fiber-0.5 mm Diameter

Orientation

Top

2.5 cm

4.0 cm

Projectile

Time

Los Alamos
Carbon - 70 microsec
Carbon - 200 microsec
Carbon - 300 microsec
Carbon - 400 microsec

SHOT 28
What is the Mechanism Driving A Large Scale Instability?

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

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

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

Los Alamos
Perturbation Is Stabilized

$t = 0.1\ ms$

$t = 0.2\ ms$

Los Alamos
Chamber Pressure vs. Radius at Different Times

![Graph showing chamber pressure versus radius at different times (t = 0.12 ms, t = 0.10 ms, t = 0.08 ms).]
Chamber Pressure vs. Time

![Graph showing chamber pressure over time.](image)

Los Alamos
Perturbation is unstable with time modulation.

0.08 ms

0.12 ms

0.14 ms

r (cm)

z (cm)

Los Alamos
Perturbation is unstable with time modulation.

- 0.18 ms
- 0.20 ms
- 0.22 ms

Los Alamos
Chamber Pressure vs. Radius
At Different Times

Without Modulation

With Modulation

Los Alamos
Chamber Pressure vs. Time

Without modulation

With modulation

Los Alamos
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

- HUNTER & BLAKE give Impetus, $\gamma$
- BKW gives Curve Fit $\gamma(P, T)$

1-D Codes

- XNOVA/KTC: $\gamma = \text{fixed}$
- REAL GAS $\gamma(P, T)$

2-D Codes with Circuit Simulation

- 2D/L: LIQUID PROPELLANT
- 2D/S: SOLID PROPELLANT

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

- MANY APPROXIMATIONS
- $\gamma$ FIXED INCONSISTENT WITH ET-C PROPELLANTS
- AWAITING TEST
- STEAM GUN SIMULATIONS
- ACHIEVED: 99%
- DUPLICATE MODEL: 80%
- INITIAL OPERATION: 100%
- PACKAGED MULTIPLEXED
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
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
EXAMPLE CALCULATION - STEAM GUN WITH CENTERLINE HEATING
DENSITY CONTOURS

-500 kW heat added on centerline

T=0.08 ms
T=0.3 ms
T=0.2 ms
T=0.1 ms

(cm)
EXAMPLE CALCULATION - STEAM GUN WITH CENTERLINE HEATING
PRESSURE CONTOURS
APPLICATIONS

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

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

- Review railgun research relevant to ETC technology
  - Analysis of plasma jets
  - Diagnostics
- Provide references to the relevant literature
Basic References for Railgun Physics

- 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
  5. Vol. 27, January 1991


# Comparison of Plasma Flows

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

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

SA90160J-6
PLASMA PARAMETERS

- **NONIDEAL PARAMETER**

\[
\gamma \equiv \frac{\text{Colomb Energy}}{\text{Thermal Energy}} = \left[ \left( \frac{4\pi}{9} \right)^{1/3} \frac{e^2}{4\pi \varepsilon_0 k} \right] \left[ \frac{\alpha (1+z)}{(1+\alpha)^{2/3}} \right] \frac{n^{1/3}}{T}
\]

- **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

<table>
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<tr>
<th>CATEGORY</th>
<th>REQUIREMENT</th>
<th>IMPLICATION</th>
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<tbody>
<tr>
<td>IDEAL</td>
<td>$\gamma &lt; 1$</td>
<td>Neglect Coulomb energy relative to thermal energy in plasma</td>
</tr>
<tr>
<td>NONIDEAL</td>
<td>$\gamma \geq 0.2$</td>
<td>Must account for Coulomb energy in determining properties</td>
</tr>
<tr>
<td>QUANTUM</td>
<td>$t_D \geq 1$</td>
<td>Free electrons no longer described by Boltzmann statistics, and plasma properties must be based on Fermi–Dirac quantum statistics</td>
</tr>
</tbody>
</table>
METAL-PLASMA ARMATURES ARE TYPICALLY NONIDEAL

Assumes Singly Ionized Plasma
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


Comparison of Measured and Predicted Conductance for Plasma Capillaries

- Predictions assume choked flow
- Measured values denote conductance in units of mhos
- Non-ideal model based on Kurilenkov and Valuev

Ideal

Non-Ideal

1/R (theoretical) vs 1/R (experimental) for different datasets: BRL1, BRL2, BRL3, BRL4, Soreq-34, Soreq-54.
Factors That Influence Current Distributions in Confined and Unconfined Discharges

- 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
THE GOAL OF THE DIAGNOSTIC DEVELOPMENT EFFORT IS TO ACQUIRE THE NECESSARY RAW INFORMATION THAT CAN BE USED TO DETERMINE COMPONENT CHARACTERISTICS AND EML PERFORMANCE.
## Overview of Advanced Railgun Diagnostics

<table>
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<th>Diagnostics</th>
<th>Measured or Inferred Parameters</th>
<th>Issues</th>
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<td>Spectroscopy of plasma armatures</td>
<td>• Composition</td>
<td>• Short optical depths</td>
<td>Keefer, et al.</td>
</tr>
<tr>
<td></td>
<td>• Temperature</td>
<td>• Data interpretation transient</td>
<td>- Ref. 1, p 217</td>
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<td></td>
<td>• Flow Structure</td>
<td>• Coating/shielding</td>
<td>- Ref. 2, p 295</td>
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<tr>
<td>X-ray absorption of plasma armature</td>
<td>• Density</td>
<td>• Initial estimate of components</td>
<td>Clothiaux, et al.</td>
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<tr>
<td></td>
<td>• Composition</td>
<td></td>
<td>- Ref. 1, p 199</td>
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<td></td>
<td>- Ref. 3, p 360</td>
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<td></td>
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<td></td>
<td>Clothiaux, et al.</td>
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<td>- Ref. 1, p 139</td>
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<td>Magnetic B-dots</td>
<td>• Armature current distribution</td>
<td>• 3-D structure</td>
<td>Cobb, et al.</td>
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<tr>
<td></td>
<td>• Armature location</td>
<td>• Quasi-steady assumptions</td>
<td>- Ref. 1, p. 189</td>
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<td>• Orientation</td>
<td>- Ref. 3, p. 507</td>
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<td>On-board diagnostics</td>
<td>• Projectile acceleration and velocity profiles</td>
<td>• Soft-catch</td>
<td>Jamison, et al.</td>
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<td></td>
<td></td>
<td>• Vibrations</td>
<td>- Ref. 2, p. 256</td>
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<td></td>
<td></td>
<td>• Mass/volume of package</td>
<td>Parker</td>
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<td>- Ref. 3, p. 487</td>
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<td></td>
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<td></td>
<td>Smith, et al.</td>
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<td>Bouvier</td>
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<td>- Ref. 3, p. 516</td>
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<td></td>
<td>Fernandez, et al.</td>
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<td>- Ref. 1, p. 185</td>
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<td>Littrell, et al.</td>
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<td>- Ref 4</td>
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<td>Grzesik, et al.</td>
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<td>- Ref. 1, p. 147</td>
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<tr>
<td>Visar</td>
<td>• Velocity profiles</td>
<td>• Shock heating of ambient gas</td>
<td>Asay, et al.</td>
</tr>
<tr>
<td></td>
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<td>• Vaporization of projectile/bore</td>
<td>- Ref. 2, p. 46</td>
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<td>• Blowby</td>
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<td>• Projectile deflection/deformation</td>
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<td></td>
<td></td>
<td>• Mechanical vibrations</td>
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<tr>
<td>Calorimetry</td>
<td>• Total thermal energy delivered to surface</td>
<td></td>
<td>Derbidge, et al.</td>
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<td>- Ref. 1, p. 202</td>
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<tr>
<td>Radiometry</td>
<td>• Heat flux</td>
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<td>Ibrahim</td>
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<tr>
<td></td>
<td></td>
<td>• High powers</td>
<td>- Ref 5, p. 2045</td>
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Reference List for Diagnostics Table

4. Third European Symposium on EML Technology
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

JANNAF Workshop
9-11 July, 1991
Aberdeen, Md
Outline

- 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

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CONVENTIONAL EXTERNAL LAUNCHER
a) INEFFICIENT
d) EASY TO SETUP
b) MULTIPLE PATHS
c) MULTIPLE MODES

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

Los Alamos
\( k = \frac{\omega}{c} \)

\( e^{-jkz} \)

\( k_{\text{imaginary (cut off)}} \)

\( k_{\text{real (propagating)}} \)

\( \omega_{\text{cote}_{11}} \)

\( 2\pi f'_{\text{op}} \)

\( 2\pi f_{\text{op}} \)

\( \omega (= 2\pi f) \)

\( f = \text{Frequency} \)

\( k = \text{Propagation constant} = \frac{2\pi}{\text{guide wavelength}} \)

\( f_{\text{op}} = \text{Operating frequency of conventional interferometer} \)

\( f'_{\text{op}} = \text{Operating frequency of fundamental-mode interferometer} \)

**PROPAGATION OF WAVEGUIDES MODES**
Microwave Interferometer Signal
If MODULATED-LASER-BEAM POSITION SENSOR

\[ \Delta \theta = \frac{4 \pi f \Delta z}{c} \]

\[ f = \frac{1}{30 \text{ cm}} \]

\[ \Delta z = \text{Projectile Displacement} \]

Developer of 500 MHz System
Gabe Luther, P-3 LANL
VISAR

Los Alamos
SIN - (-SIN)

COS - (-COS)

SUM SIGNAL
Line VISAR Velocity H1434

\[ V_{pk} = 5.5 \, \text{km/s} \]

**VELOCITY**

**TIME**

5.0 \text{ msec}

2 = 2.5cm \quad \text{Distance Across Plate}

\[ z = 3.944E+08 \, (500 \times \text{REL. 3}) \]

T = 0
SCHEMATIC OF A VISAR SYSTEM

ref. Barker and Hollenbach,
J. Appl. Phys. Vol. 43, No.11, 4669
PROJECTILE VELOCITY vs TIME

FRINGE DATA FOR PROJECTILE MOTION

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

Los Alamos
Summary

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

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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 kilogees (2.8 X 10^5 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.
IN-BORE ACCELERATION MEASUREMENTS WITH AN INSTRUMENTED RAILGUN PROJECTILE

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
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
INSTRUMENTATION

ACCELEROMETER

ENDEVCO MODEL 7270A-60K
ENDEVCO MODEL 7270A-200K

RECORDER/COMPUTER INTERFACE

IES MODEL 31

GEE SWITCH

ACCUDYNE MODEL 100050-350

POWER SUPPLY

DURACELL MODEL MN1604 (REPACKAGED)
## ACCELEROMETER SPECIFICATIONS

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<td>Model #</td>
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<tr>
<td>Range (kgees)</td>
<td>60</td>
<td>200</td>
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<td>Overrange Limits (kgees)</td>
<td>180</td>
<td>200</td>
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<tr>
<td>Non-Linearity &amp; Hysteresis (%)</td>
<td>±2</td>
<td>±2</td>
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<tr>
<td>Transverse Sensitivity (%)</td>
<td>5</td>
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<td>Frequency Response (kHz)</td>
<td>DC to 100</td>
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<td>Mounted Resonant Frequency (kHz)</td>
<td>700</td>
<td>1200</td>
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<tr>
<td>Mass (grams)</td>
<td>1.5</td>
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HOWITZER TEST SETUP

155mm Howitzer

Hardened 1 Foot Concrete Walls

2x4 Wood Target

SAND

JANNAF ETC Workshop  July 1991
RECODER 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)

*Selectsble at Factory
HOWITZER ACCELERATION DATA

![Graph showing acceleration data with time in milliseconds on the x-axis and acceleration in G's on the y-axis. Major events marked include 1st concrete wall, 2nd concrete wall, projectile leaving the gun barrel sleeve, and 2x4 wood target.](image-url)
STATIC EML SETUP

Transient Field Effects Analysis

Armature

Recorder

Current

Lower Rail

Static EML
EM INDUCED NOISE

With Respect to Circuit Board Orientation

"Perpendicular"

"Parallel"
### SUMMARY OF EML ACCELEROMETER TESTS

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<th>IBID235</th>
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<td>Maximum current (kA)</td>
<td>550</td>
<td>150</td>
<td>821</td>
<td>941</td>
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<td>Distance traveled (m)</td>
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<td>Injection velocity (m/s)</td>
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<td>0</td>
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<td>162</td>
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<td>EML velocity (m/s)</td>
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<td>Injector acceleration (kgee)</td>
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<td>Projectile mass (kg)</td>
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<td>Kinetic energy (kJ)</td>
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<td>Bore size (mm)</td>
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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
VELOCITY AND POSITION VERSUS TIME
OBTAINED VIA INTEGRATION OF IBID235 DATA

![Graph](image)

- **Velocity**
- **Position**

**Axes:**
- **Velocity (m/s)**
- **Position (meters)**

**Time (seconds):**
- 0.0 to 0.05 seconds

**Values:**
- Velocity: 0 to 500 m/s
- Position: 0 to 10.0 meters

---

JANNAF ETC Workshop July 1991

D.M. Littrell
COMPARISON OF VELOCITY MEASUREMENT TECHNIQUES

IBID235

![Graph showing velocity vs position. The graph compares IBID Data and Gun Diagnostics.](image-url)
COMPARISON OF MEASURED AND IDEAL ACCELERATION

IBID235

Acceleration (m/s/s)

- Measured Acceleration
- Difference
- ET Thrust
- Ideal Acceleration

Time (seconds)

0.017
0.0175
0.018
0.0185
0.019
0.0195
0.02

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D.M. Littrell
COMPARISON OF MEASURED AND IDEAL ACCELERATION

IBID197

![Graph showing comparison of measured and ideal acceleration.](image-url)
THEORETICAL ARMATURE RESPONSE TO VARIABLE CURRENT
1-Dimensional, Transient Plasma Armature Model

Armature Length

Time (ms)

Armature Length (cm)
THEORETICAL PROJECTILE ACCELERATION DUE TO VARIABLE CURRENT

1-Dimensional, Transient Plasma Armature Model

![Graph showing simulated and ideal acceleration over time.](image-url)
PROJECTILE ENVIRONMENT
CALCULATED MAGNETIC FIELD INTENSITY

IBID235

Distance from Front of Armature
- 10 cm  -- 15 cm  --- 20 cm

Magnetic Induction Field (Tesla)

Time (seconds)
PROJECTILE ENVIRONMENT
CALCULATED TIME RATE OF CHANGE OF MAGNETIC FIELD INTENSITY

*IBID*235

<table>
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<th>Distance from Front of Armature</th>
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<td>10 cm</td>
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![Graph showing the dB/dt (Tesla/second) vs Time (seconds) for different distances from the front of the armature.](image)
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


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
AGENDA

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, NSSLG

1:15  "Army Alternative 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
8:05 "Electrothermal-Chemical Gun Program"
8:35 "Diagnostics Development for the ETC Program"
9:05 "Development of an Upwind/Implicit Computational Model for the Advancement of Army ETC Guns"
9:40 Break
9:55 "Recent Advances in CAP Gun Modeling"
10:25 "30-MM ETC Ballistic Diagnostic Facility"
10:45 "Numerical Simulation of the Interior Ballistic Processes in an ETC Gun"
11:15 Lunch

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

12:15 "Finite-Element Modeling of Electrothermal-Chemical Guns"
12:45 "Special Diagnostics and Instrumentation"
1:15 Break
1:30 "First Principles Modeling of a DNA 60mm ETC Gun Design"
2:00 "Physics of ETC Plasma-Fluid Interactions"
2:30 "Observations and Modeling of Fundamental Electrothermal Gun Phenomena"
3:00 Adjourn
4:00 Bus leaves from Sheraton Inn to the Inner Harbor
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 Measurement Techniques" R. Bartsch
9:30 Break
9:45 "In-Bore Acceleration Measurements with an 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 ES 26 (Group P-1)
Los Alamos, NM 87545
(505) 667-9977

Dr. Rao L. Boggevarapu
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) 737-7652

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
Dahlgren, VA 22448-5000
(703) 663-8188

Dr. David S. Downes
US Army Armament Research, and
Development & 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-3R, Bldg 382  
Pickett 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. Hsiiao  
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 Resch Ctr/Mech Engr Dept  
140 Research Building "E"  
University Park, PA 16802  
(814) 863-6270

Mr. Donald H. Littrell  
WL/HNSH  
Electromagnetic Launcher Tech Branch  
Hypervelocity Research Complex  
Wright Laboratory/Armament  
Directorate  
Eglin Air Force Base, FL 32542-5434  
(904) 882-0395

Dr. John Handy  
Defense Systems Division  
General Electric Company  
100 Plastics Avenue  
Pittsfield, MA 01201  
(413) 494-5333
Dr. Ingo May
Ballistic Research Laboratory
ATTN: SLCBR-IB
APG, MD 21005-5066
(301) 278-6093

Mr. Hugh A. McElroy
Olin Ordnance
10101 9th Street North
St. Petersburg, FL 33716
(813) 578-8239

Dr. Neile Messina
Princeton Combustion Resch Lab
4275 US Highway One North
Monmouth Junction, NJ 08852
(609) 452-9200

Mr. William Morelli
US Army Armament Research, and
Development & Engineering Center
Electric Armaments Program Office
(EAPO)
ATTN: SMACR-FSC, Bldg 329 Annex
Fire Support Armaments Center
Picatinny Arsenal, NJ 07806-5000
(201) 724-6612

Dr. Walter F. Morrison
Ballistic Research Laboratory
ATTN: SLCBR-IB-B
Aberdeen Proving Ground, MD
21005-5066
(301) 278-6189

Mr. William Oberle
Ballistic Research Laboratory
ATTN: SLCBR-IB-B
Aberdeen Proving Ground, MD
21005-5066
(301) 278-6200

Dr. Gary Phillips
Science Applications Int’l Corp.
10210 Campus Point Drive
San Diego, CA 92121
(619) 546-6603

Dr. John D. Powell
Ballistic Research Laboratory
ATTN: SLCBR-IB-E
Aberdeen Proving Ground, MD
21005-5066
(301) 278-5783

Dr. Rex D. Richardson
Science Applications Int’l Corp.
2109 Air Park Road, SE
Albuquerque, NM 87106
(505) 247-8787

Mr. Todd Rosenburger
Ballistic Research Laboratory
ATTN: SLCBR-IB-A
Aberdeen Proving Ground, MD
21005-5066
(301) 278-6136

Dr. W. J. Sarjeant
Professor, State University of New
York at Buffalo
Department of Electrical Engineering
312 Bonner ECE-SUNY/AB
Buffalo, NY 14260
(716) 636-3117
Also----
W.J. Schafer Associates
(703) 558-7900

Dr. Donald W. Sweeney
Sandia National Laboratories
Combustion Research Facility,
Org. 8351
PO Box 969
Livermore, CA 94550
(415) 294-3138

Mr. Lindsey Thornhill
Science Applications Int’l Corp.
1519 Johnson Ferry Road, Suite 300
Marietta, GA 30062
(404) 973-8935

Mr. David Toeppler
General Dynamics Land Systems
Division
M1 436-21-19
PO Box 2074
Warren, MI 48090-2074
(313) 825-5273

Dr. R. James Trainor
Los Alamos National Laboratory
Group P-1, MS B526
Los Alamos, NM 87545
(505) 667-4879

Ms. Phuong Tran
Ballistic Research Laboratory
ATTN: SLCBR-IB-B
Aberdeen Proving Ground, MD
21005-5066
(301) 278-6199

Dr. Steven Vosén
Sandia National Laboratories
Division 8357
Livermore, CA 94551-0969
(415) 294-3434
Dr. Eduardo Waisman  
S-Cubed Division of Maxwell Labs  
3398 Carmel Mountain Road  
San Diego, CA 92121  
(619) 587-8486

Dr. Kevin White  
Ballistic Research Laboratory  
ATTN: SLCBR-IB-B  
Aberdeen Proving Ground, MD  
21005-5066  
(301) 278-6184

Dr. Melvin Widner  
General Dynamics Land Systems  
Division  
Mail Zone 436-21-14  
PO Box 2074  
Warren, MI 48090-2074  
(313) 825-5072

Mr. G. Mark Wilkinson  
Maxwell Laboratories  
8888 Balboa Avenue  
San Diego, CA 92123  
(619) 576-7589

Dr. Neils K. Winsor  
GT-Devices, Inc.  
5705A General Washington Drive  
Alexandria, VA 22312  
(703) 642-8150

Dr. Ronald L. Woodfin  
Sandia National Laboratories  
Advanced Projects Division V, Org. 9128  
Albuquerque, NM 87185-5800  
(505) 844-3111

Ms. Gloria P. Wren  
Ballistic Research Laboratory  
ATTN: SLCBR-IB-B  
Aberdeen Proving Ground, MD  
21005-5066  
(301) 278-6199

Mr. Alex Zielinski  
Ballistic Research Laboratory  
ATTN: SLCBR-TB  
Aberdeen Proving Ground, MD  
21005-5066  
(301) 278-3883
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